# A PETROPHYSICAL BASIS FOR GROUND PENETRATING RADAR AND VERY EARLY TIME ELECTROMAGNETICS: ELECTRICAL PROPERTIES OF SAND-CLAY MIXTURES 

by

MICHAEL DAVID KNOLL
B.Sc., Haverford College, 1983
M.Sc., Stanford University, 1988

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
in
THE FACULTY OF GRADUATE STUDIES
Department of Earth and Ocean Sciences

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
July 1996
© Michael David Knoll, 1996

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Earth and Ocean Sciences
The University of British Columbia
Vancouver, Canada

Date 31 July 1996


#### Abstract

A series of laboratory experiments was conducted to investigate relationships between electrical properties and hydrogeologic properties of unlithified geologic materials. Mixtures of sand, clay, air and water were used to systematically vary porosity ( 0.24 to 0.80 ), clay content ( 0.00 to 1.00 ), permeability ( $5.4 \times 10^{-12}$ to $4.4 \times 10^{-6} \mathrm{~cm}^{2}$ ) and water saturation ( 0.00 to 1.00 ). Different lithologies were simulated by varying the relative proportion of sand and clay in the mixtures. Compaction was simulated by packing different amounts of the same material into the sample holder. Water saturation was varied by imbibition and evaporative drying. For each mixture, measurements were made of effective electrical conductivity $\sigma_{e f}$ and dielectric constant $\kappa$ over the frequency range 100 kHz to 10 MHz . Conductivity values range from $1.8 \times 10^{-7} \mathrm{~S} / \mathrm{m}$ (dry quartz sand, 100 kHz ) to $1.0 \times 10^{-2} \mathrm{~S} / \mathrm{m}$ (water-saturated kaolinite, 10 MHz ), and dielectric constant values range from 1.9 (dry kaolinite, 10 MHz ) to 200 (dry montmorillonite, 100 kHz ). Crossplots and petrophysical modeling are used to investigate the relationships between the various electrical and hydrogeologic parameters.

Results show that electrical properties depend upon volumetric, geometric and electrochemical factors, and that the relative importance of these factors changes with frequency. For instance, in suites of sand-clay mixtures at low confining pressure, conductivity increases dramatically as clay volume fraction increases from 0.00 to about 0.20 ; this is due to clay packets forming critical conductive paths through the sand framework. At higher clay contents, clay is the load-bearing material and conductivity shows little sensitivity to clay content. This behavior is characteristic of percolation and illustrates the importance of component microgeometry. When the samples are saturated with water, ionic conduction through the fluid replaces surface conduction along the clay as the dominant conduction mechanism. Saturation eliminates much of the frequency dependence observed in the conductivity response of dry sand-clay mixtures.


For a given mixture, conductivity values increase and dielectric constant values decrease with increasing frequency. This is due to the way in which in-phase and out-of-phase components of conduction and polarization currents combine to form the measured electrical parameters. High values of the out-of-phase conduction component are the primary reason why high dielectric constant values (i.e., $\kappa>80$ ) are observed at low frequencies; this component is also the one that is most sensitive to geometric and electrochemical factors. Volumetric factors (e.g., porosity and water saturation) dominate electrical properties at high frequencies, while geometric and electrochemical factors dominate electrical properties at low frequencies.

The experimental data are compared to the predictions of three interrelated petrophysical models: (1) a microgeometrical model which describes the relationship between porosity and clay content in sand-clay mixtures, (2) a permeability model based on the Kozeny-Carmen equation, and (3) a dielectric model which incorporates geometric and electrochemical information through the use of wetted matrix parameters. Results show excellent agreement between predicted and measured data, even though relationships such as porosity-clay content, porosity-permeability and dielectric constant-permeability are nonlinear and multivalued. This suggests that, at least for these mixtures, accurate porosity, permeability and water saturation estimates may indeed be derived from dielectric measurements given appropriate constraints.

The insights developed in this study provide a petrophysical basis for improved modeling, stratigraphic interpretation and inversion of very early time electromagnetic (VETEM) and ground penetrating radar (GPR) field data. Given appropriate constraints, these data may be inverted for hydrogeologic parameters such as porosity, permeability and water saturation.

## TABLE OF CONTENTS

Abstract ..... ii
Table of Contents ..... iv
List of Tables ..... viii
List of Figures ..... ix
Acknowledgements ..... xiv
1 INTRODUCTION ..... 1
1.1 SITE CHARACTERIZATION ..... 1
1.2 GEOPHYSICAL METHODS ..... 2
1.2.1 Ground penetrating radar ..... 3
1.2.2 Very early time electromagnetics ..... 6
1.2.3 Geophysical mapping process ..... 8
1.3 PETROPHYSICAL TRANSFORMS ..... 9
1.4 RESEARCH OBJECTIVES ..... 14
1.5 THESIS OVERVIEW ..... 15
2 ELECTROMAGNETIC FIELDS, WAVES AND PARAMETERS ..... 18
2.1 INTRODUCTION ..... 18
2.2 MAXWELL'S EQUATIONS IN THE TIME DOMAIN ..... 20
2.3 CONSTITUTIVE RELATIONSHIPS ..... 22
2.4 CONDUCTION AND POLARIZATION ..... 26
2.5 FOURIER TRANSFORM CONVENTION ..... 30
2.6 AMPERE'S EQUATION IN THE FREQUENCY DOMAIN ..... 30
2.7 EFFECTIVE PARAMETERS ..... 31
2.8 COMPLEX ADMITTANCE ..... 34
2.9 WAVE EQUATIONS ..... 35
2.10 PROPAGATION PARAMETERS ..... 37
2.11 REFLECTION COEFFICIENTS ..... 39
2.12 SUMMARY ..... 40
3 EXPERIMENTAL DATA BASE AND DIELECTRIC MIXING FORMULAS ..... 41
3.1 INTRODUCTION ..... 41
3.2 EXPERIMENTAL DATA ..... 43
3.3 MATHEMATICAL MODELS ..... 48
3.3.1 Empirical models ..... 51
3.3.2 Phenomenological models ..... 52
3.3.3 Volumetric mixing formulas ..... 54
3.3.4 Effective medium theories ..... 57
3.3.5 Semiempirical models ..... 58
3.4 SUMMARY ..... 62
4 EFFECTS OF COMPACTION AND CLAY CONTENT ON THE DIELECTRIC PROPERTIES OF DRY SAND-CLAY MIXTURES ..... 63
4.1 INTRODUCTION ..... 63
4.2 EXPERIMENTAL METHOD ..... 66
4.2.1 Sample holder ..... 66
4.2.2 Component properties ..... 68
4.2.3 Sample preparation and mixing procedure ..... 70
4.2.4 Electrical measurements ..... 74
4.3 EXPERIMENTAL RESULTS ..... 78
4.3.1 Effects of compaction ..... 79
4.3.2 Effects of changing lithology ..... 85
4.4 DISCUSSION ..... 91
4.4.1 Frequency dependence of electrical parameters ..... 92
4.4.2 Modeling with the Time Propagation equation. ..... 97
4.4.3 Implications for mapping porosity and lithology using GPR and VETEM ..... 103
4.5 SUMMARY ..... 104
5 EFFECTS OF WATER SATURATION ON THE DIELECTRIC PROPERTIES OF SAND-CLAY MIXTURES ..... 105
5.1 INTRODUCTION ..... 105
5.2 SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURE ..... 107
5.3 EXPERIMENTAL RESULTS ..... 113
5.3.1 Pure silica sand ..... 113
5.3.2 Pure kaolinite clay ..... 115
5.3.3 Sand-kaolinite mixtures ..... 119
5.3.4 Drying experiments ..... 126
5.4 DISCUSSION ..... 129
5.4.1 Volumetric, geometric and surface effects ..... 129
5.4.2 Applicability of the Time Propagation Model ..... 131
5.5 SUMMARY ..... 134
6 ESTIMATING PERMEABILITY FROM DIELECTRIC MEASUREMENTS ..... 135
6.1 INTRODUCTION ..... 135
6.2 PERMEABBILITY REVIEW ..... 137
6.2.1 Definition and units ..... 137
6.2.2 Factors that affect permeability ..... 138
6.3 PETROPHYSICAL MODELS ..... 142
6.3.1 Microgeometrical model ..... 143
6.3.2 Permeability model ..... 145
6.3.3 Dielectric model ..... 147
6.3.4 Modeling procedure and parameters ..... 149
6.4 EXPERIMENTAL PROCEDURE ..... 150
6.4.1 Sample preparation ..... 150
6.4.2 Permeability measurements ..... 152
6.4.3 Dielectric measurements ..... 153
6.5 EXPERIMENTAL RESULTS ..... 154
6.6 DISCUSSION ..... 154
6.6.1 Relationship between porosity and clay volume fraction ..... 154
6.6.2 Permeability response ..... 157
6.6.3 Dielectric response ..... 160
6.6.4 Relationship between dielectric constant and permeability ..... 164
6.6.5 Implications for mapping permeability in the field ..... 167
6.7 SUMMARY ..... 177
7 CONCLUSIONS ..... 178
REFERENCES ..... 183
APPENDIX A: COMPENSATION FOR CABLE AND SAMPLE HOLDER RESIDUALS ..... 194
APPENDIX B: ERROR ANALYSIS ..... 202
APPENDIX C: DIELECTRIC CONSTANT-HYDRAULIC CONDUCTIVITY CROSSPLOT. ..... 207
APPENDIX D: EXPERIMENTAL DATA ..... 210

## LIST OF TABLES

Table 1.1. Typical values of dielectric constant, electrical conductivity, velocity and attenuation for different geologic materials at radar frequencies ..... 11
Table 1.2. Typical values of permeability and hydraulic conductivity for different geologic materials ..... 12
Table 3.1. Experimental investigations of the dielectric properties of geologic materials ..... 44
Table 3.2. Dielectric properties of common minerals ..... 47
Table 3.3. Dielectric properties of some important fluids ..... 47
Table 3.4. Mathematical models of dielectric properties ..... 50
Table 4.1. Component properties of silica sand and montmorillonite clay ..... 69
Table 5.1. Component properties of silica sand and kaolinite clay ..... 108
Table 6.1. Component properties of silica sand and kaolinite clay ..... 151
Table 6.2. Summary of measured data ..... 155
Table 6.3. Hydrogeophysical attributes for a hypothetical aquifer comprised of mixtures of silica sand and kaolinite clay at zero confining pressure ..... 169
Table A1. $\quad \mathrm{C}_{\mathrm{p}}$ and $\mathrm{G}_{\mathrm{p}}$ values used for the open/short compensation ..... 198
Table A2. $C_{p}$ and $G_{p}$ values used for the example sample holder compensation ..... 199

## LIST OF FIGURES

Figure 1.1. Three-dimensional radar image of a sand and gravel aquifer, U.S.G.S. Toxic Waste Hydrology Research Site, Cape Cod, Massachusetts ..... 5
Figure 1.2. Flow chart of the geophysical mapping process ..... 10
Figure 3.1. Effective dielectric properties of an idealized geologic material ..... 42
Figure 3.2. Relationship between porosity and dielectric constant for three soils under dry conditions. ..... 46
Figure 3.3. Relationship between volumetric moisture content and dielectric constant for three soils ..... 49
Figure 3.4. Comparison of Arithmetic, CRIM/TPO and BHS dielectric mixing models and the experimental data from Figure 3.3 ..... 56
Figure 3.5. Comparison of Wang and Schmugge's dielectric mixing model and the experimental data from Figure 3.3. ..... 61
Figure 4.1. Cross-sectional diagram of cylindrical sample holder. ..... 67
Figure 4.2. Conceptual diagram of the packing geometries for pure sand, pure clay, and sand-clay mixtures ..... 71
Figure 4.3. Schematic diagram and circuit diagram of the electrical measurement system ..... 75
Figure 4.4. Complex plane plot for a sand-montmorillonite mixture ..... 77
Figure 4.5. Electrical properties versus porosity for silica sand samples at room- dry conditions ..... 80
Figure 4.6. Electrical properties versus frequency for three silica sand samples with different porosities at room-dry conditions ..... 81
Figure 4.7. Electrical properties versus porosity for montmorillonite clay samples at room-dry conditions ..... 82
Figure 4.8. Electrical properties versus frequency for four montmorillonite samples with different porosities at room-dry conditions ..... 84
Figure 4.9. Predicted and observed relationships between porosity and clay weight fraction for sand-montmorillonite mixtures at low confining pressures ..... 86
Figure 4.10. Electrical properties versus porosity for sand-montmorillonite mixtures at room-dry conditions ..... 87
Figure 4.11. Electrical properties versus clay weight fraction for sand- montmorillonite mixtures at room-dry conditions ..... 89
Figure 4.12. Electrical properties versus frequency for six sand-montmorillonite mixtures at room-dry conditions ..... 90
Figure 4.13. Dielectric permittivity versus $\omega^{-1}$, and conductivity versus $\omega$, for room-dry silica sand with porosity equal to 0.397 ..... 94
Figure 4.14. Dielectric permittivity versus $\omega^{-1}$, and conductivity versus $\omega$, for room-dry montmorillonite sand with porosity equal to 0.598 ..... 95
Figure 4.15. Crossplots of the real and imaginary parts of complex permittivity and complex conductivity for pure sand, pure montmorillonite and their mixture ..... 96
Figure 4.16. The square root of the dielectric constant versus porosity for silica sand samples at room-dry conditions ..... 98
Figure 4.17. The square root of the dielectric constant versus porosity for montmorillonite clay samples at room-dry conditions ..... 99
Figure 4.18. Comparison of Time Propagation model with experimental data for room-dry sand-montmorillonite mixtures ..... 102
Figure 5.1. Conceptual diagram of the packing geometries for pure sand, pure clay, and sand-clay mixtures ..... 110
Figure 5.2. Predicted and observed relationships between porosity and clay weight fraction for sand-kaolinite mixtures ..... 111
Figure 5.3. Electrical properties versus porosity for silica sand at room-dry and water-saturated conditions ..... 114
Figure 5.4. Electrical properties versus frequency for silica sand at room-dry and water-saturated conditions ..... 116
Figure 5.5. Electrical properties versus porosity for kaolinite clay at room-dry and water-saturated conditions ..... 117
Figure 5.6. Electrical properties versus frequency for kaolinite clay at room-dry and water-saturated conditions ..... 118
Figure 5.7. Electrical properties versus porosity for sand-kaolinite mixtures at room-dry and water-saturated conditions ..... 121
Figure 5.8. Electrical properties versus clay weight fraction for sand-kaolinite mixtures at room-dry and water-saturated conditions ..... 122
Figure 5.9. Electrical properties versus frequency for room-dry sand-kaolinite mixtures ..... 123
Figure 5.10. Electrical properties versus frequency for water-saturated sand- kaolinite mixtures ..... 125
Figure 5.11. Electrical properties versus water saturation for a clayey sand mixture with porosity equal to 0.36 ..... 127
Figure 5.12. Electrical properties versus water saturation for a sandy clay mixture with porosity equal to 0.36 ..... 128
Figure 5.13. Dielectric constant versus water saturation for two sand-kaolinite mixtures with the same porosity but different clay contents ..... 133
Figure 6.1. Microgeometry of sand-clay mixtures at a given confining pressure ..... 144
Figure 6.2. Predicted and observed relationships between porosity and clay volume fraction for sand-kaolinite mixtures at zero confining pressure ..... 156
Figure 6.3. Permeability versus porosity for sand-kaolinite mixtures ..... 158
Figure 6.4. Permeability versus clay volume fraction for sand-kaolinite mixtures ..... 159
Figure 6.5. Dielectric constant versus porosity for sand-kaolinite mixtures ..... 162
Figure 6.6. Dielectric constant versus clay volume fraction for sand-kaolinite mixtures ..... 163
Figure 6.7. Crossplot of dielectric constant and hydraulic permeability for sand- kaolinite mixtures. ..... 165
Figure 6.8. Comparison between predicted and measured permeability data and dielectric data for sand-kaolinite mixtures ..... 166
Figure 6.9. Predicted relationship between dielectric constant and hydraulic conductivity for samples with different porosities, effective grain sizes, and levels of water saturation ..... 171
Figure 6.10. Time-distance plot for vertical radar profile conducted in well FSW-452-61 ..... 174
Figure A1. Circuit model for cable residuals ..... 196
Figure A2. Circuit model for the sample holder assembly ..... 201
Figure B1. Measured equivalent parallel capacitance values for a set of precision capacitors ..... 204
Figure B2. Measurements of the conductance and capacitance of a Plexiglas sample ..... 206
Figure C1. Relationship between the dielectric constant of the matrix and the specific surface of a material ..... 208

## ACKNOWLEDGMENTS

I would like to thank Rosemary Knight for the opportunity to come to U.B.C. and complete this research. I have benefited greatly from her advice and encouragement over the years; I am also grateful for the financial support that she has provided. Leslie Smith and Garry Clarke served on my advisory committee and provided comments on drafts of this thesis; they also generously contributed funds so that we could purchase a GPR system in 1991. Dr. Gary Olhoeft, as my external examiner, provided numerous comments that helped to improve this thesis. My heartfelt thanks also go out to Roger Beckie who stepped in as a friend at a critical time and suggested a way to bring this thesis to closure.

The most enjoyable aspect of my graduate experience has been working with the other members of the U.B.C. Rock Physics and Ground Penetrating Radar research groups. In particular, I would like to thank Ana Abad, Dave Butler, Christina Chan and Paulette Tercier for their help in the lab over the years. Discussions with David Aldridge, Guy Cross and Rob Luzitano stimulated my interest in environmental geophysics. Tom Clemo and Bruce James taught me much about hydrogeology and kept me out of trouble in the backcountry. Elizabeth Brown assisted with the permeability work described in Chapter 6. I am also grateful for the outstanding machine shop support of Ray Rodway and Doug Polson.

My work at the USGS Cape Cod site would not have been possible without the support of Denis LeBlanc and Kathy Hess. I would also like to thank John Lane for taking time out of his busy schedule to swing up to the Cape Cod site with the borehole radar unit so that we could test the vertical radar profiling idea.

Funding for this research was provided by the Natural Sciences and Engineering Research Council of Canada, and the U.S. Environmental Protection Agency. I would also like to thank Pete Haeni of the U.S. Geological Survey for summer employment opportunities, funding my GPR and seismic work at the Cape Cod site, and allowing me to stay at his farm while conducting field experiments at Haddam Meadows.

Finally, I would like to thank my parents for their moral and financial support over the years, and my wife Noreen Beckie for helping with final production of this document and, more importantly, the love, empathy, encouragement and sound counsel that have helped me to grow through the course of completing this thesis.

## Chapter 1

## Introduction

The electrical properties of composite media are of interest to many research fields. In geophysics, electrical measurements are used to infer the physical and chemical properties of different geologic materials. Because geologic materials can have complicated mineralogies, pore structures, surface properties and microscopic fluid distributions, their electrical responses can also be very complex. Unravelling this complexity is one of the fundamental goals of petrophysics.

In this thesis, I investigate the electrical properties of some simple unlithified geologic materials. The focus is on developing a better understanding of the links between a material's electrical properties (dielectric constant and electrical conductivity) and its hydrogeologic properties (e.g., porosity, permeability and water saturation) observed at the same scale. Petrophysical relationships between electrical and hydrogeologic parameters are needed before geophysical techniques such as ground penetrating radar (GPR) and very early time electromagnetics (VETEM) can realize their potential as hydrogeologic site characterization tools. The experimental results presented in this thesis should be of interest to those involved in modeling, inversion and hydrostratigraphic interpretation of GPR and VETEM data, as well as those with basic interests in the electrical properties of composite materials.

### 1.1 SITE CHARACTERIZATION

Numerical models are often used to simulate groundwater flow and contaminant transport in the subsurface. These models typically include parameters such as porosity, permeability and water saturation to represent the macroscopic hydraulic properties or states of porous media. Values of these parameters must be provided for each grid block and time step in a model. The statistical distribution and spatial connectivity of values are important factors that
can significantly affect the output of flow and transport simulations (Smith and Schwartz, 1981; Journel and Alabert, 1988). For instance, one small permeable sand channel in an otherwise impermeable clay layer can dominate the macroscopic flow and transport behavior of the entire system. This sensitivity of simulation output to simulation input has led many researchers to the conclusion that adequate site characterization is essential for reliable forecasting and cost-effective remediation of actual groundwater contamination problems.

Traditional methods of site characterization rely heavily on direct hydraulic measurements and invasive sampling. Examples of such invasive methods include pump tests, tracer tests, slug tests, flowmeter measurements and core analysis. These measurement techniques provide useful information about hydrogeologic parameter values at specific locations and scales of observation, however these techniques are often plagued by aliasing and resolution problems that limit their cost-effectiveness (Beckie, 1996). For instance, pump tests can sample large volumes of aquifer material, but these tests cannot resolve small permeable or impermeable zones that may control transport behavior. By comparison, borehole flowmeters can resolve small-scale permeability variations along the length of a well, but these instruments have a small measurement volume; if wells in a flowmeter sampling network are too far apart, then flowmeter measurements will alias the permeability field and hence fail to provide information about the spatial connectivity of high and low permeability units. To be effective, site characterization methods must be capable of efficiently sampling a broad range of scales of heterogeneity.

### 1.2 GEOPHYSICAL METHODS

One approach to solving the characterization problem is to incorporate high resolution geophysical methods into site investigations. A wide variety of methods are available, including gravity, magnetic, radiometric, nuclear magnetic resonance, resistivity,
electromagnetic induction, seismic and radar techniques. Each of these methods has limitations which are imposed by site conditions and instrumentation. Olhoeft (1992) provides a good overview of how different geophysical techniques may be used to solve specific site investigation problems. Of particular interest in this thesis are two high-frequency electromagnetic techniques: ground penetrating radar (GPR) and very early time electromagnetics (VETEM). Following is a brief description of these techniques and an overview of the geophysical mapping process.

### 1.2.1 Ground penetrating radar

Ground penetrating radar is a relatively old geophysical technique, having been first developed in Germany in 1926 (Hulsenbeck, 1926). In North America, the method was commercialized more than two decades ago (Morey, 1974) and has since been successfully applied to many engineering and earth science problems. Fundamental principles and case histories can be found in Ulriksen (1982), Daniels et al. (1988) and Davis and Annan (1989).

The basic idea of GPR is similar to reflection seismology. A voltage pulse is radiated into the ground by an antenna; this starts the propagation of an electromagnetic (EM) wave. Whenever the wave encounters a change in electrical properties, part of the energy is reflected or scattered. This backscattered energy may be detected by a receiving antenna on the surface, and then amplified, filtered, digitized and stored by the processing and recording components of the radar system. The result is a record of voltage (amplitude) as a function of time. By moving the antennas and repeating the sounding process, an image of the subsurface can be constructed. Since the process only takes a few seconds per station, thousands of stations can be occupied in a day. This makes GPR one of the fastest and least expensive measurement techniques available.

Most GPR systems use electric dipole antennas that have a bandwidth of about two octaves in the frequency range 1 MHz to 1 GHz . Because of the broad bandwidth and high frequencies employed, GPR has excellent resolving capability. For instance, a typical 100 MHz antenna will transmit energy between about 50 MHz and 200 MHz in air (or about 40 MHz and 160 MHz in the ground) and have a vertical resolution of approximately one meter. Even greater resolution is possible if higher frequency antennas are used (e.g., centimeter scale resolution with 1 GHz antennas), the tradeoff being less depth of penetration. Penetration depths can range from 0 to 60 meters (Smith and Jol, 1995) depending on instrumentation factors (e.g., antenna frequency, transmitter power and receiver sensitivity) and site conditions (Davis and Annan, 1989). The most important factor affecting depth of penetration is the electrical conductivity of the soil. If the conductivity is greater than about $0.050 \mathrm{~S} / \mathrm{m}$, even low frequency antennas (e.g., 12.5 MHz antennas) will image no deeper than a meter. GPR works best in resistive environments with conductivities less than $0.001 \mathrm{~S} / \mathrm{m}$ (Olhoeft, 1984).

As an example of the imaging capabilities of GPR, Figure 1.1 shows part of a threedimensional, 80 MHz , radar data set collected by the author in 1990 at the U.S. Geological Survey's Toxíc Waste Hydrology Research Site on Cape Cod (Knoll et al., 1991). The image, which has had minimal processing, shows a portion of an unconfined sand and gravel aquifer that is contaminated by a sewage plume. The dimensions of the volume are $56 \mathrm{~m}(\mathrm{~N}-\mathrm{S})$ by 22 $\mathrm{m}(\mathrm{E}-\mathrm{W})$ by 15 m (vertical). The data were acquired by taking radar soundings every 10 cm along N-S lines spaced 1.5 meters apart, so that the image in Figure 1.1 shows about 10,000 traces. This is roughly one tenth of the total data set which was acquired in one day by three people. The strong continuous horizontal reflector (blue-orange-blue event) about a third of the way from the top of the image is the water table at a depth of 6 meters; a multiple of this reflection is also apparent. The discontinuous dipping reflectors, some of which cross and appear to bend at the water table, are stratigraphic layers within the glacial outwash deposit,


Figure 1.1. Radar image of the subsurface at the U.S. Geological Survey Toxic Waste Hydrology Research Site, Cape Cod, Massachusetts. The NE, SE, SW and NW corners of the image volume correspond to meter positions $(6.44,129.85),(12.04,185.81),(-9.80$, 188.00 ) and ( $-15.40,132.04$ ), respectively, on the local coordinate system established by LeBlanc et al. (1991, Fig. 8); the horizontal dimensions are 56 m by 22 m . The total vertical scale is $\sim 15$ meters. The prominant reflector (blue-orange-blue event) about a third of the way from the top of the image is the water table ( $\sim 6$ meters depth). Reflections from southwarddipping stratigraphic layers are also apparent.
resolved to a scale of about a meter. Other radar data from the site shows these dipping layers to be part of a large bowl-shaped structure, probably formed when a large block of ice melted out from within the outwash deposit (Knoll et al., 1991). Such structures could potentially affect contaminant migration if indeed there is a relationship between radar stratigraphy and hydrostratigraphy.

The question of correspondence between radar stratigraphy and hydrostratigraphy has yet to be completely answered. Comparisons between GPR, well log and continuous core data suggest that some GPR reflections may be strongly correlated with changes in water saturation, porosity, and/or clay content (Greenhouse et al., 1987; Beres and Haeni, 1991; Huggenberger, 1995). Before more specific and reliable GPR interpretations can be made, a better understanding is required of the interrelationships between these parameters and the electrical parameters that govern EM wave propagation.

### 1.2.2 Very early time electromagnetics

In contrast to ground penetrating radar, very early time electromagnetics is a relatively young geophysical technique. Research and development began in 1990 (Stewart et al., 1994) and the technology has yet to be commercialized (Pellerin et al., 1995). The technique is being developed by a team of leading researchers from academia, the U.S. Department of Energy and the U.S. Geological Survey (Pellerin et al., 1994). What brought these researchers together is the problem of characterizing the uppermost 10 meters of highly conductive sites, since this is where many contamination problems occur. Traditional EM induction methods (e.g., terrain conductivity meters operating in the frequency domain; Haeni, 1986) have poor sounding capabilities and hence poor vertical resolution. Conventional transient EM sounding methods (e.g., Fitterman, 1987) generally cannot detect anomalies shallower than 10 meters due to slow transmitter turn-off and late first-sample times; these techniques are also slow at profiling.

Ground penetrating radar, as discussed in the previous section, cannot penetrate more than a meter if conductivity is high (e.g., if wet clays are present). Because of these limitations, there is a serious gap in the detection capabilities of existing geophysical methods; the purpose of VETEM is to fill this gap.

The VETEM method actually consists of two systems: a frequency domain system (Stewart et al., 1994) and a time domain system (Wright et al., 1995). The time domain system is better for rapid reconnaissance, while the frequency domain system is better for detailed mapping of electrical property variations. Both systems use magnetic loop antennas, instead of electric dipole antennas which become impractically long at low frequencies, to transmit and receive signals in the frequency range 10 kHz to 150 MHz (Wright et al., 1995). The VETEM system also differs from GPR in that the driving function is a current pulse instead of a voltage pulse, and the data must be inverted differently to arrive at an interpretable result.

Much of the VETEM research effort has been directed towards solving the inverse problem which can be very difficult in the kilohertz and low megahertz frequency range. In this frequency range, one cannot make the usual assumptions to simplify the governing EM field equations because both diffusion and propagation are important. The output of VETEM inversions is a map of electrical conductivity and dielectric permittivity values as a function of subsurface position (and sometimes frequency). Resolution of the images is comparable to that of low-frequency radar, i.e., meter scale.

Analysis of published VETEM images (e.g., Stewart et al., 1994) suggests that some imaged structures correlate well with known geology, while other structures do not correlate well. As a result, the same question arises as concerns radar: how should VETEM images be interpreted in terms of hydrogeology? The laboratory experiments on well-characterized
materials described in this thesis provide the petrophysical foundation needed to address this question.

### 1.2.3 Geophysical mapping process

It must be remembered that geophysical parameter values, in and of themselves, are of little value to hydrogeologists and other end-users. For instance, hydrogeologists do not need voltage values measured in a radar survey to run their hydrogeological models. Only by transforming geophysical data to other forms is the data made valuable.

In hydrogeologic applications, geophysics is used primarily to obtain structural information about the subsurface. This includes information about the location, scale and geometry of different units. An implicit assumption is that the boundaries mapped by geophysics also correspond to hydrogeologic boundaries. This is often the case, but not always. At present, surface geophysical data are rarely used to estimate hydrogeologic parameter values of subsurface materials. Instead, other methods, such as well tests, are relied upon to attach hydrogeologic parameter values to the structural units mapped by geophysics. This is an effective approach when many direct hydraulic measurements are available or interpreters have significant experience in an area.

However, there may be additional information about hydrogeologic properties that is currently untapped in EM geophysical data. This would not be surprising considering the evolution of the seismic industry (e.g., bright spots, amplitude versus incidence angle, multicomponent seismology, etc., as fluid and lithology indicators) over past several decades. If inversion and petrophysical transform techniques can be developed to access this information, then geophysical techniques will become even more valuable site characterization tools.

The geophysical mapping process that is envisioned is pictured in Figure 1.2. The first step in the process is acquisition of field data; Annan and Cosway (1991) provide a good description of this step. This is followed by processing to improve image quality (e.g., Fisher et al., 1992; Gerlitz et al., 1993; Annan, 1993). Processing can also yield estimates of EM wave parameters such as velocity, attenuation and reflectivity (Turner, 1994; Tillard and Dubois, 1995). These parameters can be inverted to produce a map of dielectric properties; Duke (1990) and Sena and Toksov (1990) demonstrate the mechanics of this step. Finally, given an understanding of petrophysical relationships (as well as other data such as well test data), the dielectric property map can be transformed to produce one or more hydrogeologic property maps; initial steps in this direction have been made by Sanders (1994).

Although this mapping strategy has yet to be fully demonstrated using EM data, it has been demonstrated using seismic data. In particular, researchers from the University of California and Stanford University have demonstrated through synthetic modeling the potential benefits of incorporating seismic data into field identification of permeability values (Rubin et al., 1992; Copty et al., 1993; Hyndman et al., 1994; Copty and Rubin, 1995).

In my opinion, the weakest link in the geophysical mapping process at the present time is the last step: the petrophysical transform step. In the next section, I review the current state-ofpractise in estimating material properties from EM data.

### 1.3 PETROPHYSICAL TRANSFORMS

Consider the problem of estimating permeability values from radar data, a common inverse problem in site investigations where there is a limited number of direct hydraulic measurements. The current state-of-practise involves the use of look-up tables such as Tables 1.1 and 1.2 which rely on lithology as a bridge. Table 1.1 relates radar parameters to lithology, while Table 1.2 relates lithology to permeability. Suppose that a particular radar unit


Figure 1.2. Flow chart showing important steps in the geophysical mapping process.

Table 1.1. Typical values ${ }^{1}$ of dielectric constant ( $\kappa$ ), electrical conductivity ( $\sigma$ ), velocity $(V)$ and attenuation $(\alpha)$ for different geologic materials at radar frequencies.

| Material | $\kappa$ | $\sigma(\mathrm{mS} / \mathrm{m})$ | $V(\mathrm{~m} / \mathrm{ns})$ | $\alpha(\mathrm{dB} / \mathrm{m})$ |
| :--- | :---: | :---: | :---: | :---: |
| Air | 1 | 0 | 0.30 | 0 |
| Fresh water | 80 | 0.5 | 0.033 | 0.1 |
| Dry sand | $3-5$ | 0.01 | 0.15 | 0.01 |
| Saturated sand | $20-30$ | $0.1-1.0$ | 0.06 | $0.03-0.3$ |
| Shales | $5-15$ | $1-100$ | 0.09 | $1-100$ |
| Silts | $5-30$ | $1-100$ | 0.07 | $1-100$ |
| Clays | $5-40$ | $2-1000$ | 0.06 | $1-300$ |
| Granite | $4-6$ | $0.01-1$ | 0.13 | $0.01-1$ |
| Limestone | $4-8$ | $0.5-2$ | 0.12 | $0.4-1$ |
| Dry salt | $5-6$ | $0.01-1$ | 0.13 | $0.01-1$ |
| Ice | $3-4$ | 0.01 | 0.16 | 0.01 |

[Adapted from Davis and Annan, 1989, p. 535.]

[^0]Table 1.2. Typical values of permeability $k$ and hydraulic conductivity $K$ for different geologic materials.

[From Freeze and Cherry, 1979, p. 29.]
has a dielectric constant of 25 and a conductivity of $1 \mathrm{mS} / \mathrm{m}$. Based on these measurements alone, it would be impossible to determine from Table 1.1 whether the structure is a saturated sand or silt layer. The range of permeability values given in Table 1.2 for sand and silt spans seven orders of magnitude ( $10^{-5}$ to $10^{-12} \mathrm{~cm}^{2}$ ); obviously, there is little value in such an uncertain estimate. In both tables, there is no guide as to the probability that a particular lithology will have a particular dielectric constant, electrical conductivity or hydraulic permeability value. Since the ranges of electrical parameter values and permeability values overlap for different lithologies, lithology is not a good bridge between these parameters.

Next consider a forward modeling problem. Suppose that we know from coring that a unit in the unsaturated zone has a permeability of $10^{-10} \mathrm{~cm}^{2}$, a porosity of 0.20 and a water saturation of 0.40 . What is the dielectric constant and conductivity of this unit? Could the unit be distinguished in a radar survey from another unit that has a permeability of $10^{-6} \mathrm{~cm}^{2}$, a porosity of 0.40 and a water saturation of 0.20 ? These sorts of questions cannot be answered by the information in Tables 1.1 and 1.2.

There is also the question of how the electrical parameter values listed in Table 1.1 are affected by changes in frequency. Table 1.1 is applicable to radar data collected above about 50 MHz . At present, there is no analogous look-up table for VETEM operating at lower frequencies. Furthermore, there have been relatively few laboratory studies of electrical properties in the VETEM frequency range. Most measurements have been made either below 100 kHz or above 100 MHz .

Results of previous laboratory studies (reviewed in Chapter 3) show that numerous parameters can affect the electrical properties of geologic materials, including porosity, clay content, clay mineralogy, permeability and water saturation. Electrical properties are also dependent on frequency, temperature and pressure, to various degrees. All this is complicated
by the fact that petrophysical parameters are often weakly correlated with one another; this makes modeling electrical properties very difficult.

Previous attempts to establish petrophysical transform relationships have been frustrated by the lack of available experimental data on the electrical properties of well-characterized materials. Experimental data are needed that document the effects of varying individual component properties, volume fractions, microgeometries and surface properties. Providing such an extensive, well-characterized, data set is the primary goal of this research.

### 1.4 RESEARCH OBJECTIVES

For GPR and VETEM to realize their full potential, a better understanding is needed of the relationships between electrical and hydrogeologic properties of geologic materials. To this end, I have undertaken a systematic laboratory study of the electrical properties of sand-clay-air-water mixtures as a function of porosity, clay content, clay mineralogy and water saturation. A physical modeling approach is adopted to simulate the coupled parameter changes that occur during compaction, lithologic variation within a facies unit, imbibition and evaporative drying. Crossplots and petrophysical modeling are then used to explore and quantify the relationships between the various parameters.

Specific questions which are addressed include the following:

- How do the electrical properties of sediments vary with porosity, clay content, water saturation and permeability in the frequency range 100 kHz to 10 MHz ?
- How do interrelationships between these hydrogeologic parameters affect electrical properties?
- Is it possible to model electrical properties in this frequency range using a simple volumetric mixing model that incorporates surface effects through the definition of the matrix parameters?
- Can accurate estimates of hydrogeologic parameters be obtained from inversion and petrophysical transformation of electrical measurements?

The physical modeling and systematic laboratory experiments on well-characterized sandclay mixtures are used to answer the first two questions, and the petrophysical modeling is used to address the last two questions.

### 1.5 THESIS OVERVIEW

This thesis is comprised of seven chapters and four appendices. The next chapter (Chapter 2) presents an overview of electromagnetic theory. Its main purpose is to show how electromagnetic parameters measured in the laboratory (e.g., equivalent parallel conductance and capacitance) relate to those measured in the field (e.g., velocity, attenuation and reflectivity). It also provides the necessary background to understand the experimental portion of the thesis.

Chapter 3 reviews some of the previous experimental and theoretical work on electrical properties of geologic materials. Emphasis is placed on identifying the physical parameters and state variables that predominantly influence the electrical response of geologic materials. Different approaches to modeling electrical properties are also summarized. Based on this review, it was concluded that additional laboratory experiments were required to resolve inconsistencies in the experimental data base. These experiments are described in Chapters 4 through 6. To quantify petrophysical relationships, a simple volumetric mixing model was selected for comparison with the new experimental data.

Chapter 4 investigates the effects of compaction (changing porosity) and clay content (changing lithology) on the electrical properties of dry sand-clay mixtures. The apparatus that was built to measure the electrical properties of unconsolidated materials is described in this chapter, as is the technique (physical modeling approach) used to generate mixtures with systematically varying hydrogeologic properties. Results are compared to predictions of the simple volumetric mixing formula. The petrophysical insights developed in this chapter can be used to improve interpretations of electrical measurements made in the unsaturated zone.

The effect of water saturation on the dielectric response of sand-clay mixtures is investigated in Chapter 5. Physical and petrophysical modeling are again used to demonstrate how interrelationships between porosity, clay content and water saturation are responsible for much of the apparent complexity (i.e., scatter) in electrical parameter-hydrogeologic parameter relationships. The volumetric mixing formula is found to fit the experimental data remarkably well when surface effects are incorporated through the definition of the matrix parameters. Results from this chapter also shed light on the relative importance of volumetric and surface effects in different frequency ranges for different materials, and point the way to a possible petrophysical relationship between permeability and dielectric constant.

Chapter 6 investigates the relationship between permeability and dielectric constant of sand-clay mixtures. Results show that permeability and dielectric constant each depend on porosity and specific surface, among other parameters. By coupling models for permeability and dielectric constant that involve these parameters, it is possible to accurately predict the nonunique relationship between permeability and dielectric constant for sand-clay mixtures under low confining pressures. The model is then tested on a surface-to-borehole radar data set acquired at a well characterized field site (the USGS Cape Cod site) where permeability values have been measured with a borehole flowmeter. The field test provides insight into the applicability of the geophysical mapping strategy.

Conclusions of this work and suggestions for further study are summarized in Chapter 7. Appendices A and B describe the calibration, compensation and error analysis of the electrical measurement system. Details about the integrated petrophysical model used for the field test are included in Appendix C. Finally, Appendix D lists all the experimental data for the hundred or so sand-clay-air-water mixtures studied in Chapters 4 through 6.

The insights developed in this study provide a petrophysical basis for improved modeling, stratigraphic interpretation and inversion of GPR and VETEM field data. Given appropriate constraints, these data may be inverted for hydrogeologic parameters such as porosity, permeability and water saturation. This provides strong encouragement for the further development of ground penetrating radar and very early time electromagnetics as hydrogeologic site characterization tools.

## Chapter 2

## Electromagnetic fields, waves and parameters

### 2.1 INTRODUCTION

This chapter reviews electromagnetic (EM) theory as it applies to two problems: (1) laboratory measurement of dielectric properties using impedance analyzers, and (2) field mapping of dielectric properties using GPR and VETEM. Although fundamental aspects of this theory were developed more than a century ago (Maxwell, 1891) and can be found in many textbooks (e.g., Stratton, 1941; Balanis, 1989) and standard publications (IEEE, 1990), there is still some confusion within the geophysical community concerning application of this theory. This confusion is due to differences in the constitutive relationships, EM parameter naming conventions, Fourier transform sign conventions, and domain of application (time or frequency) used by different investigators.

For instance, some authors refer to conductivity and permittivity as being complex quantities (Ruffet et al., 1991), while other authors refer to these parameters as being real and "effective" quantities (Fuller and Ward, 1970). Note that both types of quantities have been used in dielectric mixing formulas and effective media theories (Shen et al., 1985; Knight and Endres, 1990). In some papers constitutive relationships are given in the time domain (Casper and Kung, 1993), while in other papers they are given in the frequency domain (Ward and Hohmann, 1988). In some texts the out-of-phase components of conductivity and permittivity carry the same sign (King and Smith, 1981), while in other texts they carry different signs (Ward and Hohmann, 1988). All this is complicated by the fact that physicists and electrical engineers tend to use different sign conventions for the Fourier transforms of time and space variables.

These observations lead to the following questions: What are the parameters that are measured by impedance analyzers in the laboratory? What are the parameters that are measured by GPR and VETEM in the field? How do these parameters relate to each other and to Maxwell's equations? What parameters should be used in different dielectric mixing formulas and effective medium theories? The purpose of this chapter is to address these questions and hence bridge the gap between theory and practice, laboratory and field. This is accomplished by using a consistent terminology to develop the working time-domain and frequency-domain equations associated with the different EM measurement techniques.

The theoretical development begins with the time-domain differential equations proposed by Maxwell. These equations are coupled via constitutive relationships involving frequencydependent complex parameters that represent the microscopic electromagnetic properties of idealized materials. The concept of effective parameters arises because the out-of-phase component of conduction currents combines with the in-phase component of displacement currents, and vice versa, obscuring microscopic mechanisms. All measured macroscopic quantities are therefore "effective" quantities. For instance, the parameters measured by impedance analyzers in the laboratory are the equivalent parallel conductance and capacitance of a material; under the assumption of quasi-static fields, these parameters are directly proportional to effective electrical conductivity and dielectric permittivity.

Maxwell's equations and the constitutive relationships are then used to derive the EM wave equations. Transformation from the time domain to the frequency domain, and vice versa, is accomplished using the engineer's version of the Fourier transform. The electric field (E-field) wave equation is the one that applies to GPR, since GPR receivers record voltage (amplitude) as a function of time. The magnetic field ( H -field) wave equation is the one that applies to VETEM. The solution to these wave equations includes polarized plane waves that can propagate in any direction. Analysis of the wave equations and their solution leads to
expressions for phase velocity, attenuation, and other propagation parameters. Consideration of boundary conditions leads to expressions for plane wave reflection coefficients. Propagation parameters and reflection coefficients are important parameters that may be determined from GPR and VETEM data.

### 2.2 MAXWELL'S EQUATIONS IN THE TIME DOMAIN

In the late nineteenth century, Maxwell (1891) postulated the following system of equations to describe the macroscopic behavior of EM fields in terms of the sources of these fields:
and

$$
\begin{array}{ll}
\nabla \cdot \mathbf{d}=q_{\nu} & \text { (Gauss's law for electric fields), } \\
\nabla \cdot \mathbf{b}=0 & \text { (Nonexistence of isolated magnetic charge) } \\
\nabla \times \mathbf{e}=-\frac{\partial \mathbf{b}}{\partial t} & \text { (Faraday's law), } \\
\nabla \times \mathbf{h}=\mathbf{j}+\frac{\partial \mathrm{d}}{\partial t} & \text { (extension of Ampere's law). } \tag{2.4}
\end{array}
$$

In these equations $\mathbf{d}$ is dielectric displacement $\left(\mathrm{C} / \mathrm{m}^{2}\right), \mathbf{b}$ is magnetic induction $\left(\mathrm{Wb} / \mathrm{m}^{2}\right), \mathbf{e}$ is electric field intensity $(\mathrm{V} / \mathrm{m}), h$ is magnetic field intensity $(\mathrm{A} / \mathrm{m}), \mathrm{j}$ is electric current density $\left(\mathrm{A} / \mathrm{m}^{2}\right), q_{\nu}$ is volume charge density $\left(\mathrm{C} / \mathrm{m}^{3}\right), t$ is time $(\mathrm{s})$, and $\nabla$ is a vector partial-differential operator. In this thesis, bold characters are used for vector functions and normal characters are used for scalar functions.

The fields $\mathbf{d}, \mathbf{b}, \mathbf{e}, \mathbf{h}$ and $\mathbf{j}$ are real-valued vector functions of space and time; for example, $\mathrm{e}=\mathbf{e}(x, y, z, t)$ in the rectangular coordinate system. At a given position and time, each of these fields can be represented mathematically as the sum of three orthogonal components. For example, the electric field at position ( $x, y, z$ ) can be written $\mathbf{e}=e_{x} \mathbf{n}_{x}+e_{y} \mathbf{n}_{\mathbf{y}}+e_{z} \mathbf{n}_{\mathbf{z}}$, where $e_{x}, e_{y}$ and $e_{z}$ are the components of the field in the directions defined by the unit vectors $\mathbf{n}_{\mathbf{x}}, \mathbf{n}_{\mathbf{y}}$ and $\mathbf{n}_{\mathbf{z}}$. Later these functions will be transformed to the Fourier domain. To help distinguish
physical domain functions from Fourier (i.e., frequency and/or wavenumber) domain functions, lower case letters will be used for physical domain functions [e.g., $\mathrm{e}=\mathrm{e}(x, y, z, t)$ ] and upper case letters will be used for Fourier domain functions [e.g., E (x,y,z, $\omega$ ) and $\left.\mathbf{E}\left(k_{x}, k_{y}, k_{z}, \omega\right)\right]$.

Maxwell's equations recognize two sources of electromagnetic fields: (1) a distribution of electric charge, and (2) a distribution of current. Coulomb discovered in 1785 that electrostatic fields result from stationary charge distributions. The first equation (2.1) states that the total electric flux through any closed surface is equal to the total charge enclosed by that surface; equivalently, the density of charge in a region is equal to the divergence of electric flux density.

The second equation (2.2) states that the divergence of magnetic flux density (i.e., the net magnetic flux through a closed surface) is always zero. This implies that there are no point sources or sinks of magnetic fields, i.e.; no isolated magnetic "charges" analogous to the source of electrostatic fields. Consequently, all magnetic field lines form closed paths.

The third equation (2.3) deals with currents caused by a changing magnetic field. This equation is based on experiments conducted in 1831 by Faraday and Henry. These scientists discovered independently that when a magnet is moved near a closed electric circuit, a current is induced in the circuit. Moreover, as indicated by equation (2.3), the induced electromagnetic force or voltage in the circuit is equal to the time-rate of change of the magnetic flux linkage with the circuit. Unlike the two previous equations, equation (2.3) shows the fundamental interdependence of electric and magnetic fields.

The fourth equation (2.4) also links electric and magnetic field behavior. In 1820, Oersted discovered that a steady electric current produces a circulating magnetic field. Ampere then showed that, under static conditions, the intensity of the magnetic field varies with the electric current density. This led him to propose the equation $\nabla \times \mathbf{h}=\mathbf{j}$ which has come to be
known as Ampere's "law". Maxwell noted an incompatibility between Ampere's law and the continuity equation,

$$
\begin{equation*}
\nabla \cdot \mathbf{j}=-\frac{\partial q_{v}}{\partial t} \tag{2.5}
\end{equation*}
$$

which expresses the principal of charge conservation. To resolve this incompatibility, Maxwell added the displacement current term ( $\partial \mathrm{d} / \partial t$ ) to Ampere's law so that it would remain valid under transient conditions. This seemingly simple addition has profound implications since it predicts the existence of electromagnetic waves and hence unifies the theories of electromagnetism, light and optics.

The previous discussion highlights the fact that, in their most basic form, Maxwell's equations are time-domain equations based on experimental observations of electric and magnetic fields. Although the equations are empirical, no experiment has shown them to be invalid. For this reason, they are the logical starting point for any discussion of electromagnetic field behavior. In addition, it is important to note that Maxwell's equations say nothing about material parameters such as electrical conductivity $\sigma$, dielectric permittivity $\varepsilon$, and magnetic permeability $\mu$. These parameters only take on meaning after certain constitutive relationships (e.g., Ohm's law $\mathbf{J}=\sigma \mathbf{E}$ ) between field vectors are assumed. Equations (2.1) through (2.4) are general in that the media can be nonlinear, heterogeneous and anisotropic; the only restrictions are that the media must be stationary with respect to the coordinate axes and that the dimensions are large compared to atomic scales.

### 2.3 CONSTITUTIVE RELATIONSHIPS

Although $\mathbf{d}$ appears in equations (2.1) and (2.4), and $\mathbf{b}$ appears in equations (2.2) and (2.3), Maxwell's equations are not entirely coupled or determinate. Given the continuity equation (2.5), the two divergence equations (2.1 and 2.2) can be derived from the two curl
equations (2.3 and 2.4). The two curl equations represent six independent scalar equations with 15 unknowns, one unknown for each principal component of $\mathbf{d}, \mathbf{b}, \mathbf{e}, \mathbf{h}$ and $\mathbf{j}$. This means that Maxwell's equations cannot be solved without additional information. The way around this problem is to assume certain constitutive relationships between current density and electric field, dielectric displacement and electric field, and magnetic induction and magnetic field.

In principle, these relationships can take any form (assuming causality and other basic principles also hold); only experimentation can determine their validity. One possible form, deducible from atomic considerations and consistent with most experimental observations, is the following set of steady-state, frequency-domain, equations:
and

$$
\begin{align*}
& \mathbf{J}=\sigma^{*}(x, y, z, \omega, \mathbf{E}, T, P, \ldots) \mathbf{E}  \tag{2.6}\\
& \mathbf{D}=\varepsilon^{*}(x, y, z, \omega, \mathbf{E}, T, P, \ldots) \mathbf{E}  \tag{2.7}\\
& \mathbf{B}=\mu^{*}(x, y, z, \omega, \mathbf{H}, T, P, \ldots) \mathbf{H} \tag{2.8}
\end{align*}
$$

where the proportionality factors $\sigma^{*}, \varepsilon^{*}$ and $\mu^{*}$ are complex tensor functions of position $(x, y, z)$, angular frequency $\omega$, field intensity $\mathbf{E}$ or $\mathbf{H}$, temperature $T$, pressure $P$, and other less important parameters; these proportionality factors or constitutive parameters have been given the names electrical conductivity $(\mathrm{S} / \mathrm{m})$, dielectric permittivity $(\mathrm{F} / \mathrm{m})$ and magnetic permeability ( $\mathrm{H} / \mathrm{m}$ ), respectively.

The functional form of $\sigma^{*}, \varepsilon^{*}$ and $\mu^{*}$ is determined by the behavior of charges at the microscopic scale. As a result, these parameters can be thought of as characterizing the microscopic electromagnetic properties of a material. Specifically, electrical conductivity is a measure of the ability of a material to transport charge, dielectric permittivity is a measure of the ability of a material to polarize or store energy through bound charge separation, and magnetic permeability is a measure of the ability of a material to be magnetized in the presence of an external field.

In this thesis, I make five assumptions about the form of the constitutive parameters. Firstly, I assume that materials are homogeneous at the measurement scale. A homogeneous material is one in which parameter values do not vary with position. Here "position" refers specifically to points within the sample or measurement volume, not necessarily points outside this volume. Although geologic materials are clearly inhomogeneous at microscopic scales, the measurement process effectively filters or averages microscopic properties over some finite volume. As a result, the constitutive parameters actually represent the electromagnetic parameters of a homogeneous material that is electromagnetically equivalent to the measured material. With this understanding, the ( $x, y, z$ ) dependence can be eliminated from equations (2.6), (2.7) and (2.8) for laboratory measurements of electromagnetic parameters.

Secondly, I assume that all materials are isotropic with respect to electromagnetic properties. An isotropic medium is one in which $\sigma^{*}, \varepsilon^{*}$ and $\mu^{*}$ do not vary with the direction of the field vectors; in such a medium, $\mathbf{J}$ is parallel to $\mathbf{E}, \mathbf{D}$ is parallel to $\mathbf{E}$, and $\mathbf{B}$ is parallel to H. Under this assumption, the constitutive parameters become scalar functions.

Thirdly, I assume that the constitutive relationships are linear, i.e., that the relationships between $\mathbf{J}$ and $\mathbf{E}, \mathbf{D}$ and $\mathbf{E}$, and $\mathbf{B}$ and $\mathbf{H}$ are independent of the magnitudes of the fields. This assumption is supported by laboratory experiments on several electrical standard materials (see Appendix B) that show that electromagnetic parameters do not vary significantly with changes in applied voltage over the range of 0.1 to 1 volts. For comparison, voltages in GPR experiments typically range from $10^{-6}$ to $10^{3}$ volts; these voltages are generally assumed to be within the range of linear behavior for most geologic materials, although there are times when this assumption is not valid (e.g., Olhoeft, 1979c).

Fourthly, I assume that constitutive parameters are independent of time, temperature and pressure. Stationarity is assumed only over the small time scales associated with laboratory and field measurements. Over larger time scales, values of the constitutive parameters are
allowed to vary due to changes in other parameters such as the level of water saturation. Temperature and pressure effects at the laboratory and field conditions encountered in this research (i.e., temperatures between $10^{\circ}$ and $30^{\circ} \mathrm{C}$, pressures close to atmospheric) have been shown to be negligible by Topp et al. (1980), Garrouch and Sharma (1994), and many others. These assumptions allow $T$ and $P$ (and time) to be eliminated from the expressions for $\sigma^{*}, \varepsilon^{*}$ and $\mu^{*}$ in equations (2.6), (2.7) and (2.8).

Finally, I assume that the magnetic permeability of all materials investigated in this thesis is frequency independent, purely real, and equivalent to the magnetic permeability of free space, i.e., $\mu_{0}=1.257 \times 10^{-6} \mathrm{H} / \mathrm{m}$. This assumption is adequate for most geologic materials except those containing appreciable amounts of iron, nickel or cobalt (e.g., magnetite, ulvospinel, hematite, ilmenite, maghemite and pyrrhotite) (Strangway, 1972). In the experimental portion of this thesis, care was taken to ensure that no significant magnetic components were present by passing the material through a magnetic separator. Studies where non-free space magnetic properties have been shown to be important include Olhoeft and Strangway (1974) and Olhoeft and Capron (1994).

Given these assumptions, the constitutive relationships in equations (2.6), (2.7) and (2.8) can be written:
and

$$
\begin{align*}
& \mathbf{J}=\left[\sigma^{\prime}(\omega)+i \sigma^{\prime \prime}(\omega)\right] \mathbf{E},  \tag{2.9}\\
& \mathbf{D}=\left[\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)\right] \mathbf{E},  \tag{2.10}\\
& \mathbf{B}=\mu_{0} \mathbf{H}, \tag{2.11}
\end{align*}
$$

where the real and imaginary parts of complex conductivity and complex permittivity are denoted by single (') and double (") primes, respectively, and the signs associated with these parts are chosen to satisfy the condition that parameter values, determined by experimentation, are strictly positive. Note that both real and imaginary parts are frequency dependent; this is a requirement of causal systems involving complex parameters (Fuller and Ward, 1970).

The sign convention adopted in equations (2.9) and (2.10) for the imaginary parts of complex conductivity and complex permittivity is the same as that adopted in Olhoeft (1979b), Ward and Hohmann (1988) and several other studies, although it is not the only sign convention that appears in the literature. For example, some authors such as Sherman (1988) switch the signs associated with $\sigma^{\prime \prime}(\omega)$ and $\varepsilon "(\omega)$ and write $\sigma^{*}(\omega)=\sigma^{\prime}(\omega)-i \sigma^{\prime \prime}(\omega)$ and $\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)+i \varepsilon^{\prime \prime}(\omega)$. Other authors assume that the imaginary part of each constitutive relationship is preceded by the same sign. For instance, King and Smith (1981), Ulriksen (1982) and Turner and Siggins (1994) write $\sigma^{*}(\omega)=\sigma^{\prime}(\omega)-i \sigma^{\prime \prime}(\omega)$ and $\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)$, while Fuller and Ward (1970) and Keller (1988) write $\sigma^{*}(\omega)=\sigma^{\prime}(\omega)+i \sigma^{\prime \prime}(\omega)$ and $\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)+i \varepsilon^{\prime \prime}(\omega)$. This lack of concensus is a potential source of confusion since the sign convention will affect both parameter values and inferred microscopic mechanisms; the non-standardization also makes it difficult to compare results from different experimental studies. As stated above, I advocate the sign convention $\sigma^{*}(\omega)=\sigma^{\prime}(\omega)+i \sigma^{\prime \prime}(\omega)$ and $\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)$ because this convention results in positive values for $\sigma^{\prime}(\omega), \sigma^{\prime \prime}(\omega), \varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$.

One additional comment is required at this stage in the theoretical development. Although the constitutive parameters $\sigma^{*}, \varepsilon^{*}$ and $\mu^{*}$ represent the electromagnetic properties of a material, these are not the parameters that are directly measured in experiments. The parameters measured in experiments are the real, effective, parameters which will be described in Section 2.7. This fact is not recognized or clearly stated in many laboratory dielectric and field GPR/VETEM studies.

### 2.4 CONDUCTION AND POLARIZATION

Electrical properties describe the ability of charge to move inside a material when an external electrical force is applied. There are two "types" of charge movement, depending
upon whether charges are effectively "free" or "bound". In idealized materials comprised only of free charges and bound charges, it is easy to relate characteristics of the electrical response to conduction and polarization mechanisms; for this reason, the following discussion begins with a description of charge movement in "idealized" materials. However, in real materials, it is much more difficult to relate electrical properties to specific conduction and polarization mechanisms. The difficulty springs from the inability to measure directly the complex parameters associated with the movement of so-called free and bound charges.

Let us begin by considering a material that contains both free and bound charges. When an electric field $\mathbf{E}$ is applied, the free charges in the material move to produce a volume current density $\mathbf{J}$. This current density (i.e., the current per unit volume $\Delta v$ of the material) is a function of the number $n$, charge $q$, and velocity $\mathbf{v}$ of charge carriers, i.e.,

$$
\begin{equation*}
\mathbf{J}=\lim _{\Delta \mathrm{v} \rightarrow 0} \frac{\sum_{i=1}^{n} q_{i} \mathbf{v}_{i}}{\Delta \mathrm{v}} \tag{2.12}
\end{equation*}
$$

These charge carriers may be electrons (electronic conduction) or ions (ionic conduction). Their velocity is affected by the number of collisions they have with other charges and so is a function of temperature, pressure and charge size.

Similarly, charges of opposite polarity that are bound to each other will be displaced relative to their equilibrium positions when an $\mathbf{E}$ field is applied. The distorted charge distribution is equivalent, by the principle of superposition, to the original distribution plus a collection of dipoles. If there are $n$ dipoles in the material, the total polarization will be the sum of the moments of these dipoles: $q_{1} \mathbf{d}_{1}+q_{2} \mathbf{d}_{2}+\ldots+q_{n} \mathbf{d}_{\mathrm{n}}$, where $\mathbf{d}$ is the distance vector from $-q$ to $+q$ of each dipole. The polarizability $\mathbf{P}$ of the material is defined as the dipole moment per unit volume $\Delta v$ of the material, i.e.,

$$
\begin{equation*}
\mathbf{P}=\lim _{\Delta v \rightarrow 0} \frac{\sum_{i=1}^{n} q_{i} d_{i}}{\Delta v} \tag{2.13}
\end{equation*}
$$

For materials that exhibit electrically linear behavior, $\mathbf{P}$ will vary directly as the applied electric field

$$
\begin{equation*}
\mathbf{P}=\mathbf{D}-\varepsilon_{0} \mathbf{E}=\left(\varepsilon-\varepsilon_{0}\right) \mathbf{E} \tag{2.14}
\end{equation*}
$$

where $\varepsilon$ is the dielectric permittivity of the material and $\varepsilon_{0}$ is the dielectric permittivity of free space ( $\varepsilon_{0}=8.854 \times 10^{-12} \mathrm{~F} / \mathrm{m}$ ).

There are various ways in which dipoles can be established in materials. Polar molecules such as water possess built-in permanent dipoles and hence tend to have large dielectric permittivities ( $\varepsilon_{\text {water }} \sim 7.083 \times 10^{-10} \mathrm{~F} / \mathrm{m}$ ). In the absence of an applied field, these dipoles, or the molecules themselves, are randomly oriented in the material. When an electric field is applied, the dipolar particles experience a torque which tends to align them with the field; this mechanism is the dipolar or orientational polarization mechanism.

In non-polar materials, the applied $\mathbf{E}$ field actually creates the dipolar species. These species can take different forms, ranging from atoms and molecules with distorted electron clouds (atomic and molecular polarization mechanisms), to mineral grains with polarized surface charge (interfacial polarization or the Maxwell-Wagner effect), to the electrical double layer in adsorbed water films (electrochemical polarization), to regions of the pore space where charge screening occurs (membrane polarization). Note that when the $\mathbf{E}$ field is removed, the bound charges return to their equilibrium positions. Additional information about microscopic and larger-scale polarization mechanisms may be found in von Hippel (1954) and Hasted (1973).

Given this basic understanding of microscopic conduction and polarization mechanisms, let us now relax the assumption that charges are perfectly free or bound at all frequencies. In most real materials, the simple correspondence of movement of free charges to conductivity and displacement of bound charges to permittivity does not hold up at many frequencies. At low frequencies, polarized species can respond instantly to the field so that the net dipole
vectors are aligned in the direction of the $\mathbf{E}$ field vector. At higher frequencies, however, frictional and inertial effects cause the species to begin to lag the $\mathbf{E}$ field. This causes $\mathbf{P}$ to have both an in-phase and an out-of-phase component. This can be represented in equation (2.14) by making $\varepsilon$ complex, i.e., $\varepsilon=\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)$. The out-of-phase component represents charges whose motion follows the time-derivative of the $\mathbf{E}$ field. As will be shown, at the macroscopic scale, this out-of-phase (microscopic) polarization current is indistinguishable from a true conduction current; similarly, the out-of-phase (microscopic) conduction current is indistinguishable from a true polarization current.

For pure materials such as water that have a single, well-defined, polarization mechanism with a corresponding relaxation time $\tau_{r}$, the observed frequency dependence can be accurately modeled using the Debye (1929) model:

$$
\begin{equation*}
\varepsilon^{*}(\omega)=\varepsilon_{\infty}+\frac{\varepsilon_{S}-\varepsilon_{\infty}}{1+i \omega \tau_{r}} \tag{2.15}
\end{equation*}
$$

where $\varepsilon_{S}$ and $\varepsilon_{\infty}$ are the static (zero-frequency) and infinite-frequency dielectric permittivities for the material, respectively, $\omega$ is angular frequency and $\tau_{r}$ is the relaxation time.

In most real materials, there are several polarization mechanisms that contribute to the total polarization response in a given frequency range. Each mechanism may have its own characteristic relaxation time, or spectrum of times. Cole and Cole (1941) suggested the following expression to model such systems:

$$
\begin{equation*}
\varepsilon^{*}(\omega)=\varepsilon_{\infty}+\frac{\varepsilon_{S}-\varepsilon_{\infty}}{1+\left(i \omega \tau_{r}\right)^{1-c}} \tag{2.16}
\end{equation*}
$$

where, in addition to the parameters defined previously, $c$ is the Cole-Cole distribution parameter $(0<c<1)$ which accounts for the distribution of relaxation times. Equation (2.16) is widely used in the literature to model the observed frequency dependence of dielectric permittivity. It can also be used to model the frequency dependence of electrical conductivity and magnetic permeability if the parameters are redefined (i.e., substitute $\sigma$ or $\mu$ for $\varepsilon$ ). Over a
wide frequency range, electrical properties, particularly dielectric permittivity, can exhibit several distinct dispersion events (Hasted, 1973). To model multiple dispersion events, additional terms can be added to the right hand side of equation (2.16) and summed (e.g., Drury, 1978; Olhoeft, 1979b; Olhoeft, 1985). Most researchers work in a restricted frequency range where the phenomenological single-dispersion Cole-Cole model (equation 2.16) is quite applicable.

### 2.5 FOURIER TRANSFORM CONVENTION

Time domain functions can be transformed to the frequency domain by invoking the Fourier transform. Different conventions for the Fourier transform are used by physicists and engineers. In this work, I adopt the engineer's convention that harmonic time dependence is given by $e^{i \omega t}$. This choice of harmonic time dependence corresponds to the Fourier transform pair:

$$
\begin{gather*}
F(\omega)=\int_{-\infty}^{+\infty} f(t) e^{-i \omega t} d t  \tag{2.17}\\
f(t)=\frac{1}{2 \pi} \int_{-\infty}^{+\infty} F(\omega) e^{i \omega t} d \omega \tag{2.18}
\end{gather*}
$$

### 2.6 AMPERE'S EQUATION IN THE FREQUENCY DOMAIN

For harmonic fields with time-dependence $e^{i \omega t}$, equation (2.4) can be rewritten

$$
\begin{equation*}
\nabla \times \mathbf{H}=\mathbf{J}_{\mathbf{c}}+i \omega \mathbf{D}=\mathbf{J}_{\mathbf{t}} \tag{2.19}
\end{equation*}
$$

where the time-derivative $d / d t$ has the Fourier transform pair $i \omega$, and angular and linear frequency are related by $\omega=2 \pi f$. $\mathrm{J}_{\mathbf{c}}$ is the component due to free charge transport, $\mathbf{D}$ is the component due to bound charge polarization, and $\mathbf{J}_{\mathbf{t}}$ is total current density. Combining
equation (2.19) with Ohm's law (2.9) and the constitutive dielectric relation (2.10), yields the following equivalent expressions for $\mathbf{J}_{\mathbf{t}}$ :

$$
\begin{equation*}
\mathbf{J}_{\mathbf{t}}=\left[\sigma^{*}(\omega)+i \omega \varepsilon^{*}(\omega)\right] \mathbf{E}=\left[\left\{\sigma^{\prime}(\omega)+i \sigma^{\prime \prime}(\omega)\right\}+i \omega\left\{\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)\right\}\right] \mathbf{E} . \tag{2.20}
\end{equation*}
$$

### 2.7 EFFECTIVE PARAMETERS

The real and imaginary parts of complex conductivity and complex permittivity in equation (2.20) can be combined to form effective parameters. The equivalent expression is:

$$
\begin{equation*}
\mathbf{J}_{\mathbf{t}}=\left[\sigma_{e f}(\omega)+i \omega \varepsilon_{e f}(\omega)\right] \mathbf{E} \tag{2.21}
\end{equation*}
$$

where the subscript "ef" is used to indicate that the in-phase and out-of-phase components of the electrical response are now being observed at the macroscopic level; note that $\sigma_{e f}$ and $\varepsilon_{e f}$ are each real-valued quantities, things that one can actually measure. The units of $\sigma_{e f}$ and $\varepsilon_{e f}$ are $\mathrm{S} / \mathrm{m}$ and $\mathrm{F} / \mathrm{m}$, respectively. Equation (2.21) is the operational version of Ampere's law that applies to all experimental measurements.

Measured values of $\sigma_{e f}$ range over 29 orders of magnitude, the second largest variation of any physical property (viscosity varies over 40 orders of magnitude) (Olhoeft, 1979b). Typical $\sigma_{e f}$ values for common geologic materials are listed in Table 1.1 of the previous chapter and span about five orders of magnitude $\left(0.00001 \mathrm{~S} / \mathrm{m}<\sigma_{e f}<1 \mathrm{~S} / \mathrm{m}\right)$. Measured values of $\varepsilon_{e f}$ span a slightly smaller range, about four orders of magnitude, from $8.854 \times 10^{-12}$ $\mathrm{F} / \mathrm{m}$ (the permittivity value for free space) to $\sim 1 \times 10^{-7} \mathrm{~F} / \mathrm{m}$ (the permittivity value for wet montmorillonite clay at low frequencies) (Scott et al., 1967); there is still some controversy concerning the maximum possible value for $\varepsilon_{e f \text {. For simple materials like pure gases, liquids }}^{\text {. }}$ and solids (crystals), values of $\varepsilon_{e f}(\omega)$ are approximately equal to the static value $\left[\varepsilon_{e f}(\omega=0)\right]$ for all $\omega$ up to the gigahertz range, and the values for different materials cluster between $8.854 \times$ $10^{-12} \mathrm{~F} / \mathrm{m}$ and $7.083 \times 10^{-10} \mathrm{~F} / \mathrm{m}$ (the permittivity value for water). As a result, to simplify reporting, most people normalize $\varepsilon_{e f}$ values by the permitivity of free space, and define:

$$
\begin{equation*}
\kappa \equiv \frac{\varepsilon_{e f}(\omega)}{\varepsilon_{0}}, \tag{2.22}
\end{equation*}
$$

so that $\kappa$ values for simple materials range from 1 (free space) to 80 (water). The real-valued dimensionless parameter $\kappa$ is called the "real effective relative dielectric permittivity", or simply "dielectric constant" for short. Some people do not like the term dielectric constant because $\kappa$ can vary with frequency as equation (2.22) clearly indicates; nevertheless, this is the term that is used in most of the literature and in this thesis.

Equating equations (2.20) and (2.21), the relationships between effective and complex parameters become apparent, i.e.,

$$
\begin{align*}
& \sigma_{e f}(\omega)=\sigma^{\prime}(\omega)+\omega \varepsilon^{\prime \prime}(\omega),  \tag{2.23}\\
& \varepsilon_{e f}(\omega)=\varepsilon^{\prime}(\omega)+\frac{\sigma^{\prime \prime}(\omega)}{\omega} . \tag{2.24}
\end{align*}
$$

Similarly, one can expand equation (2.22) to explicitly show the contributions of $\varepsilon^{\prime}(\omega), \sigma^{\prime \prime}(\omega)$ and $\omega$ to the dielectric constant:

$$
\begin{equation*}
\kappa=\frac{\varepsilon^{\prime}(\omega)}{\varepsilon_{0}}+\frac{\sigma^{\prime \prime}(\omega)}{\omega \varepsilon_{0}} \tag{2.25}
\end{equation*}
$$

Equations (2.23), (2.24) and (2.25) are important because they show that the real parameters $\sigma_{e f}, \varepsilon_{e f}$ and k measured in the laboratory or in the field will each include contributions from both free and bound charge carriers, and depend upon angular frequency $\omega$. These macroscopic parameters combine all effects from both free and bound charges into a single complex quantity $\left[\sigma_{e f}(\omega)+i \omega \kappa(\omega) \varepsilon_{0}\right.$ ], while the microscopic parameters $\sigma^{\prime}(\omega), \sigma^{\prime \prime}(\omega)$, $\varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$ describe in-phase and out-of-phase effects from idealized "types" of charges.

In terms of microscopic mechanisms, $\sigma$ ' represents energy transfer by charge migration (ohmic conduction), $\varepsilon^{\prime}$ is energy transfer by displacement currents, $\sigma^{\prime \prime}$ is energy loss due to faradaic diffusion, and $\varepsilon^{\prime \prime}$ is energy loss due to polarization lag. Except at high frequencies, the real parts should be greater than the imaginary parts of $\sigma^{*}$ and $\varepsilon^{*}$ for most materials,
though one should think twice about dropping $\sigma^{\prime \prime}$ and $\varepsilon^{\prime \prime}$ from equations (2.23) or (2.24) at any frequency because these components are scaled by angular frequency. In this thesis, I make no assumptions about the relative size or importance of $\sigma^{\prime}, \sigma^{\prime \prime}, \varepsilon^{\prime}$ and $\varepsilon^{\prime \prime}$, but instead just show the measured effective parameters $\sigma_{e f}$ and $\kappa$.

Given causality, it should be possible to invert measurements of $\sigma_{e f}(\omega)$ and $\varepsilon_{e f}(\omega)$ to obtain estimates of $\sigma^{\prime}(\omega), \sigma^{\prime \prime}(\omega), \varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$ (Fuller and Ward, 1970; Sherman, 1988). There are four equations and four unknowns. Two of the equations are the non-linear equations (2.23) and (2.24). The other two equations result from the causality condition. This condition requires that $\sigma^{\prime}(\omega)$ and $\sigma^{\prime \prime}(\omega)$, and $\varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$, satisfy the Kramers-Kronig dispersion relationship and be Hilbert transform pairs. For example, for conductivity, the equations are:

$$
\begin{gather*}
\sigma^{\prime}(\omega)=-\frac{1}{\pi} p \int_{-\infty}^{\infty} \frac{\sigma^{\prime \prime}\left(\omega^{\prime}\right)}{\omega-\omega^{\prime}} d \omega^{\prime}  \tag{2.26}\\
\text { and } \quad \sigma^{\prime \prime}(\omega)=\frac{1}{\pi} p \int_{-\infty}^{\infty} \frac{\sigma^{\prime}\left(\omega^{\prime}\right)}{\omega-\omega^{\prime}} d \omega^{\prime}  \tag{2.27}\\
\text { or, equivalently, } \quad \sigma^{\prime \prime}(\omega)=\sigma^{\prime}(\omega) * \frac{1}{\pi \omega} \tag{2.28}
\end{gather*}
$$

where * indicates convolution, and $p$ indicates exclusion of the singular point $\left(\omega^{\prime}=\omega\right)$ or definition of the integral as the Cauchy principle value (Fuller and Ward, 1970; Sherman, 1988). However, in practice, the system of equations is difficult to solve and requires accurate (four-electrode) measurements over a broad frequency range. To my knowledge, only Olhoeft (1979c, 1985) and Sherman (1988) have performed such an inversion and obtained estimates of $\sigma^{\prime}(\omega), \sigma^{\prime \prime}(\omega), \varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$. All other studies that I am aware of report either effective parameters $\sigma_{e f}$ and $\varepsilon_{e f}$ or some other concoction such as "complex" parameters inferred from
fits to the Cole-Cole model. Further discussion of the distinction between complex and effective parameters may be found in Fuller and Ward (1970).

Unless otherwise stated, all parameters reported in this thesis are real effective parameters. For notational convenience, sometimes the subscript ef is dropped. In addition, all effective parameters are frequency dependent, whether explicitly stated or not.

### 2.8 COMPLEX ADMITTANCE

There are many ways to measure effective conductivity $\sigma_{e f}$ and permittivity $\varepsilon_{e f}$. Olhoeft (1979b) provides an overview of the most important laboratory measurement techniques. The technique that $I$ use in this thesis (Chapters 4 through 6) is based on simple inversion of frequency-domain complex admittance measurements of samples in a two-electrode paralleldisk sample holder. The inversion formulas are based on quasi-static theory (Shen et al., 1987). The measurements are made with a Hewlett Packard 4192A low-frequency impedance analyzer over the frequency range of 100 kHz to 10 MHz .

The Hewlett Packard 4192A impedance analyzer is an auto-balancing bridge that effectively allows one to determine the series or parallel resistor-capacitor $(R C)$ circuit that is equivalent to a sample. When the admittance of geologic materials is measured, a parallel $R C$ circuit is generally assumed. The relationship between admittance and the circuit elements is:

$$
\begin{equation*}
Y=G_{p}+i \omega C_{p} \tag{2.29}
\end{equation*}
$$

where $G_{p}$ is parallel conductance $[\mathrm{S}]$ and $C_{p}$ is parallel capacitance $[\mathrm{F}]$.
The problem now is to relate the measured parameters, $C_{p}$ and $G_{p}$, to the parameters of interest, $\varepsilon_{e f}$ and $\sigma_{e f}$. The usual approach is to solve the electromagnetic boundary value problem for $\varepsilon_{e f}$ and $\sigma_{e f}$ given the sample holder geometry and assuming quasi-static electromagnetic field theory (Shen et al., 1987). In this theory, magnetic effects are neglected
entirely, as are higher-order terms of the electric field; the quasi-static field is the zeroith-order electric field. The solutions are:

$$
\begin{align*}
\sigma_{e f} & =\frac{G_{p} d}{A}  \tag{2.30}\\
\varepsilon_{e f} & =\frac{C_{p} d}{A} \tag{2.31}
\end{align*}
$$

where $A$ is the area and $d$ the separation of the two electrode surfaces.
Shen et al. (1987) compare equations (2.30) and (2.31), derived from quasi-static theory, to the expression for admittance derived from more rigorous dynamic electromagnetic field theory, i.e.,

$$
\begin{equation*}
Y=G_{p}+i \omega C_{p}=\frac{A}{d}\left(\sigma_{e f}+i \omega \varepsilon_{e f}\right) \frac{2 J_{1}(k r)}{k r J_{0}(k r)} \tag{2.32}
\end{equation*}
$$

where $J_{0}$ and $J_{I}$ are Bessel functions of orders 0 and 1 , respectively, $r$ is the radius of the electrode surface, and $k$ is the wavenumber (see Section 2.9 for definition). Their analysis shows that equations (2.30) and (2.31) are only accurate if the term containing the Bessel functions in equation (2.32) is close to unity; this only occurs if frequency is less than 20 MHz and $\sigma_{e f}$ is less than $0.3 \mathrm{~S} / \mathrm{m}$. As shown in subsequent chapters, both these conditions are met in my work, hence I used the simpler equations (2.30) and (2.31) for my inversions. Equation (2.32) shows the rigorous link between the parameters measured in the laboratory ( $Y=G_{p}+$ $i \omega C_{p}$ ) and the parameters measured in the field ( $k$ and other propagation parameters).

### 2.9 WAVE EQUATIONS

Taking the curl of both sides of Faraday's law (2.3), substituting the magnetic constitutive relation (2.11), then substituting (2.4) and (2.21) yields, after some vector algebra, the frequency-domain representation of the electric-field wave equation:

$$
\begin{equation*}
\nabla^{2} \mathbf{E}=-\left(\omega^{2} \mu_{e f} \varepsilon_{e f}-i \omega \mu_{e f} \sigma_{e f}\right) \mathbf{E} \tag{2.33}
\end{equation*}
$$

The corresponding magnetic-field wave equation is:

$$
\begin{equation*}
\nabla^{2} \mathbf{H}=-\left(\omega^{2} \mu_{e f} \varepsilon_{e f}-i \omega \mu_{e f} \sigma_{e f}\right) \mathbf{H} \tag{2.34}
\end{equation*}
$$

Both these equations (2.33 and 2.34) are also known as the Helmholz equation. The quantity in parentheses on the right hand side of equations (2.33) and (2.34) is the square of the complex wavenumber $k$, i.e.,

$$
\begin{equation*}
k^{2}=\omega^{2} \mu_{e f} \varepsilon_{e f}-i \omega \mu_{e f} \sigma_{e f} \tag{2.35}
\end{equation*}
$$

This quantity groups the three fundamental electromagnetic parameters and frequency together, and hence fully characterizes the interaction of the EM field with the medium. Physically, the wavenumber $k$ gives the magnitude of the wave vector in the direction of propagation.

Before developing expressions for propagation parameters, it is worthwhile to consider the wavenumber definition in equation (2.35). Some authors define it differently and hence there is potential for confusion. For instance, some authors (e.g., Ulaby et al., 1981; Duke, 1990) write the E-field wave equation (2.33) as:

$$
\begin{equation*}
\nabla^{2} \mathrm{E}=-\left(\omega^{2} \mu_{e f} \mathrm{E}_{T}^{*}\right) \mathrm{E} \tag{2.36}
\end{equation*}
$$

where $k^{2}=\omega^{2} \mu_{e f} \varepsilon_{T}^{*}$, and $\varepsilon_{T}^{*}$ is a new parameter called the complex total permittivity. In this case, as discussed by Powers et al. (1992), $\varepsilon_{T}^{*}$ must be defined as $\varepsilon_{T}^{*}=\left(\varepsilon^{\prime}-i \varepsilon^{\prime \prime}\right)-i\left(\sigma^{\prime} / \omega+\right.$ $i \sigma " / \omega$ ). In other cases (e.g., Olhoeft, 1976; Olhoeft, 1981), the same equation is written in diffusion equation form, i.e.,

$$
\begin{equation*}
\nabla^{2} \mathbf{E}=i \mu_{e f} \omega \sigma_{T}^{*} \mathbf{E} \tag{2.37}
\end{equation*}
$$

where $k^{2}=i \mu_{e f} \omega \sigma_{T}^{*}$, and $\sigma_{T}^{*}$, the complex total conductivity, must be defined as $\sigma_{T}^{*}=\left(\sigma^{\prime}+\right.$ $\left.i \sigma^{\prime \prime}\right)+i \omega\left(\varepsilon^{\prime}-i \varepsilon^{\prime \prime}\right)$. For equations (2.33), (2.36) and (2.37) to be equivalent, $\sigma_{T}^{*}$ must be related to $\varepsilon_{T}^{*}$ by the relationship $\sigma_{T}^{*}=i \omega \varepsilon_{T}^{*} \quad$ (Powers et al., 1992).

To complicate matters further, some authors write the E-field wave equation (2.33) as:

$$
\begin{equation*}
\nabla^{2} E=\gamma^{2} E \tag{2.38}
\end{equation*}
$$

where $\gamma=i k$ is called the propagation constant. Like the wavenumber, the propagation constant is a complex quantity. The confusion lies in the terms used to describe the real and imaginary parts of the propagation constant and the wavenumber. Some authors (e.g., Ulriksen, 1982; Duke, 1990) write $\gamma=\alpha+i \beta$ and refer to $\alpha$ as the attenuation constant and $\beta$ as the phase constant; this is consistent with the IEEE standard definition (IEEE, 1990) that phase is the real part of the wavenumber and attenuation is the imaginary part (i.e., $k=\beta-i \alpha$ ). However, other authors (e.g., Stratton, 1941; Ward and Hohmann, 1988) write $k=\alpha-i \beta$ and refer to $\alpha$ as the phase constant and $\beta$ as the attenuation constant, hence reversing the names of $\alpha$ and $\beta$ (Powers et al., 1992). In this thesis, I follow the IEEE standard definition.

### 2.10 PROPAGATION PARAMETERS

Solutions to the Helmholz equations include polarized plane waves that may propagate in any direction. For example, a time-harmonic wave propagating in the positive $z$-direction with electric field parallel to the $x$-direction is described by:

$$
\begin{equation*}
\mathrm{E}(z, t)=\mathrm{E}_{0} e^{i(\omega t-k z)} \mathbf{n}_{\mathbf{x}} \tag{2.39}
\end{equation*}
$$

where $\mathrm{E}_{0}$ is the magnitude at timezero of the electric field at the origin $[\mathrm{V} / \mathrm{m}]$, and $\mathbf{n}_{\mathbf{x}}$ is the unit vector in the $x$-direction.

In this thesis, I define the propagation constant $\gamma$ and the wavenumber $k$ as:

$$
\begin{equation*}
\gamma=\alpha+i \beta \quad \text { and } \quad k=\beta-i \alpha \tag{2.40}
\end{equation*}
$$

where $\alpha$ is the attenuation constant and $\beta$ is the phase constant. Taking the square root of equation (2.35) and solving for real and imaginary parts leads to the following expressions for $\alpha$ and $\beta$ :

$$
\begin{equation*}
\alpha=\omega \sqrt{\frac{\mu \varepsilon_{e f}}{2}\left(\sqrt{1+\left(\frac{\sigma_{e f}}{\omega \varepsilon_{e f}}\right)^{2}}-1\right)} \tag{2.41}
\end{equation*}
$$

$$
\begin{equation*}
\beta=\omega \sqrt{\frac{\mu \varepsilon_{e f}}{2}\left(\sqrt{1+\left(\frac{\sigma_{e f}}{\omega \varepsilon_{e f}}\right)^{2}}+1\right)} \tag{2.42}
\end{equation*}
$$

The ratio $\sigma_{e f} f \omega \varepsilon_{e f}$ is very important because it governs the overall behavior of propagation. This ratio is called the loss tangent, i.e.,

$$
\begin{equation*}
\tan \delta=\frac{\sigma_{e f}}{\omega \varepsilon_{e f}} \tag{2.43}
\end{equation*}
$$

Equation (2.41) shows that for constant permittivity and frequency, attenuation increases as conductivity increases. For constant permittivity and conductivity, attenuation increases as frequency increases.

Re-expressing the solution to the wave equation (2.39) in terms of the attenuation and phase constants yields:

$$
\begin{equation*}
\mathbf{E}(z, t)=\mathrm{E}_{0} e^{-\alpha z} e^{i(\omega t-\beta z)} \mathbf{n}_{\mathbf{x}} \tag{2.44}
\end{equation*}
$$

The first exponential term in equation (2.44) governs the intrinsic attenuation of the wave, while the second exponential term governs propagation.

From the first exponential term in equation (2.44) it is apparent that the magnitude of the electric field normalized by $\mathrm{E}_{0}$ will decay to $1 / e$ at a distance $z=1 / \alpha$. This distance is called the skin depth $\Delta$, i.e.,

$$
\begin{equation*}
\Delta=\frac{1}{\alpha} \tag{2.45}
\end{equation*}
$$

The attenuation factor (or skin depth) can be used in conjunction with system performance factors and target information to estimate the penetration depth or range of GPR in different field situations (Davis and Annan, 1989).

The second exponential term in equation (2.44) determines the phase velocity $v$ and wavelength $\lambda$ of a plane wave, i.e.,

$$
\begin{equation*}
v=\frac{\omega}{\beta} \tag{2.46}
\end{equation*}
$$

and

$$
\begin{equation*}
\lambda=\frac{2 \pi}{\beta}=\frac{\nu}{f} . \tag{2.47}
\end{equation*}
$$

Keeping other parameters constant, phase velocity decreases with increasing permittivity, increasing frequency, and decreasing conductivity. In low loss materials $(\tan \delta \ll 1)$, equation (2.46) reduces to the following commonly used approximation:

$$
\begin{equation*}
v \approx \frac{c_{0}}{\sqrt{\kappa}} \tag{2.48}
\end{equation*}
$$

where $c_{0}$ is the speed of light in a vacuum ( $c_{0}=2.998 \times 10^{8} \mathrm{~m} / \mathrm{s}$ ), and $\kappa$ is the measured dielectric constant. Because variation in $\kappa$ is less than variation in $\sigma_{e f}$ for most earth materials, phase velocity is usually less variable than attenuation.

### 2.11 REFLECTION COEFFICIENTS

Electrical impedance $Z$ is defined as the ratio of the amplitude of the orthogonal electric and magnetic field pairs, i.e.,

$$
\begin{equation*}
Z=\frac{|\mathbf{E}|}{|\mathbf{H}|}=\sqrt{\frac{i \omega \mu_{e f}}{\sigma_{e f}+\omega \varepsilon_{e f}}} . \tag{2.49}
\end{equation*}
$$

Impedance is the reciprocal of admittance (see Section 2.9). When a propagating EM wave impinges upon a boundary between two layers, 1 and 2 , some of the energy will be reflected and some of the energy will be transmitted. The partitioning of energy depends on the angle of incidence of the wave and the contrast in impedance across the layers.

Most GPR surveys are conducted with transmitter and receiver antennas separated only a short distance (1-2 meters). Except for very shallow reflectors, most incidence angles in GPR surveys are close to 90 degrees. The normal incidence reflection coefficient $R C$ is defined as:

$$
\begin{equation*}
R C=\frac{Z_{2}-Z_{1}}{Z_{2}+Z_{1}} \tag{2.50}
\end{equation*}
$$

where $Z_{1}$ and $Z_{2}$ are the intrinsic impedances of layers 1 and 2 , respectively. The transmission coefficient is defined as $1-R C$. Propagation parameters and reflection coefficients are important parameters that may be determined from inversion of GPR and VETEM field data.

### 2.12 SUMMARY

This chapter presents a review of electromagnetic theory as it applies to laboratory and field measurement of electrical properties. The review is unique in that it draws connections between the different types of parameters used by theorists, instrument designers, laboratory experimentalists and field geophysicists. It is hoped that this will help reduce some of the confusion that exists in the literature and in general practice. The development also provides the necessary theoretical background to interpret the laboratory measurements described in Chapters 4 through 6.

## Chapter 3

## Experimental data base and dielectric mixing formulas

### 3.1 INTRODUCTION

To extract hydrogeologic information such as porosity, clay content and water saturation values from ground penetrating radar and very early time electromagnetic data, the relationships between dielectric parameters and hydrogeologic parameters of geologic materials must be known. This chapter reviews previous experimental and theoretical work to establish these relationships.

Section 3.2 presents a survey of the experimental data base. Emphasis is placed on identifying the physical parameters and state variables that influence the dielectric response of geologic materials. Apparent inconsistencies between studies are considered in terms of the experimental differences between the studies such as differences in sample composition, sample preparation and measurement procedure. This review sheds light on the complexity of dielectric-hydrogeologic parameter relationships and is motivation for the laboratory experiments described in Chapters 4,5 and 6.

In Section 3.3, I review some of the mixing formulas that have been proposed to the model dielectric properties of geologic materials. Five "types" of models are considered: empirical models, phenomenological models, volumetric models, effective medium theories and semiempirical models. This classification scheme is used to highlight differences in the approach and assumptions of the different models.

Figure 3.1 illustrates the forward modeling problem. Given only a pore-scale description of a material, the problem is to compute the dielectric constant of the bulk material. While it is clear that the bulk dielectric constant will be a product of (1) the individual dielectric constants of the components, (2) the volume fractions of the components, (3) the geometries of the


Figure 3.1. Effective dielectric properties of an idealized geologic material. $\kappa_{1}, \kappa_{2}$ and $\kappa_{3}$ are the dielectric constants of the solid, liquid and gas components, respectively, while $\kappa$ is the macroscopic dielectric constant of the bulk material. The function $f\left(\kappa_{1}, \kappa_{2}, \kappa_{3}\right)$ represents the effective medium theory.
components, and (4) the electrochemical interactions between the components, it is unclear how to incorporate these elements into mathematical models; this is why so many different mixing formulas and effective medium theories have been proposed over the years. The work in this chapter provides a framework and suggestions for selecting a model, and hence should be of interest to petrophysicists and GPR/VETEM researchers alike.

### 3.2 EXPERIMENTAL DATA

The electrical properties of geologic materials have been measured by many researchers over the years. Table 3.1 lists pertinent details about some of these studies, including the materials, frequency range and physical properties of interest.

Although it may appear from Table 3.1 that many types of materials have been studied over a broad frequency range, this is generally not true; the data base is far from complete. From an experimental point of view, the important variables that may affect the dielectric constant are measurement frequency, soil texture (i.e., grain size distribution, etc.), porosity, water saturation and water salinity. If we consider these variables as axes of a hypercube, the experimental measurements would cluster in a very small portion of the volume. The vast majority of measurements have been on natural soils and rocks where water saturation was the control variable. Because water saturation is being varied, and to avoid complications of changing salinity, most workers have used distilled water in their measurements. Furthermore, most dielectric measurements have been performed at relatively high frequencies ( $>10 \mathrm{MHz}$ ).

In addition, there are apparent inconsistencies in the database. For instance, the data reported by Hoekstra and Delaney (1974) support the conclusion that soil textural composition has a very minor influence on the dielectric constant of moist soil, while the data of Lundien (1971) and Wang and Schmugge (1980) show significant differences in the magnitude of the dielectric constant for different soil textures at the same volumetric water content. Experimental
Table 3.1. Experimental investigations of the dielectric properties of geological materials.

| Study | Frequency range | Material | Physical properties correlated with $\kappa$ |
| :---: | :---: | :---: | :---: |
| Smith-Rose (1933) | $100 \mathrm{kHz}-10 \mathrm{MHz}$ | Natural soils | Water content |
| Keller and Licastro (1959) | $50 \mathrm{~Hz}-30 \mathrm{MHz}$ | Rocks | Water content |
| Scott et al. (1967) | $100 \mathrm{~Hz}-1 \mathrm{MHz}$ | Natural soils and rocks. | Water content |
| Arulanandan and Mitchell (1967) | $30 \mathrm{~Hz}-100 \mathrm{kHz}$ | Clay | Clay microstructure, salinity |
| Lundien (1971) | $10 \mathrm{MHz}-1.5 \mathrm{GHz}$ | Natural soils | Water content, bulk density, lithology |
| Birchak et al. (1974) | $4 \mathrm{GHz}-6 \mathrm{GHz}$ | Clay and crushed limestone | Water content |
| Hipp (1974) | $30 \mathrm{MHz}-4 \mathrm{GHz}$ | Natural soils | Water content, bulk density |
| Hoekstra and Delaney (1974) | $100 \mathrm{MHz}-26 \mathrm{GHz}$ | Natural soils | Water content |
| Poley et al. (1978) | $1.5 \mathrm{kHz}-2.4 \mathrm{GHz}$ | Sandstones and carbonates | Lithology, porosity, water saturation |
| Hall and Rose (1978) | $200 \mathrm{~Hz}-1 \mathrm{GHz}$ | Clays | Water saturation, clay microstructure |
| Okrasinski et al. (1979) | $390 \mathrm{MHz}-1.5 \mathrm{GHz}$ | Natural soils | Water content, porosity |
| Topp et al. (1980) | $20 \mathrm{MHz}-1 \mathrm{GHz}$ | Glass beads and natural soils | Water content |
| Wang and Schmugge (1980) | $1.4 \mathrm{GHz}-5 \mathrm{GHz}$ | Natural soils | Water content, clay content |
| Lockhart (1980a, 1980b) | $10 \mathrm{~Hz}-100 \mathrm{kHz}$ | Clays | Cation exchange capacity, clay microstructure |
| Sen et al. (1981) | 1.1 GHz | Sintered glass beads | Porosity, geometry, pore fluid content |
| Klein and Sill (1982) | $0.01 \mathrm{~Hz}-1 \mathrm{kHz}$ | Glass bead-clay mixtures | Grain size, clay content and type, salinity |
| Lange (1983) | $100 \mathrm{MHz}-1 \mathrm{GHz}$ | Glass beads and natural soils | Porosity, surface area/pore volume, saturation |
| Kenyon (1984) | $500 \mathrm{kHz}-1.3 \mathrm{GHz}$ | Carbonates | Water-filled porosity, grain geometry |
| Hallikainen et al. (1985) | $1.4 \mathrm{GHz}-18 \mathrm{GHz}$ | Natural soils | Water content, clay content |
| Shen et al. (1985) | $800 \mathrm{MHz}-1.2 \mathrm{GHz}$ | Sedimentary rocks | Water-filled porosity |
| Sherman (1986) | 1.1 GHz | Sandstones and limestones | Porosity |
| Kutrubes (1986) | $500 \mathrm{kHz}-1 \mathrm{GHz}$ | Natural soils | Bulk density, fluid composition |
| Knight and Nur (1987) | $60 \mathrm{kHz}-4 \mathrm{MHz}$ | Sandstones | Water saturation, surface area/pore volume |
| Olhoeft (1987) | $0.001 \mathrm{~Hz}-1 \mathrm{GHz}$ | Sand-clay mixtures | Porosity, water saturation, clay content |
| Taherian et al. (1990) | $10 \mathrm{MHz}-1.3 \mathrm{GHz}$ | Sandstones and carbonates | No specific correlations investigated |

differences in sample composition, sample preparation, and measurement procedure make it difficult to reconcile these inconsistencies in the data. Theoretical modeling is further frustrated by a relative lack of concern by experimenters for characterization of the soil material under study; this is due in large part to the applied nature of most of the research.

In spite of these limitations, the data base supports the following five conclusions concerning the dielectric properties of geologic materials:
(1) The dielectric constant of geologic materials is a function of both the material's textural composition and its volumetric water content over the entire $\mathrm{kHz}-\mathrm{MHz}$ frequency range (Lundien, 1971; Poley et al., 1979; Wang and Schmugge, 1980; Lange, 1983; Kenyon, 1984; Knight and Nur, 1987).
(2) For extremely dry soils, the dielectric constant is essentially independent of soil texture and frequency and depends only on porosity (or dry bulk density). Figure 3.2 shows the relationship between dielectric constant and porosity for three soils: a sand, a silt and a clay. These data, collected by Okrasinski et al. (1979), suggest that the relationship between dielectric constant and porosity is almost linear. Measured k values fall between 1 (high porosities) and 4 (low porosities) regardless of lithology. Olhoeft (1979a) has compiled data on the density-reduced (zero-porosity) dielectric constant values for many minerals; values for some common minerals are listed in Table 3.2. For the most part, the values range from 4 to 9 (Olhoeft, 1979a). The large dielectric constants of clay minerals, particularly montmorillonite, are thought to be due to the presence of adsorbed surface water at the time of the electrical measurements.
(3) The dielectric constant of dry soil is always less than the dielectric constant of the same soil with water added (Topp et al., 1980; Wang and Schmugge, 1980). This is due to the difference between the dielectric constants of air (1) and water (80). The dielectric constants of some other important fluids are listed in Table 3.3 for comparison purposes. Note that many


Figure 3.2. Measured relationship between dielectric constant ( $390 \mathrm{MHz}-1.5 \mathrm{GHz}$ ) and porosity for three types of soil under dry conditions. Data from Okrasinski et al. (1979).
Table 3.2. Dielectric properties of common minerals.
Mineral Dielectric Constant (1 MHz)
Albite ..... 7.0
Calcite ..... 6.4
Halite ..... 5.9
Ice ..... 3.4
Kaolinite ..... 11.8
Montmorillonite ..... 210.0
Olivine ..... 7.2
Orthoclase ..... 5.6
Pyroxene ..... 8.5
Quartz ..... 4.5
[From Olhoeft, 1979a]
Table 3.3. Dielectric properties of some important fluids.
Fluid Dielectric Constant ( 1 MHz )
Acetone ..... 20.9
Air ..... 1.0
Benzene ..... 2.3
Carbon Tetrachloride ..... 2.2
Chloroform ..... 4.8
Cyclohexane ..... 2.0
Ethylene Glycol ..... 38.7
Methanol ..... 33.6
Tetrachloroethene ..... 2.3
Trichloroethene ..... 3.4
Toluene ..... 2.4
Water ..... 80
[From Lucius et al., 1989]
organic contaminants have dielectric constant values (2-4) that are significantly lower than that of water; it may be possible to use this difference as the basis for direct detection of contaminants in the saturated zone (Kutrubes, 1986).
(4) For all soils (i.e., given a specific textural composition), the dielectric constant increases slowly at first with increasing water content, and then more rapidly once a critical water content value is reached. As shown in Figure 3.3, this critical value in water content is found to vary with soil type or texture, being smaller for sandy soils (e.g., Yuma sand) than for clay-rich soils (e.g., Miller clay). For a given volumetric water content, the dielectric constant in the microwave frequency range decreases with increasing clay content (Wang and Schmugge, 1980; Hallikainen et al., 1985).
(5) Everything else being equal, the dielectric constant of a soil decreases, or remains the same, with increasing frequency or decreasing temperature below $0^{\circ} \mathrm{C}$. Upon freezing, the dielectric constant of water drops from near 80 to about 3 (Hoekstra and Delaney, 1974).

### 3.3 MATHEMATICAL MODELS

A number of different approaches have been taken to model the dielectric properties of geologic materials. These approaches include empirical models, phenomenological models, volumetric mixing formulas, effective medium theories and semiempirical models. Table 3.4 lists examples of each approach that are commonly cited in the soil and rock properties literature. These models are described in the following sections. Several of these models were compared by Wang and Schmugge (1980) to the experimental data collected by Lundien (1971) and Newton (1977); the comparison illustrates several important points about the dielectric properties of geologic materials so I have reproduced several of Wang and Schmugge's plots in this section. Further background on dielectric mixing formulas may be found in van Beek


Figure 3.3. Measured relationship between dielectric constant ( $1.4-5.0 \mathrm{GHz}$ ) and volumetric moisture content for three soils. The data for Yuma sand and Vernon loam are from Lundien (1971), and the data for Miller clay are from Newton (1977). These data were also included in the study by Wang and Schmugge (1980).

Table 3.4. Mathematical models of dielectric properties.

## Name and reference

## 1. Empirical models

A. Polynomial rule (Topp et al., 1980)
B. Logarithmic rule (Olhoeft and Strangway, 1975)

## 2. Phenomenological models

A. Debye and Cole-Cole models
(Wang, 1980)

## 3. Volumetric mixing formulas

A. Harmonic average (Roth et al., 1990)
B. Arithmetic average (Brown, 1956; Lange, 1983)
C. Complex Refractive Index and Time Propagation models
(Birchak et al., 1974; Wharton et al., 1980; Alharthi and Lange, 1987)
4. Effective medium theories
A. Bruggeman-Hanai-Sen model (Sen et al., 1981)
5. Semiempirical models
A. Wang and Schmugge (1980)
B. Dobson et al. (1985)
(1967), Dukhin (1971), Tinga et al. (1973), Landauer (1978), Nielsen (1978) and Berryman (1995).

### 3.3.1 Empirical models

Perhaps the simplest approach to modeling dielectric properties is to select functional relationships between the dielectric constant K and other measurable material properties. Two such empirical relationships are presently in common usage. The first is the third-order polynomial relationship between $\kappa$ and volumetric water content $\theta_{v}$ found by Topp et al. (1980),

$$
\begin{equation*}
\kappa=3.03+9.30\left(\theta_{v}\right)+146.00\left(\theta_{v}\right)^{2}-76.70\left(\theta_{v}\right)^{3} \tag{3.1}
\end{equation*}
$$

This equation was determined from regression analysis on data from four mineral soils ranging in clay content from 9 to 66 percent by weight. In addition, the curve was constrained to pass through $(81.5,1)$ the data point assumed for pure water at $20^{\circ} \mathrm{C}$. The authors provide an error estimate by stating that 93 percent of the measured data falls within the band formed by shifting the above curve by $\pm 0.025$ in $\theta_{v}$.

Equation (3.1) can also be inverted to yield an expression for $\theta_{v}$ in terms of K :

$$
\begin{equation*}
\theta_{v}=-5.3 \times 10^{-2}+2.92 \times 10^{-2}(\kappa)-5.5 \times 10^{-4}(\kappa)^{2}+4.3 \times 10^{-6}(\kappa)^{3} \tag{3.2}
\end{equation*}
$$

Equation (3.2) is commonly used by practitioners of time domain reflectometry to yield estimates of soil water content (e.g., Dasberg and Dalton, 1985). The main advantage of this equation is that it does not require determination of any soil parameters except the dielectric constant. Disadvantages include (1) the fact that there is no physical justification for the equation and (2) that its validity has not been demonstrated for the whole range of possible water contents, clay contents and porosities (Roth et al., 1990).

The second commonly used empirical relationship is the logarithmic rule:

$$
\begin{equation*}
\kappa=\left(\kappa_{\mathrm{m}}\right)^{\rho_{b}} \tag{3.3}
\end{equation*}
$$

proposed by Olhoeft and Strangway (1975) to describe the relationship between $\kappa$ and dry bulk density $\rho_{b}$ of dry geologic materials. In this equation, $\kappa_{m}$ is the zero-porosity dielectric constant of the rock, determined from regression to be approximately 1.92 for most rocks. This equation is sometimes used to extract bulk density and porosity information from radar measurements. As stated by Olhoeft (1986), the formula only works for dry rocks and can give very misleading results for wet rocks.

### 3.3.2 Phenomenological models

Another approach to modeling dielectric properties is to relate frequency dependent behavior to a distribution of characteristic relaxation times. This is a phenomenological approach in which the data are modeled without regard to component properties or geometrical relationships. Commonly used models include the Debye and Cole-Cole models discussed in Chapter 2. Papers in the soil literature that take this approach include those by Hoekstra and Delaney (1974) and Wang (1980). Wang's model is particularly interesting, and so will be discussed in this section, because it makes a connection between a material's specific surface area and its dielectric properties.

Wang (1980) used the Debye model (equation 2.15) to predict the dielectric behavior of soil-water systems over the frequency range 300 MHz to 1.4 GHz . Given appropriate estimates of the static-frequency and infinite-frequency dielectric constants, $\kappa_{s}$ and $\kappa_{\infty}$, Wang found that he could model the experimental data by adjusting just two parameters, (1) the width of the activation energy of the soil solution, and (2) the mean relaxation frequency of the soilwater mixture. Both of these parameters are functions of the relaxation time (i.e., the activation
energy is proportional to the logarithm of the relaxation time, and the relaxation frequency is the relaxation time divided by $2 \pi$ ) and are defined for each measurement (i.e., different frequency, soil type or water content). In comparing the wet sand results with the wet clay results, Wang found that both the effective net activation energy and the mean relaxation frequency increase with soil water content and that these values are soil specific such that the range of mean relaxation frequencies required to fit the data is lower for clayey soils (1.8-9.6 GHz ) than for sandy soils ( $5.5-23.7 \mathrm{GHz}$ ). Additionally, Wang found that the activation energy is relatively constant for sands as a function of water content, whereas it increases markedly for clays.

Although his model is phenomenological, Wang attempted to provide physical justification for his choice of different mean relaxation frequencies and activation energies for different soils. This justification is based largely on the work of Hasted (1973) who showed that the activation energy of water molecules around soil particles is highest for the first layer and decreases monotonically for subsequent layers. The result is that the relaxation frequency is lowest for the first layer and increases with each successive layer of water molecules. Since sandy soils have a small specific surface area, not much water is needed to reach the state where the activation energy is equal to that for bulk water. As a result, sands tend to have high mean relaxation frequencies. On the other hand, clay-rich soils have high specific surface areas, and a high proportion of their water is held in the bound state. This leads to a low mean relaxation frequency and high activation energy. In this way, Wang is able to explain the apparent dependence of a material's dielectric response on its specific surface area.

Although this approach has been found to adequately describe the experimental data over the frequency range 300 MHz to 1.4 GHz , its usefulness is limited by its dependence upon adjustable frequency-specific parameters. In addition, there is no explicit incorporation of
geometrical factors which have been shown to have an effect on the dielectric constant of composite mixtures (Kenyon, 1984).

### 3.3.3 Volumetric mixing formulas

A third approach to modeling dielectric properties is to relate the bulk dielectric constant of a multiphase mixture to the dielectric constants and volume fractions of its constituents, based on assumptions about the apparent geometrical arrangement of the constituents. In its most general form, this is known as the Lichtenecker-Rother (1937) equation,

$$
\begin{equation*}
k^{\alpha}=\sum_{i=1}^{N} V_{i} k_{i}^{\alpha} \tag{3.4}
\end{equation*}
$$

where $V_{i}$ and $\kappa_{i}$ are the volume fractions and dielectric constants of the $i^{\text {th }}$ component, respectively, and $\alpha$ is a 'geometrical' factor that relates the direction of effective layering of the components to the direction of the applied electric field. The parameter $\alpha$ may range from -1 (harmonic average or series arrangement of dielectric components) to +1 (arithmetic average or parallel arrangement of dielectric components); these values represent the extreme cases for a dielectric composed of more than one material.

For a two-phase mixture, the harmonic average formula $(\alpha=-1)$ is:

$$
\begin{equation*}
\frac{1}{\kappa}=\frac{V_{1}}{\kappa_{1}}+\frac{V_{2}}{\kappa_{2}} . \tag{3.5}
\end{equation*}
$$

A plot of $\kappa$ versus component volume fraction has a very low slope until near saturation of the high dielectric constant component. Generally, this equation does not fit experimental data well so it is rarely used except to show the limiting case (e.g., Roth et al., 1990).

The arithmetic average formula $(\alpha=+1)$ for a two-phase mixture is

$$
\begin{equation*}
\kappa=V_{1} \kappa_{1}+V_{2} \kappa_{2} . \tag{3.6}
\end{equation*}
$$

This is the mixing formula used by Brown (1956) and Lange (1983). Although it is clearly inappropriate to apply this two-phase model to three-phase soil-water-air mixtures, equation (3.6) is one of the mixing laws that was used in the comparative study by Wang and Schmugge (1980).

Figure 3.4 shows three of the models considered by Wang and Schmugge (1980) and discussed in this chapter. The arithmetic model (equation 3.6) has a steep slope over the entire water content range; note that the air and grains are considered to be one component, and water the other component, in this 'two-phase' model. The slope of the curve, with some constant offset, matches the overall trend of the high water content data, but fails to reproduce the curvature associated with the low water content data.

Setting $\alpha=0.5$ in equation (3.4) results in the basic equation of both the Complex Refractive Index (CRIM) and Time Propagation (TP) models, i.e.,

$$
\begin{equation*}
\sqrt{\kappa}=\sum_{i=1}^{N} V_{i} \sqrt{\kappa_{i}} \tag{3.7}
\end{equation*}
$$

Equation (3.7) is called CRIM if the dielectric parameters are complex quantities (e.g., $\varepsilon^{*}$ ), and TP if the parameters are real (e.g., $\kappa$ or $\varepsilon_{e f}$ ). The TP equation can be derived from traveltime calculations for electromagnetic waves through an isotropic material, since the square root of the dielectric constant is proportional to propagation time (e.g., equation 2.48 in the previous chapter). In this sense, the TP equation is analogous to Wyllie's time average equation for acoustics (Wyllie et al., 1956).

In the soil literature, the two-phase version of equation (3.7) was used by Birchak et al. (1974) and the three-phase version was used by Alharthi and Lange (1987). As shown in Figure 3.4, the CRIM/TP model is the two-phase model that falls closest to the majority of Lundien (1971) and Newton's (1977) experimental data.


Figure 3.4. Comparison of three dielectric mixing models with the experimental data from Figure 3.3. The Arithmetic, CRIM/TP and BHS models are given by equations (3.6), (3.7) and (3.8), respectively, in the text. These models were also analyzed by Wang and Schmugge (1980).

All of the models described in this section depend upon the properties of the components and their volume fractions. In addition, an assumption must be made about the value of the factor $\alpha$. An obvious limitation of these models is that they do not explicitly take into account the microgeometry of the components or the electrochemical interactions that may occur between components.

### 3.3.4 Effective medium theories

Various effective medium theories have also been applied to modeling the dielectric properties of geologic materials. These theories are potentially very useful because they can incorporate certain geometrical factors into their formalism. The basic idea is to compute a material property by successive substitutions. The process begins by assuming a homogeneous background material (component 1). A small amount of this material is then replaced by another material (component 2) and an analytical expression (e.g., Wagner's (1914) equation) used to compute the effective properties of the mixture. The solution is then used as the background for the next substitution step. The process continues until the desired volume fraction of each component is reached.

When implementing these theories, choices must be made about the number of components, the initial background material, the order of embedding, the shape and form of the inclusions, and the analytical expression used to compute the effective properties. These variables determine the form of the final mixing equation. Landauer (1978), Tinga et al. (1973) and van Beek (1967) discuss details of these theories.

The most common form of effective medium theory used to model dielectric properties of geologic materials is the Bruggeman-Hanai-Sen (BHS) equation (Bruggeman, 1935; Hanai, 1961; Sen et al., 1981), i.e.,

$$
\begin{equation*}
1-V_{1}=\left(\frac{\kappa_{1}-\kappa}{\kappa_{1}-\kappa_{2}}\right)\left(\frac{\kappa_{2}}{\kappa}\right)^{d} \tag{3.8}
\end{equation*}
$$

Typically when this equation is used, $\mathrm{V}_{1}$ is the grain volume fraction, $\kappa_{1}$ is the grain dielectric constant, $\kappa_{2}$ is the pore fluid dielectric constant, and $\kappa$ is the bulk dielectric constant to be determined. The exponent $d$ is the depolarization factor which can vary from 0 to 1 depending upon the geometrical distribution of the matrix material and the saturating fluid in the pore system. When $d=1 / 3$ the inclusion geometry is spherical. This formula has been shown (Sen et al., 1981) to yield accurate approximations to the dielectric constant of water-saturated materials with non-interacting components. While it is possible to run this model multiple times to simulate a multiphase saturated system, this approach is cumbersome and is rarely used in practice.

### 3.3.5 Semiempirical models

None of the models shown in Figure 3.4 can fit each of the lithologies (Yuma sand, Vernon loam and Miller clay) equally well over the entire water content range. This could be due to the fact that the models in Figure 3.4 are only two-component models, whereas the soil-water-air system is comprised of three components, or it could be because the models do not explictly account for the electrochemical interactions that occur when water is present in the system. Two semiempirical models have been proposed by Wang and Schmugge (1980) and Dobson et al. (1985) to address these issues. These models are categorized as 'semiempirical' rather than 'empirical' to emphasize the volumetric and geometrical foundations of the models; nevertheless, the models are still dependent upon adjustable soil parameters.

In Wang and Schmugge's (1980) model, the dielectric constant is estimated using a volumetric mixing formula that considers the contributions of the soil, air and water. Water in the soil is considered to be made up of two parts divided at a transition moisture content $\left(\theta_{\mathrm{t}}\right)$.

Based on the shape of the experimental data (Figure 3.4), Wang and Schmugge hypothesized that at gravimetric moisture contents $\theta_{\mathrm{m}}$ below $\theta_{\mathrm{t}}$, the water is tightly bound to the soil surface and hence has a $\kappa$ value smaller than the $\kappa$ value for free water (but greater than the $\kappa$ value for ice). The parameter $\theta_{t}$, and the dielectric properties of the bound water, are related to soil texture through a second parameter $W P$, the estimated wilting point of the soil, which is expressed in terms of measured sand and clay weight fractions. The following expressions are given for the dielectric constant k of a soil-water-air mixture over these two moisture regions:

$$
\begin{align*}
& \text { (i) } \theta_{\mathrm{m}} \leq \theta_{\mathrm{t}}: \quad \kappa=\theta_{\mathrm{m}} \kappa_{\mathrm{bw}}+\left(\phi-\theta_{\mathrm{m}}\right) \kappa_{\mathrm{a}}+(1-\phi) \kappa_{\mathrm{g}}  \tag{3.9}\\
& \text { with } \quad \kappa_{\mathrm{bw}}=\kappa_{\mathrm{i}}+\left(\kappa_{\mathrm{w}}-\kappa_{\mathrm{i}}\right) \frac{\theta_{\mathrm{m}}}{\theta_{\mathrm{t}}} \gamma  \tag{3.10}\\
& \text { (ii) } \theta_{\mathrm{m}} \geq \theta_{\mathrm{t}}: \quad \begin{array}{l}
\kappa=\theta_{\mathrm{t}} \kappa_{\mathrm{bw}}+\left(\theta_{\mathrm{m}}-\theta_{\mathrm{t}}\right) \kappa_{\mathrm{w}}+\left(\phi-\theta_{\mathrm{m}}\right) \kappa_{\mathrm{a}}+(1-\phi) \kappa_{\mathrm{g}} \\
\text { with } \quad \kappa_{\mathrm{b} w}=\kappa_{\mathrm{i}}+\left(\kappa_{w}-\kappa_{\mathrm{i}}\right) \gamma .
\end{array}
\end{align*}
$$

Here $\phi$ is the porosity of the dry soil. $\kappa_{\mathrm{a}}, \kappa_{\mathrm{w}}, \kappa_{\mathrm{g}}$ and $\kappa_{\mathrm{i}}$ are the dielectric constants of air, water, grain and ice, respectively. $\kappa_{b w}$ is the inferred dielectric constant of the bound water fraction. $\gamma$ is a parameter whose value is chosen to fit equations (3.10) and (3.12) to the experimental data. Applying linear regression analysis, Wang and Schmugge (1980) show how $\gamma$ and $\theta_{\mathrm{t}}$ are related to soil texture via the estimated wilting point (WP) of each soil,

$$
\begin{align*}
& \gamma=-0.57 W P+0.481  \tag{3.13}\\
& \theta_{\mathrm{t}}=0.49 W P+0.165 \tag{3.14}
\end{align*}
$$

$W P$ is estimated by:

$$
\begin{equation*}
W P=0.06774-0.00064\left(W_{s}\right)+0.00478\left(W_{c l}\right) \tag{3.15}
\end{equation*}
$$

where $W_{s}$ and $W_{c l}$ are the percent dry weight sand and percent dry weight clay of the soil, respectively.

Figure 3.5 shows a comparison between the calculated dielectric constants from Wang and Schmugge's (1980) model and the measured values at 1.4 GHz for the three soils. As can be seen, their model matches the data better than the previously considered mixing formulas. In particular, the model is able to account for the different trends presented by the various soil textures. The model shows that the bound water is positively correlated with clay content. Wang and Schmugge attribute the success of their model to the fact that it takes into account the anomalous properties of the initially adsorbed water molecules. A good feature of this model is that the required input parameters are readily available in most cases. The principle drawback is that the model is still basically empirical, relying as it does on two adjustable soil-specific parameters.

Dobson et al. (1985) also developed a semiempirical model that provides a good match to laboratory data and utilizes readily available input parameters. They began by writing the Lichtenecker-Rother equation for four phases:

$$
\begin{equation*}
\kappa^{\alpha}=V_{g} \kappa_{g}^{\alpha}+V_{a} \kappa_{a}^{\alpha}+V_{w} \kappa_{w}^{\alpha}+V_{b w} \kappa_{b w}^{\alpha} \tag{3.16}
\end{equation*}
$$

where the subscripts $g, a, w$ and $b w$ refer to grains, air, free water and bound water, respectively. They then made a series of approximations to estimate $V_{w}$ and $V_{b w}$, and $\kappa_{w}$ and $\kappa_{b w}$; as part of these approximations, they introduced an empirical parameter which they later relate to the weight percentages of sand and clay in the soil. They determined the value of the geometric factor $\alpha$ by regression from data for different frequencies ( $1.4-18 \mathrm{GHz}$ ) and soil types (ranging from sandy loam to silty clay); the $\alpha$ value that produced the best fit to their experimental data is $\alpha=0.65$. Using this model, Dobson et al. (1985) were able to obtain


Figure 3.5. Comparison of Wang and Schmugge's (1980) dielectric model with the experimental data from Figure 3.3. The model is given by equations (3.9) - (3.15) in the text. Yuma sand is comprised of 100 percent sand and has a wilting point of $0.004 \mathrm{~cm}^{3} / \mathrm{cm}^{3}$; its model parameters are $\theta_{\mathrm{t}}=0.17, \gamma=0.5$ and $\alpha=0.0$. Vernon loam is comprised of 72 percent sand/silt and 28 percent clay, and has a wilting point of $0.192 \mathrm{~cm}^{3} / \mathrm{cm}^{3}$; its model parameters are $\theta_{\mathrm{l}}=0.28, \gamma=0.45$ and $\alpha=0.26$. Miller clay is comprised of 38 percent sand/silt and 62 percent clay, and has a wilting point of $0.361 \mathrm{~cm}^{3} / \mathrm{cm}^{3}$; its model parameters are $\theta_{\mathrm{t}}=0.33$, $\gamma=0.3$ and $\alpha=0.20$.
good agreement with their measured data at frequencies greater than 4 GHz , however at frequencies less than 4 GHz , the model's performance deteriorated, presumably because of the effects of the bound water.

### 3.4 SUMMARY

An overview has been presented of some of the mixing formulas commonly used to model the dielectric properties of multiphase-saturated geologic materials. Five types of models were considered: empirical models, phenomenological models, volumetric mixing formulas, effective medium theories and semiempirical models. The review highlights basic differences in the approach and assumptions of the different models.

The experimental data show that the dielectric properties of a soil-water mixture depend on both the texture of the soil and its water content. In addition, it appears that the water molecules initially adsorbed to grain surfaces behave differently from the water molecules in the center of pores. Since the amount of bound water depends upon the surface area of the pore space, the amount of clay in a mixture is important. The two semiempirical models that explicitly consider the bound water phase do a much better job of fitting the experimental data than do the models that neglect this phase. However, these models are only applicable over a limited frequency range ( GHz frequencies). Further work is necessary to develop models that can explain the dielectric properties of geologic materials over the entire $\mathrm{kHz}-\mathrm{MHz}$ frequency range covered by VETEM and radar. There is also a clear need for additional laboratory experiments to resolve inconsistencies in the existing experimental data base. Systematic studies of the influence of porosity, clay content, clay mineralogy and water saturation on the dielectric properties of geologic materials would be very useful. These topics are taken up in the next three chapters.

## Chapter 4 <br> Effects of compaction and clay content on the dielectric properties of dry sand-clay mixtures

### 4.1 INTRODUCTION

A window exists in the electromagnetic (EM) spectrum between roughly 100 kHz and 10 GHz where EM energy may propagate with relatively little attenuation through earth materials. A number of geophysical techniques have been developed to operate within this frequency range and exploit the propagation characteristics of EM waves. These techniques include ground penetrating radar (GPR), borehole radar, time domain reflectometry, dielectric well logging and very early time electromagnetics (VETEM).

The basic material properties that affect EM wave propagation are magnetic permeability $\mu$, dielectric permittivity $\varepsilon$, and electrical conductivity $\sigma$. The magnetic permeability of most geologic materials is so close to the magnetic permeability of free space ( $\mu_{0}=1.257 \times 10^{-6}$ $\mathrm{H} / \mathrm{m}$ ) that it may be considered constant for most practical purposes. Dielectric permittivity and electrical conductivity, in contrast, vary greatly for different materials at a given frequency and for a given material across the EM spectrum. For a given frequency, $\varepsilon$ and $\sigma$ determine both the phase velocity and the intrinsic attenuation of EM waves in a material. In addition, $\varepsilon$ and $\sigma$ determine the electrical impedance of a material, affecting how EM energy is partitioned at interfaces.

By inverting EM wave velocity, attenuation, and reflectivity information obtained from geophysical experiments, it is possible to estimate $\varepsilon$ and $\sigma$ of subsurface materials. Duke (1990) and Sena and Toksov (1991) demonstrate how maps of $\varepsilon$ and $\sigma$ may be reconstructed from GPR and crosshole radar data, respectively. These dielectric property maps may then be transformed to hydrogeologic property maps given appropriate relationships between dielectric
and hydrogeologic properties. An important question then is how are dielectric and hydrogeologic properties related?

A number of experimental investigations have been conducted to address this question (e.g., see Table 3.1 in the previous chapter). The most important parameters affecting the dielectric response of geologic materials are generally thought to be porosity ( $\phi$ ), clay content, water saturation ( $S_{w}$ ) and measurement frequency, though there is little agreement as to the specific form of dielectric property-hydrogeologic property relationships due to scatter in the experimental data and apparent inconsistencies between studies regarding the relative importance of these parameters. These inconsistencies are difficult to reconcile due to experimental differences in sample composition, sample preparation and measurement procedures, as discussed in Chapter 3.

In order to develop a better understanding of dielectric property-hydrogeologic property relationships, there is a clear need for experimental investigations in which dielectric and hydrogeologic parameters are varied systematically. As demonstrated in the next three chapters, sand-clay mixtures can be used for this purpose. In this chapter, I investigate the dielectric properties of room-dry sand-clay mixtures as a function of porosity and clay content. In the next chapter, I study the dielectric response when water is added to the mixtures. Finally, in Chapter 6, I pull various results together to consider the relationship between dielectric constant and permeability.

The sand-clay mixtures studied in this chapter are representative of sediments from the unsaturated zone, while those in the next chapter are representative of sediments from the saturated zone. A novel "physical modeling" method is used to systematically control the porosity, clay content and effective degree of compaction of the mixtures (Yin, 1993). The method is based on a microgeometrical model for sand-clay mixtures proposed by Marion et al.
(1992); this method is described in the next section. Using this method, three suites of mixtures ( 28 samples) were generated for study in this chapter:
(1) a suite of pure silica sand mixtures with different porosities;
(2) a suite of pure montmorillonite clay mixtures with different porosities; and
(3) a suite of silica sand-montmorillonite clay mixtures with different porosities and clay contents but the same degree of compaction.

For each sample, measurements were made of the effective dielectric constant $\kappa$ and electrical conductivity $\sigma_{e f}$ of the material over the frequency range 100 kHz to 10 MHz . The electrical measurement system constructed for this study is described in the next section. The experimental results are presented in two ways: (1) plots of electrical parameters versus frequency, and (2) plots of electrical parameters versus porosity and clay content. The first set of plots is useful for investigating the linkage between conduction and polarization phenomena that affect measured effective electrical parameters. The second set of plots is useful for characterizing the relationships between electrical and hydrogeologic parameters that may exist in different geological settings.

The different suites of mixtures show how electrical properties vary when porosity is reduced by two mechanisms: compaction and pore-filling (i.e., changing lithology). As will be shown, the form of the $\kappa-\phi$ relationship is determined by the mechanism responsible for the porosity variation, so that there is not in general a one-to-one relationship between $\kappa$ and $\phi$. This has important consequences for the inversion and hydrostratigraphic interpretation of GPR, VETEM and other high-frequency electromagnetic data.

Because the volume fraction of each component is known for each mixture, the data set presented in this chapter may also be used to test the applicability of different dielectric mixing formulas. As a first test, I attempt to model the experimental data using the Time Propagation
(TP) equation, one of the volumetric mixing formulas described in the previous chapter (Section 3.3.3). Results show that this model is capable of accurately predicting dielectric property-hydrogeologic property relationships throughout the frequency range of 100 kHz to 10 MHz , provided that component dielectric properties are appropriately defined as effective parameters. This provides insight into the relative importance of volumetric, geometric and surface effects for different materials, as well as an explanation for some of the scatter reported in previous investigations.

### 4.2 EXPERIMENTAL METHOD

The objective of this study is to characterize the relationships between electrical properties and hydrogeological properties of sand-clay mixtures over the frequency range 100 kHz to 10 MHz . Following are descriptions of the sample holder, the sand and clay components, the mixing procedure, and the hydrogeological and electrical property measurement systems used in this research.

### 4.2.1 Sample holder

A cylindrical sample holder was constructed to hold the unlithified materials for both hydrogeologic and electrical property measurements; this eliminates problems associated with changing the packing of particles between the different measurements. A schematic of the sample holder is shown in Figure 4.1. The central cylinder that holds the sample is made of acrylic and has an internal diameter of 4.205 cm . The electrodes are gold-coated copper plugs that fit into tapers which were machined into the ends of the cylinder, in this way the electrodes are held parallel with a known separation of 0.432 cm . The distance between the electrodes was kept small relative to electrode area to limit the effects of fringing and stray capacitance on the electrical measurements. The gold coat on the copper protects against oxidation and other


Figure 4.1. Cross-sectional view of cylindrical sample holder.
electrochemical reactions; sputtering was used to ensure smooth and even coating of the gold on the electrode surfaces. The total internal volume $V_{t}$ of the sample holder is $5.999 \mathrm{~cm}^{3}$.

### 4.2.2 Component properties

The mixtures that were prepared in this study consisted of various proportions of two solid components: a clean silica sand and a standard montmorillonite clay. The sand is from Lane Mountain, Washington, and the clay (SWy-1) is from the Clay Mineral Society at the University of Missouri. These materials were selected for their high degree of purity and ready commercial availability.

Table 4.1 lists relevant physical properties of the two solid components. The mineralogy of the two components (quartz and Na-montmorillonite) was determined from chemical analyses provided by the manufacturers. Prior to use, the sand was sieved to reduce grain size variation, washed in dilute hydrochloric acid to remove minor iron staining, passed through a magnetic separator to remove grains containing magnetic components, and rinsed repeatedly in distilled water to remove any salts that may have been present in the source supply. Grain densities and bulk sample porosities were determined using a Helium pycnometer. The grain density listed in Table 4.1 for montmorillonite ( $\rho_{c l}=2.383 \mathrm{~g} / \mathrm{cm}^{3}$ ) is somewhat lower than published values for montmorillonite (e.g., $\rho_{c l}=2.608 \mathrm{~g} / \mathrm{cm}^{3}$, Olhoeft, 1979a) because the montmorillonite used in this study contains a significant amount of adsorbed surface water at room dry conditions. An indication of the amount of adsorbed surface water is given by the ratio of the mass of water expelled by thermo-vacuum drying and the total mass of the roomdry montmorillonite; this ratio is approximately $0.10 \mathrm{~g} / \mathrm{g}$. Repeated pycnometry tests on different samples showed that the reported grain densities for both sand and clay components are reproducible to within 0.9 per cent. The grain diameter of the sand was determined from sieve analysis (number 20-25 mesh), and the particle diameter of the clay was taken from the

Table 4.1. Component properties.

| Material | Mineralogy | Grain <br> Density <br> $\left[\mathrm{g} / \mathrm{cm}^{3}\right]$ | Grain <br> Diameter <br> $[\mathrm{cm}]$ | Specific <br> Surface <br> $\left[\mathrm{cm}^{2} / \mathrm{g}\right]$ | Cation <br> Exchange <br> $[\mathrm{meg} / 100 \mathrm{~g}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Sand | Quartz | 2.645 | $7 \times 10^{-2}-8 \times 10^{-2}$ | $3.9 \times 10^{2}$ | not measured |
| Clay | Na-montmorillonite | 2.383 | $<1 \times 10^{-5}$ | $6.5 \times 10^{5}$ | 76.4 |
|  |  |  |  |  |  |

literature (Hillel, 1980, p. 76). The shape of the sand grains is characterized as sub-angular based on optical and scanning electron microscopy. The montmorillonite particles are diskshaped and form microporous honeycomb structures that coat whatever they contact (Lockhart, 1980a). The surface area of the sand was determined from nitrogen adsorption isotherms using the BET equation (Brunauer et al., 1938), and the surface area of the clay was determined using the EGME adsorption technique (Carter et al., 1965). The cation exchange capacity of the clay was taken from the literature (van Olphen and Fripiat, 1979). Prior to use, both the sand and the clay were dried in an oven for 24 hours at 105 degrees Celsius and then allowed to equilibrate with room humidity conditions.

### 4.2.3 Sample preparation and mixing procedure

Prior to mixing, calculations were made to determine the mass sand $M_{s}$ and mass clay $M_{c l}$ needed to produce mixtures with specific porosities and clay contents. In this way, the effects of compaction and lithologic variation on dielectric properties could be investigated systematically. Three suites of mixtures were generated: (1) a suite of pure sand mixtures with different porosities, (2) a suite of pure clay mixtures with different porosities, and (3) a suite of sand-clay mixtures with different porosities and clay contents but the same degree of compaction. These suites of mixtures are shown schematically in Figure 4.2. The pure sand and pure clay mixtures are represented by the boxes in the left and right columns, respectively, while the sand-clay mixtures are represented by the boxes along the top of the figure.

The pure sand and pure clay samples were produced by putting material directly into the sample holder with its top electrode removed. Grain densities $\rho_{g}$ were used to compute the mass $M$ needed to obtain samples with specific porosity values according to the relation,

$$
\begin{equation*}
M=(1-\phi) \rho_{g} V_{t} \tag{4.1}
\end{equation*}
$$



$\mathrm{Cl}_{\mathrm{p}}=0$
$C l_{p}=\phi_{s}$
Increasing clay content


Figure 4.2. Conceptual diagram of the packing geometries for pure sand, pure clay, and sandclay mixtures in terms of the experimental parameters: porosity (or the degree of compaction) and clay content. $C l_{p}$ is clay content and $\phi_{s}$ is the porosity of pure sand as defined in the text.

The top electrode was then replaced so that the electrical measurements could be performed. After the electrical measurements, the actual porosity of the samples was determined by placing the holder with undisturbed sample in the pycnometer. Using this procedure, I was able to create mixtures with measured porosities within 0.5 percent of the porosity predicted by equation (4.1); this confirms the uniformity of the sand and clay grain densities. At the end of the experiment, each sample was transferred to a beaker and dried in a vacuum oven for 24 hours at 105 degrees Celsius. The water saturation at the time of electrical measurement was then determined by weighing the dried sample.

A similar procedure was followed to produce the sand-clay mixtures. In this case, however, the mixtures were blended in a beaker, stirred until the sand and clay appeared uniformly distributed, and then transferred to the sample holder. A simple microgeometrical model for sand-clay mixtures proposed by Marion et al. (1992) was used as the basis for deriving mass equations analogous to equation (4.1) for both the sand and the clay in the sandclay mixtures. Use of this model provided a means of obtaining sand-clay mixtures that filled, but were not compacted in, the sample holder. In this way I was able to eliminate compaction as a variable in these experiments.

The boxes along the top of Figure 4.2 show the microgeometry of sand and clay that is assumed in the mixtures. At low clay contents, it is assumed that clay particles fit within the pore space of the sand pack. This sort of geometry is naturally favored when the volume fraction of porous clay $C l_{p}$ is less than the inherent porosity of the sand pack $\phi_{s} . C l_{p}$ is defined as the ratio of the volume of room-dry clay packets (i.e., clay particles with associated bound water and intraparticle porosity $\phi_{c l}$ ) to the volume of sand plus clay packets. As clay fills the pore space of the sand pack, total porosity decreases according to the relation:

$$
\begin{equation*}
\phi=\phi_{s}-C l_{p}\left(1-\phi_{c l}\right) \quad \text { for } C l_{p} \leq \phi_{s} \tag{4.2}
\end{equation*}
$$

At high clay contents, where $C l_{p}$ is greater than $\phi_{s}$, a different geometrical arrangement of sand and clay particles is assumed. Here, the clay is the framework or matrix material and the sand grains are disconnected. As $C l_{p}$ increases, total porosity also increases, this time according to the relation:

$$
\begin{equation*}
\phi=C l_{p} \phi_{c l} \quad \text { for } C l_{p}>\phi_{s} \tag{4.3}
\end{equation*}
$$

because microporous packets of clay are effectively replacing zero-porosity sand grains. Clay weight fraction $W_{c l}$ and clay volume fraction $V_{c l}$ (without microporosity) can also be defined in terms of the mass and grain density of sand and clay, and the microgeometrical model parameters: $C l_{p}, \phi_{s}$ and $\phi_{c l}$. The clay weight fraction is given by the expressions:

$$
\begin{gather*}
W_{c l}=\frac{C l_{p}\left(1-\phi_{c l}\right) \rho_{c l}}{C l_{p}\left(1-\phi_{c l}\right) \rho_{c l}+\left(1-\phi_{s}\right) \rho_{s}} \quad \text { for } C l_{p} \leq \phi  \tag{4.4}\\
W_{c l}=\frac{C l_{p}\left(1-\phi_{c l}\right) \rho_{c l}}{C l_{p}\left(1-\phi_{l l}\right) \rho_{c l}+\left(1-C l_{p}\right) \rho_{s}} \quad \text { for } C l_{p}>\phi, \tag{4.5}
\end{gather*}
$$

and clay volume fraction is given by the expression:

$$
\begin{equation*}
V_{c l}=\frac{\frac{M_{c l}}{\rho_{c l}}}{\frac{M_{s}}{\rho_{s}}+\frac{M_{c l}}{\rho_{c l}}} \tag{4.6}
\end{equation*}
$$

where the mass sand $M_{s}$ and mass clay $M_{c l}$ are:

$$
\begin{array}{llll}
M_{s}=\left(1-\phi_{s}\right) \rho_{s} V_{t} & \text { and } & M_{c l}=C l_{p}\left(1-\phi_{c l}\right) \rho_{c l} V_{t} & \text { for } C l_{p} \leq \phi_{s} \\
M_{s}=\left(1-C l_{p}\right) \rho_{s} V_{t} & \text { and } & M_{c l}=C l_{p}\left(1-\phi_{c l}\right) \rho_{c l} V_{t} & \text { for } C l_{p}>\phi_{s} \tag{4.8}
\end{array}
$$

### 4.2.4 Electrical measurements

The effective electrical conductivity $\sigma_{e f}$ and dielectric permittivity $\varepsilon_{e f}$ of each sample was determined by measuring the equivalent parallel conductance $G_{p}$ and capacitance $C_{p}$ of the sample in the test apparatus and applying the following inversion formulas:

$$
\begin{align*}
\sigma_{e f} & =\frac{G_{p} d}{A}  \tag{4.9}\\
\varepsilon_{e f} & =\frac{C_{p} d}{A} \tag{4.10}
\end{align*}
$$

where $A$ is the area and $d$ the separation of the two electrode surfaces. The dielectric constant $\kappa$ was calculated from $\kappa=\varepsilon_{e f} / \varepsilon_{0}$. The measurements were made with a Hewlett Packard 4192a low frequency impedance analyzer at 31 frequencies spaced logarithmically between 10 Hz and $10 \mathrm{MHz} . C_{p}$ and $G_{p}$ are related to electrical impedance $Z$ through:

$$
\begin{equation*}
Z=\frac{1}{G_{p}+i \omega C_{p}} \tag{4.11}
\end{equation*}
$$

where $\omega$ is angular frequency $(\omega=2 \pi f)$. The peak-to-peak oscillation level of the input signal was set at 1 volt. Additional information about determining $\sigma_{e f}$ and $\varepsilon_{e f}$ values from complex impedance measurements is contained in Section 2.8 of this thesis.

The sample holder containing the sand-clay mixtures was connected to the impedance analyzer using a four-terminal pair configuration, as shown in Figure 4.3. An aluminum box, grounded through the impedance analyzer, was used to shield the sample from external electrical fields. An open/short compensation and a sample holder compensation (based on air as a standard) were performed to reduce the effect of impedance contributions due to the sample holder, test cables and measurement circuit. Appendix A contains details about these compensations.


Figure 4.3. (a) Schematic diagram and (b) circuit diagram of the electrical measurement system.

To test the accuracy of the electrical measurement system over the range of $\kappa$ values expected, measurements were made of the electrical properties of several standards. Details about these measurements are contained in Appendix B. The tests show that the measurement system is capable of measuring dielectric constant values to within 2 percent of accepted values.

A potential problem in two-electrode impedance measurements is electrode polarization at low frequencies. If not detected, this polarization can lead to interpretation problems. Knight (1983) shows how the effects of electrode polarization can be recognized in complex plane plots of electrical impedance. I used complex plane analysis to ensure that the values reported for $\kappa$ and $\sigma_{e f}$ of sand-clay mixtures are not corrupted by electrode polarization effects. An example of a complex plane plot is shown in Figure 4.4 for the sand-clay mixture with $W_{c l}=$ 0.152 . The figure shows the imaginary part of $Z$ plotted against the real part of $Z$. Two features are evident in the plot: an inclined line and a depressed semicircle. The frequency of the measurements increases down the line and counterclockwise across the semicircle. The cusp separating these two regions is labelled $f_{0}$ and corresponds to the impedance measurement made for this sample at 159 Hz ; the peak of the semicircle corresponds to the measurement made at 25.1 kHz . Knight (1983) identified the low frequency linear portion of such complex plane plots as the response of the sample-electrode interface, while the higher frequency semicircular portion corresponds to the bulk sample response. This implies that for the sandclay mixture shown in Figure 4.4, only the data above 159 Hz can be reliably interpreted as being representative of the sample's true electrical properties.

Comparison of complex plane plots for all the sand-clay mixtures shows that values of $f_{0}$ increase with increasing clay content. For samples with $W_{c l}<0.107$, only the leftmost portion of the semicircle is observed which indicates that $f_{0}$ is less than 10 Hz . For high clay content samples, cusps are observed in all the complex impedance plots. As $W_{c l}$ increases from 0.107


Figure 4.4. Complex impedance plot for the dry sand-montmorillonite mixture with clay weight fraction $W_{c l}=0.152$ and porosity $\phi=0.282$.
to 1.000 , the length of the inclined line increases and the whole plot shifts to lower impedance values. The maximum value of $f_{0}$ that was observed is 251 Hz ; this value is characteristic of all mixtures with $W_{c l}>0.193$. By analyzing the data in this way, it is possible to distinguish between electrode effects and the bulk response of the samples. Since our interest is in the bulk sample response, most of the results in this thesis are confined to the frequency range 100 kHz to 10 MHz , well above the range of indicated electrode effects.

### 4.3 EXPERIMENTAL RESULTS

To aid interpretation, the measurements of the electrical and hydrogeological properties of the pure sand, pure clay and sand-clay mixtures will be presented in two ways. First, I show dielectric constant and conductivity values plotted against porosity and/or clay content for each of the three suites of mixtures. In these plots, three frequencies are shown: 100 kHz (square symbols), 1 MHz (circles) and 10 MHz (triangles). In some cases, there is significant dispersion (i.e., frequency dependence) in the dielectric response. To better illustrate this dispersion and show the linkage between K and $\sigma_{e f}$ values, I also show K and $\sigma_{e f}$ plotted against frequency. In this second set of plots, measurements are shown for all eleven frequencies investigated between 100 kHz and 10 MHz , but for a limited number of samples. Together, these two ways of presenting the data are useful for exploring the interrelationships between electrical and hydrogeologic parameters.

Overall, the results are organized under the headings "Effects of compaction" and "Effects of changing lithology" to indicate which geologic process, compaction or changing lithology, is being simulated by the suite of mixtures.

### 4.3.1 Effects of compaction

In this section, I present the data for the pure silica sand mixtures and the pure montmorillonite clay mixtures. The geologic process that is simulated in the two suites of mixtures is compaction. The hydrogeologic parameter of interest is porosity, since lithology remains constant within the two suites of mixtures.

Figure 4.5 shows the relationship between $\kappa$ and porosity, and $\sigma_{e f}$ and porosity, for five dry sand mixtures ranging in porosity from 0.357 to 0.477 . The $\kappa$ and $\sigma_{e f}$ data are presented for three frequencies: $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz . For a given frequency, $\kappa$ shows a minor but steady increase with decreasing porosity; the slope is approximately 0.05 K units per porosity unit. There is little scatter about the $\kappa-\phi$ curve, suggesting strong correlation between $\kappa$ and porosity. If the data are extrapolated to zero porosity, matrix parameters close to 4 are obtained; this is in general agreement with published values for quartz at 1 MHz (e.g., $\kappa_{\text {quartz }}=$ 4.10-4.34, Handbook of Physics and Chemistry (1986); $\kappa_{\text {quartz }}=4.5$, Olhoeft, 1979a). There is also very little observed frequency dependence in the dielectric response of the sand. As shown in Figure 4.6a, where now the data are plotted as a function of frequency, $\kappa$ values vary only 0.2 dielectric units over the frequency range 100 kHz to 10 MHz .

The conductivity response for pure sand is shown in Figures 4.5 b and $4.6 \mathrm{~b} . \sigma_{e f}$ is found to be less than $10^{-4} \mathrm{~S} / \mathrm{m}$ for all samples at all frequencies between 100 kHz and 10 MHz . Porosity reduction causes an increase in $\sigma_{e f .}$. In contrast to the $\kappa$ results, $\sigma_{e f}$ of pure sand is strongly frequency dependent with $\sigma_{e f}$ increasing with increasing frequency.

Figure 4.7 shows $\kappa$ versus porosity, and $\sigma_{e f}$ versus porosity, for thirteen montmorillonite clay samples. The porosity of these samples ranges from 0.243 to 0.800 . As with the sand samples, $\kappa$ and $\sigma_{e f}$ of the clay increase with decreasing porosity, but the increase is much more dramatic in the clay data set. At $1 \mathrm{MHz}, \kappa$ increases from 4 to 95 as porosity is


Figure 4.5. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for six pure silica sand samples at room-dry conditions. Measurement frequencies are $100 \mathrm{kHz}, 1$ MHz and 10 MHz .


Figure 4.6. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for three silica sand samples with different porosities at room-dry conditions.


Figure 4.7. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for 13 pure montmorillonite clay samples at room-dry conditions. Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz .
reduced from 0.80 to 0.24 . At $10 \mathrm{MHz}, \kappa$ increases from 3.4 to 44 over the same porosity range. Figure 4.8 shows the frequency response of the samples with porosity values equal to $0.800,0.599,0.394$ and 0.243 . As is clearly shown in this figure, the enhancement in $\kappa$ with compaction is strongly correlated with conductivity; the higher the conductivity, the greater the dispersion in $\kappa$. For instance, the sample with a porosity of 0.800 has relatively low conductivity values (e.g., $5 \times 10^{-5} \mathrm{~S} / \mathrm{m}$ at 1 MHz ) and the difference in $\kappa$ values for this sample between 100 kHz and 10 MHz is just 2 dielectric units. By comparison, the difference in $\kappa$ values for the sample with a porosity of 0.24 and much higher conductivity values (e.g., $5 \times 10^{-}$ ${ }^{3} \mathrm{~S} / \mathrm{m}$ at 1 MHz ) is 159 dielectric units--a much greater range. This behavior is significantly different from that of the sand; there are clearly different polarization mechanisms operating in the clay samples than in the sand samples.

Another interesting characteristic of the electrical behavior of montmorillonite that can be seen in Figure 4.7 is the break in slope in both the $\kappa-\phi$ and $\sigma_{e f}-\phi$ relationships near a porosity of 0.60 . This break in slope is related to the microgeometry of the conductive clay particles. As porosity is reduced from 0.80 to 0.60 , conductivity increases dramatically because the clay particles are effectively forming critical conductive connections between the two electrodes. The conductivity response levels out at lower porosities because the conductive network is essentially fully established at $\phi=0.60$. Further evidence that there is a fundamental change in the microgeometry of the clay-air system results from the fact that as compaction proceeds the mixture with $\phi=0.60$ is the first clay mixture that required pressure to seat the electrodes in the sample holder. As will be argued later in this chapter, the break in slope of the dielectric response is a direct consequence of the change in the $\sigma_{e f}$ response that occurs around $\phi=0.60$.


Figure 4.8. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for four montmorillonite samples with different porosities at room-dry conditions.

### 4.3.2 Effects of changing lithology

In this section, I present the data for the silica sand-montmorillonite clay mixtures. The geologic process that is simulated in this suite of mixtures is changing lithology (e.g., lithofacies variations along the length of a depositional system). Although porosity varies in the mixtures along with clay content, the confining pressure and hence the effective degree of compaction remain essentially constant. The hydrogeologic parameters of interest are porosity and clay content, so each of these parameters will be plotted against the two electrical parameters $\kappa$ and $\sigma_{e f}$.

Eleven sand-clay mixtures were prepared for this part of the study. The microgeometrical model performed well as a guide to controlling clay content, porosity and the effective degree of compaction of the mixtures. This can be seen in Figure 4.9 where predicted and observed porosity values are plotted versus clay weight fraction. The good match between the predicted and observed data means that the conceptual microgeometrical model and the relationships given in Section 4.2.3 should be directly applicable to the interpretation of the dielectric results.

Figure 4.10 shows $\kappa$ versus porosity, and $\sigma_{e f}$ versus porosity, for all the sandmontmorillonite mixtures. These mixtures are assumed to be under zero-confining pressure so that each sample is essentially uncompacted in the sample holder. In contrast to the $\kappa-\phi$ and $\sigma_{e f-}-\phi$ relationships for pure sand and pure clay, the $\kappa-\phi$ and $\sigma_{e f}-\phi$ relationships for sand-clay mixtures are not well-defined one-to-one relationships; rather, these relationships are multivalued or scattered. For instance, the data in Figure 4.10 show that different sand-clay mixtures can have the same porosity but different dielectric constants at a given frequency. This is clearly due to the fact that clay content is varying along with porosity in this suite of mixtures.

## Sand - Montmorillonite Mixtures



Figure 4.9. Predicted and observed relationships between porosity and clay weight fraction for 11 sand-montmorillonite mixtures at low confining pressures and room-dry conditions.


Figure 4.10. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for 11 sand-montmorillonite mixtures at room-dry conditions. Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz . The arrow is meant to direct the eye along the path of increasing clay content for the 1 MHz data.

Note however that the "scatter" in the $\kappa-\phi$ and $\sigma_{e f} \phi$ relationships for these sand-clay mixtures is not random or chaotic; rather, it is very regular and predictable. There is a single discontinuity in the $\kappa-\phi$ and $\sigma_{e f}-\phi$ curves defined for each frequency that occurs at the point corresponding to the minimum porosity in the series. Referring to Figure 4.2, it is apparent that this point of minimum porosity is also the point in the sand-clay series where the matrix material changes. Moving across this point from low clay content to high clay content, samples change from being sand-supported to being clay-supported.

Figure 4.11 shows the relationships between electrical parameters and clay content. As with the porosity plots, three frequencies are shown: $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz . For a given frequency, $\kappa$ increases continuously as clay weight fraction increases. There are no multivalued regions in the $\kappa-W_{c l}$ and $\sigma_{e f}-W_{c l}$ relationships like there are in the $\kappa-\phi$ and $\sigma_{e f} \phi$ relationships. Note however that there is a change in slope of the conductivity response, and an associated enhancement in the $\kappa$ response, in the vicinity of $W_{c l}=0.193$ (the sample corresponding to the porosity minimum). As observed for the pure montmorillonite samples, there is a strong correlation between conductivity and the magnitude of dispersion in $\kappa$. Highly conductive (high clay content) mixtures depend much more strongly on frequency than do less conductive (low clay content) mixtures. At $W_{c l}=0.0$ (pure sand), the $\kappa$ values at all frequencies are about 3 , while at $W_{c l}=1.0$ (pure clay), $\kappa$ ranges from 10 at 10 MHz to 32 at 100 kHz . This correlation between conductivity and dispersion in $\kappa$ is also clearly indicated in Figure 4.12 which shows the detailed frequency response of six of the sand-montmorillonite mixtures.

The data in Figure 4.12 also show a correlation between the magnitude of $\kappa$ and the frequency dependence in $\sigma_{e f}$. Samples with low $\kappa$ values show greater conductivity dispersion than do samples with high $\kappa$ (and $\sigma_{e f}$ ) values. This is further evidence of the linkage between dielectric and conductivity responses.


Figure 4.11. (a) Dielectric constant versus clay weight fraction, and (b) conductivity versus clay weight fraction, for 11 sand-montmorillonite mixtures at room-dry conditions. Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz .


Figure 4.12. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for six sand-montmorillonite mixtures at low confining pressures and room-dry conditions. The legend in the upper plot shows the clay weight fraction and porosity of each mixture.

### 4.4 DISCUSSION

Inferring hydrogeologic information from dielectric measurements can be a difficult task due to the complexity of most geologic materials. Not only are soils and rocks comprised of many different components, but these components may be arranged in complicated geometries and interact electrochemically with each other. By experimentally limiting the number and microgeometry of components, one can begin to unravel the fundamental relationships between dielectric and hydrogeologic parameters.

The results of this laboratory study show how the dielectric properties of dry sand-clay mixtures vary with porosity (Figures 4.5, 4.7 and 4.10 ) and clay content (Figure 4.11) as other parameters are held constant or are systematically varied (Figure 4.9). In addition, the data show how K and $\sigma_{e f}$ depend upon each other and upon frequency (Figures 4.6, 4.8 and 4.12). This is most evident when the two parameters, $\kappa$ and $\sigma_{e f}$, measured at various frequencies, are juxtaposed on the same figure. To successfully model or invert dielectric data, the interrelationships of all these parameters must be considered.

In the following sections, I discuss various aspects of the problem of modeling dielectric properties of geologic materials in the kilohertz and low megahertz frequency range. First, I consider the cause of the frequency dependence in $\kappa$ since this will affect any modeling or inversion effort. Then I attempt to model the two-component and three-component experimental data using a volumetric mixing formula that accounts for surface and geometric effects (Sen, 1981), or the enhancement in $\kappa$ caused by conduction phenomena, through the use of appropriately defined "effective" matrix parameters. I conclude by considering some of the consequences of this study for inversion and stratigraphic interpretation of GPR and VETEM field data.

### 4.4.1 Frequency dependence of electrical parameters

As numerous researchers (e.g., Scott et al., 1967; Sen, 1981) have noted, one of the most outstanding features of the dielectric response of geologic materials is the extraordinarily high values of dielectric constant that are observed at low frequencies; values as high as $10^{6}$ have been observed in the kilohertz frequency range for conductive geologic materials. In the present study, K values greater than 80 were measured for samples containing appreciable amounts of clay (e.g., see the data for the low-porosity montmorillonite samples in Figure 4.8). These values are remarkable because the highest dielectric constant of any isolated component in a geologic material is $\sim 80-$ the value for water. Somehow, when components are combined, the measured dielectric constant of the bulk material can become greater than the measured dielectric constant of any of the pure components.

Numerous explanations have been proposed for this anomalous behavior. Many researchers believe that such high dielectric constants are due to interfacial and electrochemical polarization mechanisms that can only operate in multicomponent systems (Sen, 1981; Sen et al., 1981; Chew and Sen, 1982; Endres and Knight, 1993). While I do not dispute the importance of these mechanisms, I believe that there is a simpler phenomenological explanation for the high dielectric constants that is supported by the experimental data presented in this chapter.

The explanation is simply that out-of-phase conduction currents are contributing to the measured effective dielectric constant. In Section 2.7, the following expressions were developed for effective electrical conductivity $\sigma_{e f}$ and dielectric constant $\kappa$ :

$$
\begin{align*}
\sigma_{e f}(\omega) & =\sigma^{\prime}(\omega)+\omega \varepsilon^{\prime \prime}(\omega),  \tag{4.12}\\
\kappa(\omega) & =\frac{\varepsilon^{\prime}(\omega)}{\varepsilon_{0}}+\frac{\sigma^{\prime \prime}(\omega)}{\omega \varepsilon_{0}} . \tag{4.13}
\end{align*}
$$

It is clear that if $\sigma^{\prime \prime}(\omega)$ is larger than $\omega \varepsilon_{0}$, then $\kappa(\omega)$ will increase as $\omega$ decreases (presuming that $\varepsilon^{\prime}(\omega)$ does not also decrease to counteract the effect). Since $\sigma^{\prime \prime}(\omega)$ is related to $\sigma^{\prime}(\omega)$ by the Hilbert transform (i.e., equation 2.28), $\sigma^{\prime \prime}(\omega)$ will increase directly with $\sigma^{\prime}(\omega)$. This explains the observed correlation between $\sigma_{e f}$ and the magnitude of the dispersion in $\kappa$ for sand-clay mixtures. Dispersion in $\kappa$ is high for both the conductive (low porosity) montmorillonite samples and the conductive (high clay content) sand-montmorillonite samples, while it is low for the resistive sand samples.

One way to test the hypothesis that $\kappa(\omega)$ and $\sigma_{e f}(\omega)$ are linked by equations (4.12) and (4.13) is to assume that $\sigma^{\prime}(\omega), \sigma^{\prime \prime}(\omega), \varepsilon^{\prime}(\omega)$ and $\varepsilon^{\prime \prime}(\omega)$ are constant. This is a reasonable assumption if frequency is confined to a small range. Given this condition, equations (4.12) and (4.13) become linear functions of $\omega$ and $\omega^{-1}$, respectively, and can be solved directly using standard regression techniques.

Figures 4.13 and 4.14 show linear least-squares fits to the $\varepsilon_{e f}$ versus $\omega^{-1}$ and $\sigma_{e f}$ versus $\omega$ experimental data for pure sand ( $\phi=0.397$ ) and pure montmorillonite ( $\phi=0.605$ ) over the frequency range 251 kHz to 4 MHz . The equations of the best-fit lines are shown on the plots. The values of the slope and intercept of the two lines represent estimates of $\sigma^{\prime}, \sigma^{\prime \prime}, \varepsilon^{\prime}$ and $\varepsilon^{\prime \prime}$. As indicated by the computed correlation coefficients which are also listed in the figures, the least-squares fits are very good.

The next step is to investigate the relationships between $\sigma^{\prime}$ and $\sigma^{\prime \prime}$, and $\varepsilon^{\prime}$ and $\varepsilon^{\prime \prime}$, since these relationships will be indicative of the linkage between effective electrical parameters. Plots of these relationships for all 28 of the pure sand, pure montmorillonite, and sandmontmorillonite mixtures are shown in Figure 4.15. As can be seen, $\sigma^{\prime}$ and $\sigma^{\prime \prime}$, and $\varepsilon^{\prime}$ and $\varepsilon^{\prime \prime}$, are strongly correlated. This suggests that, to first order, the frequency dependence of electrical parameters can be accurately described by the explicit frequency terms in equations (4.12) and (4.13).


Figure 4.13. Dry silica sand sample with porosity $=0.399$. (a) Relationship between dielectric permittivity and $\omega^{-1}$. The intercept and slope of the best-fit line are estimates of $\varepsilon^{\prime}$ and $\sigma^{\prime \prime}$, respectively. (b) Relationship between conductivity and $\omega$. The intercept and slope of the best-fit line are estimates of $\sigma^{\prime}$ and $\varepsilon^{\prime \prime}$, respectively.

(b)


Figure 4.14. Dry montmorillonite clay sample with porosity $=0.598$. (a) Relationship between dielectric permittivity and $\omega^{-1}$. The intercept and slope of the best-fit line are estimates of $\varepsilon^{\prime}$ and $\sigma^{\prime \prime}$, respectively. (b) Relationship between conductivity and $\omega$. The intercept and slope of the best-fit line are estimates of $\sigma^{\prime}$ and $\varepsilon^{\prime \prime}$, respectively.


Figure 4.15. Crossplots of the real and imaginary parts of complex permittivity (plot a) and complex conductivity (plot b) for pure sand, pure montmorillonite and their mixture. The values of $\varepsilon^{\prime}, \varepsilon^{\prime \prime}, \sigma^{\prime}$ and $\sigma^{\prime \prime}$ for each sample were determined from regression analysis as described in the text and illustrated in Figures 4.12 and 4.13.

### 4.4.2 Modeling with the Time Propagation equation

To determine the extent to which volumetric factors alone determine the dielectric response of pure sand, pure clay and sand-clay mixtures, an attempt was made to model the experimental data using a simple volumetric mixing formula. The mixing formula used was the Time Propagation (TP) equation which, for dry sand-clay mixtures, can be written:

$$
\begin{equation*}
\sqrt{\kappa}=\phi \sqrt{\kappa_{a}}+(1-\phi) V_{c l} \sqrt{\kappa_{c l}}+(1-\phi)\left(1-V_{c l}\right) \sqrt{\kappa_{s}} \tag{4.14}
\end{equation*}
$$

where $\phi$ is porosity (i.e., the volume fraction of air), $V_{c l}$ is the volume fraction of clay, and $\kappa_{a}$, $\kappa_{c l}$ and $\kappa_{s}$ are the dielectric constants of air, clay and sand components, respectively. This is the same mixing formula as discussed in Section 3.3.3 of the previous chapter. Note that by setting $V_{c l}$ equal to 0 or 1 , equation (4.14) can be used to model the two-component pure sand or pure clay mixtures as well. Because $\phi$ and $V_{c l}$ are volumetric parameters, the agreement between the modeled data (assuming constant values for $\kappa_{a}, \kappa_{c l}$ and $\kappa_{s}$ ) and the experimental data is a measure of the extent to which volumetric factors determine the dielectric response of sand-clay mixtures.

Equation (4.14) was fit to the dielectric data measured at $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz for the pure sand mixtures, given the measured porosities of the mixtures and the dielectric constant of air (i.e., $\kappa_{a}=1.0006$ ). The fits were constrained to pass through the data point for air. The result is shown in Figure 4.16. The model fits the experimental data well, suggesting that the dielectric response of dry sand is dominated by volumetric factors. The implied dielectric constants for silica ( $\kappa_{s}=3.9-4.2$ ) determined from projections of the best-fit curves to $\phi=1.0$ are in the range of generally accepted values for quartz at 1 MHz (Handbook of Physics and Chemistry, 1986; Olhoeft, 1979a).

The dielectric response of the pure montmorillonite mixtures is more complicated than that of the pure sand mixtures. Figure 4.17 shows a TP model fit to the dry montmorillonite


Figure 4.16. The square root of the dielectric constant versus porosity for five silica sand samples at room-dry conditions. (a) 100 kHz data. (b) 1 MHz data. (c) 10 MHz data. The best-fit lines are used to estimate the matrix parameter of silica Ks (i.e., the zero-porosity dielectric constant) at each frequency, assuming the TP model. The misfit is the mean of the absolute normalized deviations between the predicted and observed dielectric data.


Figure 4.17. The square root of the dielectric constant versus porosity for 13 montmorillonite clay samples at room-dry conditions. (a) 100 kHz data. (b) 1 MHz data. (c) 10 MHz data. The best-fit lines are used to estimate the matrix parameter of the clay Kcl (i.e., the zeroporosity dielectric constant) at each frequency, assuming the TP model. The misfit is the mean of the absolute normalized deviations between the predicted and observed dielectric data.
data at the three frequencies. The model fits the data relatively well at high frequencies (10 MHz ) but poorly at low frequencies ( 100 kHz ). I suggest that this is because the $\sigma^{\prime \prime}(\omega)$ component of the clay matrix parameter $\kappa_{c l}$ is varying as the mixtures are compacted, yet $\kappa_{c l}$ is assumed to be constant in the TP modeling. Another explanation is that the magnitude of the surface effects change when the clay is compacted. At high clay contents, the clay particles are distributed loosely in the sample holder and do not interact strongly with each other. The dielectric constant of the mixtures is low $(\kappa<10)$ because air occupies a large percentage of the mixtures. As the amount of clay in the mixtures increases, the dielectric constant increases slowly at first, much like the sand, and then much more rapidly once porosity values less than 0.60 are reached. In contrast, the conductivity of the mixtures (recall Figure 4.7) increases dramatically as porosity is reduced from 0.80 to 0.60 , and then much more gradually as porosity is further reduced below 0.60 . The dramatic increase in conductivity with compaction is due to the establishment of critical conductive pathways through the samples. These pathways are fully established (i.e., percolate) once porosity reaches 0.60 , so that further compaction has little effect on conductivity. Note that the montmorillonite mixture with $\phi=$ 0.599 is the first mixture that required pressure to seat the electrodes in the sample holder, hence this mixture was chosen as the uncompacted clay end-member in the sandmontmorillonite suite (i.e., $\phi_{c}=0.60$ in the microgeometrical model).

Having modeled the pure sand data and the pure clay data, it is interesting to consider whether the dielectric response of the three-component sand-clay-air mixtures can also be modeled using the same volumetric mixing formula. In the sand-montmorillonite suite, both porosity and clay content are variable. However, the mixtures in this suite were generated in such a way as to minimize variation in the degree of compaction. This suggests that the compaction-dependent clay matrix value associated with the pure clay end-member (i.e., the
clay sample with $\phi=0.599$ ) may in fact be the appropriate $\kappa_{c l}$ value to use for all the samples in the sand-clay suite. This constitutes a testable hypothesis.

The result of applying the TP model (equation 4.14) in a forward modeling sense to predict the dielectric response at 1 MHz of the room-dry, three-component, sandmontmorillonite mixtures is shown in Figure 4.18. The modeling procedure involved computing $\kappa$ values given the measured $\phi$ and $V_{c l}$ values for each sample, and assuming $\kappa_{a}=$ $1.0006, \kappa_{s}=4.111$ and $\kappa_{c l}=72.202$. Axes for both porosity and clay volume fraction are plotted in Figure 4.18 to show how the data snake through the multi-dimensional parameter space. The experimental measurements are plotted as " O " symbols and the TP model data are plotted as " $x$ " symbols. Note the excellent agreement between the predicted and observed data.

The two- and three-component modeling procedure described above was also repeated for the sand-clay data acquired at 100 kHz and 10 MHz . Similar results were obtained to those shown in Figure 4.18. For both the pure sand mixtures and the sand-montmorillonite mixtures, the agreement between the predicted and observed data is excellent. This is remarkable, particularly considering the complexity of the dielectric response of the sandmontmorillonite mixtures in the frequency range 100 kHz to 10 MHz . To my knowledge, no study has matched this success in modeling the dielectric properties of such a wide range of materials in the kilohertz and low megahertz frequency range.

Although the dielectric response of the dry sand-montmorillonite mixtures is complex, the dielectric mixing model that can accurately predict this response is extraordinarily simple. There is no need for detailed modeling and superposition of interfacial and electrochemical polarization mechanisms. All that is required in the model is information about the volume fractions of components and their "effective" dielectric constant values (i.e., $\kappa_{a}, \kappa_{s}$ and $\kappa_{c l}$ ). The key to the success of the model is accounting for the contribution of $\sigma^{\prime \prime}(\omega)$ to the dielectric


Figure 4.18. Comparison of TP model predictions ( x ) with observed data ( 0 ) for room-dry sand-montmorillonite mixtures. Frequency is 1 MHz . TP model parameters are: $\kappa_{s}=4.111$, $\kappa_{c}=72.20$ and $\kappa_{a}=1.0006$.
properties of each component, since $\sigma^{\prime \prime}(\omega)$ is the parameter that determines the dispersive behavior of the dielectric constant.

### 4.4.3 Implications for mapping porosity and lithology using GPR and VETEM

Porosity variations in the subsurface may occur because of compaction or because of changes in lithology. These two mechanisms of porosity variation were simulated in the different suites of mixtures generated in this study. Electrical property measurements for each suite of mixtures show that the two mechanisms of porosity variation may affect electrical properties in different ways. Porosity reduction by compaction results in an increase in dielectric constant for dry materials because the volume fraction of high- $\kappa$ material increases in the material. Porosity reduction by pore-filling (i.e., changing lithology) can result in either an increase or a decrease in dielectric constant depending upon the volume fractions, microgeometries and surface properties of the components. As a result, the relationship between porosity and dielectric constant for dry materials can be multivalued or characterized by a high degree of scatter if lithology is variable.

The fact that different mechanisms of porosity reduction can lead to different dielectric responses has important implications for inversion and stratigraphic interpretation of ground penetrating radar and very early time electromagnetic geophysical data from the unsaturated zone. In areas where lithology is constant and known, it should be possible to invert electromagnetic data to obtain accurate estimates of porosity values. Similarly, in areas where "compaction" is constant, it should be possible to invert electromagnetic data to obtain accurate estimates of lithology types. However, in areas where both lithology and compaction are variable, the inverse problem becomes ill-posed due to non-uniqueness in the relationships between hydrogeologic and dielectric parameters. To solve this problem, additional constraints such as direct porosity or lithology measurements must be provided. The most important
problem and fundamental challenge will be to determine matrix parameter values for conductive components such as clays.

### 4.5 SUMMARY

A series of laboratory experiments was conducted to investigate the electrical properties of room-dry sand-clay mixtures as a function of porosity and clay content; the sand-clay mixtures are representative of sediments from the unsaturated zone. A microgeometrical model was used to systematically control the porosity, clay content and effective degree of compaction of the mixtures.

The different suites of mixtures show how electrical properties vary when porosity is reduced by two mechanisms: compaction and pore-filling (i.e., changing lithology). The form of the $\mathrm{k}-\phi$ relationship is determined by the mechanism responsible for the porosity variation, so that there is not in general a one-to-one relationship between dielectric constant and porosity.

Because the volume fraction of each component is known for each mixture, the data set acquired in this research is useful for testing the applicability of different dielectric mixing formulas. As a first test, I show how the data can be modeled using the Time Propagation (TP) model, a simple volumetric mixing formula. Results show that this model is capable of accurately predicting the relationships between dielectric constant and porosity, and dielectric constant and clay volume fraction, throughout the frequency range of 100 kHz to 10 MHz . The key to the success of the modeling is incorporation of the effect of conductivity on dielectric dispersion through the appropriate selection of component dielectric constant values. This provides insight into the relative importance of yolumetric, geometric and surface effects for different materials, as well as a possible explanation for some of the scatter reported in previous investigations. The results of this study also have important implications for the inversion and stratigraphic interpretation of electromagnetic field data.

## Chapter 5

## Effects of water saturation on the dielectric properties of sand-clay mixtures

### 5.1 INTRODUCTION

The presence of even a small amount of water in geologic materials can have a significant effect on bulk dielectric properties. This is due in part to the large differences that exist between the dielectric constants of water ( $\kappa_{w} \sim 80$ ), air ( $\kappa_{a \sim 1}$ ) and most other fluids ( $\kappa_{f}<5$ as shown in Table 3.3 of this thesis), and in part to polarization phenomena that arise when water adsorbs to grain surfaces (Chew and Sen, 1982; Olhoeft, 1987). In Chapter 4, I investigated how textural parameters such as porosity and clay content affect the dielectric properties of sand-clay mixtures measured under room-dry conditions. In this chapter, I investigate what happens to the dielectric response of sand-clay mixtures when water is added to the mixtures.

Four suites of sand-clay mixtures and saturation conditions are investigated:
(1) a suite of pure silica sand mixtures with different porosities, under dry and fully saturated conditions;
(2) a suite of pure kaolinite clay mixtures with different porosities, under dry and fully saturated conditions;
(3) a suite of sand-kaolinite mixtures with different porosities and clay contents but the same degree of compaction, under dry and fully saturated conditions; and
(4) a pair of sand-kaolinite mixtures with the same porosity but different clay contents, as water saturation is reduced from fully saturated to room-dry conditions through evaporative drying.

For each mixture and saturation condition, the dielectric constant $\kappa$ and effective electrical conductivity $\sigma_{e f}$ were measured over the frequency range 100 kHz to 10 MHz . The four suites of samples and the various saturation conditions represent a total of 87 multi-component mixtures. As such, this is one of the largest well-characterized dielectric data sets ever collected. The data complement other extensive studies such as Kutrubes (1986), who measured the dielectric properties of 22 soils saturated with air and water, and 2 soils saturated with benzene and methanol, over the frequency range 500 kHz to 1.3 GHz ; Topp et al. (1980), who measured the dielectric properties of 4 soils and 2 glass bead packs at numerous saturation levels and two salinity levels using time-domain reflectometry (megahertz frequency range); Taherian et al. (1990), who measured the dielectric properties of 271 brine-saturated rocks over the frequency range $10 \mathrm{MHz}-1.3 \mathrm{GHz}$; and Knight and Nur (1987) who measured the dielectric properties of 8 rocks at approximately 10 levels of water saturation over the frequency range 60 kHz to 4 MHz .

The first three suites of mixtures are analogous to those investigated in the previous chapter except that kaolinite, rather than montmorillonite, is used as the clay component and both water and air are used as the fluid component. I chose to use kaolinite, as opposed to montmorillonite, in these experiments because kaolinite does not swell as much when saturated and hence is much easier to work with; in addition, the use of another clay component with different specific surface and cation exchange values allows investigation of the effect of changing surface properties on the dielectric response of pure clay and sand-clay mixtures.

The use of two different pore fluids (air and water) in the first three experiments allows investigation of the effect of fluid substitution on the dielectric properties of sand-clay mixtures. The use of two samples with identical porosities but different lithologies in the fourth experiment allows investigation of the effect of texture on the relationship between dielectric constant and volumetric moisture content.

Because much is known about the component electrical properties, microgeometries, weight fractions and volume fractions, the data acquired in this study can be used to test dielectric mixing formulas and effective medium theories. Towards this end, I investigate the ability of a simple volumetric mixing formula (the Time Propagation model) to model the dielectric constant versus water saturation data from experiment four. The goal is to develop some insight into the relative importance of volumetric effects and surface effects in determining the dielectric response of different geologic materials.

### 5.2 SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURE

The samples generated in this study were comprised of two solid components: a silica sand and a kaolinite clay. The sand is the same as that used in the experiments described in Chapter 4 (i.e., pure silica sand from Lane Mountain, Washington), but the clay is different. Instead of Na-montmorillonite, I chose to use kaolinite as the clay component. The kaolinite is KGa-1 from the Clay Mineral Repository at the University of Missouri.

Table 5.1 lists relevant physical properties of the sand and clay components. Grain densities and bulk sample porosities were determined using a Helium pyenometer. The grain diameter of the sand was determined from sieve analysis and the particle diameter of the clay was taken from the literature (Hillel, 1980, p. 76). The surface area of the sand was determined from nitrogen adsorption isotherms using the BET equation (Brunauer et al., 1938), and the surface area of the kaolinite was determined from an adsorption experiment using ethylene glycol monoethyl ether as described by Carter et al. (1965). The cation exchange capacity (CEC) of the sand was not measured but is probably very small; the CEC value listed for kaolinite was taken from van Olphen and Fripiat (1980) who compiled extensive data on the properties of $\mathrm{KGa}-1$ kaolinite and other standard clays.
Chapter 5 -- Effects of water saturation ..... 108

Table 5.1. Component properties.

| Material | Mineralogy | Grain <br> Density <br> $\left[\mathrm{g} / \mathrm{cm}^{3}\right]$ | Grain <br> Diameter <br> $[\mathrm{cm}]$ | Specific <br> Surface <br> $\left[\mathrm{cm}^{2} / \mathrm{g}\right]$ | Cation <br> Exchange <br> $[\mathrm{meq} / 100 \mathrm{~g}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Sand | Quartz | 2.645 | $7 \times 10^{-2}-8 \times 10^{-2}$ | $3.9 \times 10^{2}$ | not measured |
| Clay | Kaolinite | 2.613 | $1 \times 10^{-5}-4 \times 10^{-4}$ | $2.5 \times 10^{5}$ | 2.0 |
|  |  |  |  |  |  |

A two-electrode cylindrical sample holder similar to the one described in the previous chapter (Section 4.2.1) was used for all electrical and hydrogeological property measurements. To provide a means of saturating the samples, two small holes were drilled through the acrylic cylinder.

The pure sand and pure clay mixtures were prepared by putting material directly into the sample holder. The sand-clay mixtures were prepared by blending sand and clay in a beaker, and then transferring the material to the sample holder. The mass sand and mass clay needed to produce each mixture was determined ahead of time using the mass-material property relationships derived in the previous chapter (Section 4.2.3) and based on the microgeometrical model for sand-clay mixtures proposed by Marion et al. (1992). These mass-material property relationships made it possible to produce samples with predetermined porosity, clay content and degree of compaction, given the total volume of the sample holder.

Figure 5.1 shows the microgeometrical arrangement of components assumed in the different mixtures. The boxes along the top of the figure represent the sand-clay mixtures, while those in the left and right columns represent the pure sand and pure kaolinite mixtures, respectively. Figure 5.2 shows the predicted and observed relationships between porosity and clay weight fraction for the seven sand-kaolinite mixtures generated for experiments 3 and 4; all reported weight fractions are for the dry mixtures. The porosity value for pure sand is 0.399 and the porosity value for pure kaolinite is 0.599 ; these end-member porosity values correspond to samples that fill but are uncompacted in the sample holder (i.e., low confining pressures). The two sand-kaolinite samples with porosity values around 0.36 are the ones used in the drying experiment; as Figure 5.2 shows, these samples fall on opposite sides of the minimum porosity or critical point which occurs at a clay weight fraction of 0.209 in this suite of mixtures. The close agreement between the experimental data and the microgeometrical model data is evidence that "ideal packings" have been generated with systematically varying hydrogeologic properties.


Figure 5.1. Conceptual diagram of the packing geometries for pure sand, pure clay, and sandclay mixtures in terms of the experimental parameters: porosity (or the degree of compaction) and clay content. $C l_{p}$ is clay content and $\phi_{s}$ is the porosity of pure sand as defined in the text.

## Sand-Kaolinite Mixtures



Figure 5.2. Predicted and observed relationships between porosity and clay weight fraction for sand-kaolinite mixtures at low confining pressures. Predicted values based on microgeometrical model for sand-clay mixtures proposed by Marion et al. (1992).

The component mass data for each mixture are listed in Appendix D along with the measured electrical properties. The electrical measurements were first made under room-dry conditions and then under saturated conditions. To saturate the samples, distilled water with a conductivity of $\sim 2 \times 10^{-4} \mathrm{~S} / \mathrm{m}(10 \mathrm{~Hz}-10 \mathrm{MHz})$ was injected through one of the access holes in the base of the sample holder. Using this procedure, I was able to obtain saturation levels greater than 0.80 for all the samples. The reported saturation values were determined gravimetrically and have been corrected for the water held in the access hole and the water coating the cylinder-electrode interface. The uncertainty in the $S_{w}$ values is $\pm 0.005$. The drying experiment (suite 4) was conducted by allowing the two saturated sand-kaolinite samples with porosity values of 0.36 to dry on the bench top with one electrode removed.

Effective electrical conductivity $\sigma_{e f}$ and dielectric permittivity $\varepsilon_{e f}$ values were calculated from measurements of the equivalent parallel conductance $G_{p}$ and capacitance $C_{p}$ of the samples using the inversion formulas (Section 2.8):

$$
\begin{equation*}
\sigma_{e f}=\frac{G_{p} d}{A} \quad \text { and } \quad \varepsilon_{e f}=\frac{C_{p} d}{A} \tag{5.1}
\end{equation*}
$$

where $A$ is the area and $d$ the separation of the two electrode surfaces. Dielectric constants were computed from $\kappa=\varepsilon_{e f} / \varepsilon_{O}$ (where $\varepsilon_{O}=8.854 \times 10^{-12} \mathrm{~F} / \mathrm{m}$ ). $C_{p}$ and $G_{p}$ were measured at 31 frequencies spaced logarithmically between 10 Hz and 10 MHz using a Hewlett Packard 4192a impedance analyzer, although for clarity only the data acquired at $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz will be shown; the rest of the data can be found in Appendix D. $C_{p}$ and $G_{p}$ are related to electrical impedance $Z$ through:

$$
\begin{equation*}
Z=\frac{1}{G_{p}+i \omega C_{p}} \tag{5.2}
\end{equation*}
$$

where $\omega$ is angular frequency ( $\omega=2 \pi f$ ). The data were also compensated for cable and sample holder residuals as described in Appendix A. Reported dielectric constant values are accurate to within two percent (Appendix B).

Note that the parameters reported in this study are real-valued effective parameters, not the complex parameters that appear in some electromagnetic theories. The relationships between effective parameters and complex parameters are given by:

$$
\begin{gather*}
\sigma_{e f}(\omega)=\sigma^{\prime}(\omega)+\omega \varepsilon^{\prime \prime}(\omega),  \tag{5.3}\\
\kappa(\omega)=\frac{\varepsilon^{\prime}(\omega)}{\varepsilon_{0}}+\frac{\sigma^{\prime \prime}(\omega)}{\omega \varepsilon_{0}}, \tag{5.4}
\end{gather*}
$$

where $\sigma^{*}(\omega)=\sigma^{\prime}(\omega)+i \sigma^{\prime \prime}(\omega)$ and $\varepsilon^{*}(\omega)=\varepsilon^{\prime}(\omega)-i \varepsilon^{\prime \prime}(\omega)$. For further background on this subject, see Sections 2.3 and 2.7 in this thesis.

### 5.3 EXPERIMENTAL RESULTS

The electrical measurements are presented in two ways: (1) as plots of $\kappa$ and $\sigma_{e f}$ versus hydrogeologic parameters (porosity, clay weight fraction and/or water saturation) for the different suites of mixtures; and (2) as plots of $\kappa$ and $\sigma_{e f}$ versus frequency for selected samples from the four suites. In the hydrogeologic plots, the data are shown for three frequencies: 100 kHz (square symbols), 1 MHz (circles) and 10 MHz (triangles). Measurements made under dry conditions are described first, then measurements made under saturated conditions. Unless otherwise indicated, open symbols represent dry samples while solid symbols represent saturated samples. Following are the results for the four suites of mixtures and saturation conditions.

### 5.3.1 Pure silica sand

Figure 5.3 shows measurements of $\kappa$ and $\sigma_{e f}$, at two levels of water saturation, for five silica sand samples with porosity values between 0.357 and 0.477 . The measured water saturation values exceed 0.96 for all the saturated samples.
(a)

(b)


Figure 5.3. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for silica sand samples at different levels of water saturation. Open symbols show electrical properties measured under room-dry conditions; solid symbols show electrical properties measured after the samples have been saturated with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz .

For a given frequency, the dielectric constant of the dry samples increases slightly with decreasing porosity. There is little scatter about the $\mathrm{k}-\phi$ curve, suggesting strong correlation between $\kappa$ and porosity. There is also little observed frequency dependence in the dielectric response of the dry sand. Conductivity values are low ( $\sigma_{e f}<10^{-4} \mathrm{~S} / \mathrm{m}$ ) but strongly frequency dependent, increasing approximately two orders of magnitude when frequency is scaled by a similar amount.

By comparison, the dielectric constant of the saturated samples decreases significantly with compaction over the porosity range shown in Figure 5.3. There is also much more dispersion in $\kappa$ for the saturated samples. The conductivity of the saturated samples is higher than that of the dry samples and depends less on frequency, registering approximately $10^{-3} \mathrm{~S} / \mathrm{m}$ for each of the three frequencies shown; it is interesting to note that the frequency dependence in conductivity disappears when the samples are saturated with distilled water, while the frequency dependence in dielectric constant increases significantly as a result of this process. This is clearly shown in Figure 5.4, which shows the detailed frequency response of the uncompacted sand sample with a porosity of 0.397 .

### 5.3.2 Pure kaolinite clay

Dielectric data for the pure kaolinite samples are shown in Figures 5.5 (porosity plot) and 5.6 (detailed frequency plot for the sample with $\phi=0.605$ ). Twelve samples were measured at room-dry conditions, and three samples were measured under saturated conditions. The level of water saturation for the saturated samples ranges from 0.804 (for the sample with $\phi=$ 0.462 ) to 0.941 (for the sample with $\phi=0.713$ ). Due to problems of entrapped air and colloidal material leaking out of the sample holder during the fluid injection process, only three samples could be measured under saturated conditions.



Figure 5.4. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for a silica sand sample at two levels of water saturation. .Open symbols show electrical properties measured under room-dry conditions ( $S_{w}=0.00$ ); solid symbols show electrical properties measured after the sample has been saturated ( $S_{w}=0.99$ ) with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). The porosity of the sand is 0.397 .


Figure 5.5. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for kaolinite clay samples at different levels of water saturation. Open symbols show electrical properties measured under room-dry conditions; solid symbols show electrical properties measured after samples have been saturated with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz . Dielectric constants measured at 100 kHz for the saturated samples are greater than 80 (i.e., outside plotting range).


Figure 5.6. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for a kaolinite clay sample at two levels of water saturation. Open symbols show electrical properties measured under room-dry conditions ( $S_{w}=0.00$ ); solid symbols show electrical properties measured after the sample has been saturated ( $S_{w}=0.84$ ) with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). The porosity of the clay is 0.605 .

For the most part, the dielectric response of the pure kaolinite mixtures is similar to the dielectric response of the pure sand mixtures, except that $\kappa$ of the saturated kaolinite mixtures is more dispersive than $\kappa$ of the corresponding sand mixtures. As shown in Figure 5.5, $\kappa$ of the dry kaolinite samples increases with compaction for each frequency studied. For the saturated samples, k values measured at 1 MHz and at 10 MHz decrease with compaction, while the values measured at 100 kHz show the opposite trend (see Appendix D for values). There is little dispersion in $\kappa$ for the dry kaolinite samples, but significant dispersion in $\kappa$ for the saturated samples.

The conductivity measurements show that kaolinite is approximately ten times more conductive than sand at the same porosity and level of water saturation. As was observed for quartz sand, the measured conductivity of kaolinite increases slowly with compaction for both the dry mixtures and the saturated mixtures. For the dry samples, $\sigma_{e f}$ scales with frequency, while for the saturated samples, $\sigma_{e f}$ is almost independent of frequency. There is also a slight break in the slope of the $\log \sigma_{e f}$-porosity relationship for dry kaolinite mixtures; this break in slope occurs at a porosity of approximately 0.60 and marks the point in the series where the mixtures begin to be compacted. Similar behavior was observed for the pure montmorillonite mixtures investigated in Chapter 4.

### 5.3.3 Sand-kaolinite mixtures

Seven sand-kaolinite mixtures were prepared to investigate the coupled effects of changing lithology and changing fluid saturation on dielectric properties. The mixtures are equivalent to the sand-montmorillonite mixtures described in Chapter 4 except that kaolinite, instead of montmorillonite, is used as the clay component. Four of the seven mixtures (i.e., those with clay weight fractions $W_{c l}$ equal to $0.000,0.062,0.129$ and 0.209 ) are sand packs with interstitial clay, while the other three mixtures (i.e., those with $W_{c l}$ equal to $0.372,0.613$ and 1.000 ) are shale-like with grains of sand suspended in a clay matrix. The mixture with
$W_{c l}=0.209$ marks the transition from clayey sand to sandy clay. Measured porosity values for the different mixtures are shown in Figure 5.2 which was presented previously as a test of the mixing procedure. The magnitude and form of the porosity-clay content relationship is as predicted by the microgeometrical model (Marion et al., 1992). Specifically, porosity decreases with increasing clay content to the critical point $W_{c l}=0.209$, and then increases to its maximum value at $W_{c l}=1.000$. The measured porosity at the critical point is 0.238 . Note too that the samples with $W_{c l}=0.062$ and $W_{c l}=0.372$ have the same porosity $(\phi=0.36$ ); these are the samples that are used in the drying experiment described in the next section.

Figures 5.7 and 5.8 show the electrical properties of the seven sand-kaolinite mixtures plotted versus porosity and clay volume fraction, respectively, at dry and water-saturated conditions. Although the data are sparse, they suggest the following trends. First, $\kappa$ of the dry samples (Figure 5.8a) increases slightly (1.4-2.0 dielectric units, depending on frequency) with increasing clay content from $W_{c l}=0.000$ to $W_{c l}=0.209$. At higher clay contents, $\kappa$ does not change much and has a value between 3.9 and 4.7 depending on frequency. Petrophysical modeling with the TP equation shows that this behavior can be explained in terms of the variation in volume fractions of air, sand and clay, and hence is quite similar to the dry sand-montmorillonite results discussed in Chapter 4.

As shown in Figures 5.8 b and 5.9 b , the conductivity of dry sand-kaolinite mixtures increases with increasing clay content over the range $W_{c l}=0.000$ to 0.209 . At clay contents greater than $W_{c l}=0.209$, conductivity is essentially constant. While the overall trends of the sand-kaolinite and sand-montmorillonite conductivity data are similar, the maximum conductivity observed for the sand-kaolinite mixtures is approximately an order of magnitude less than the maximum conductivity observed for the sand-montmorillonite mixtures (compare Figure 5.9 b in this chapter with Figure 4.12 b in the previous chapter). Dispersion in $\sigma_{e f}$ for the sand-kaolinite mixtures is somewhat greater than the dispersion in $\sigma_{e f}$ for the sandmontmorillonite mixtures. Furthermore, there is a subtle but direct relationship between the


Figure 5.7. (a) Dielectric constant versus porosity, and (b) conductivity versus porosity, for seven sand-kaolinite mixtures at different levels of water saturation. Open symbols show electrical properties measured under room-dry conditions; solid symbols show electrical properties measured after samples have been saturated with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz . The arrows are meant to direct the eye along the path of increasing clay content for the 1 MHz data.


Figure 5.8. (a) Dielectric constant versus clay weight fraction, and (b) conductivity versus clay weight fraction, for seven sand-kaolinite mixtures at low confining pressures and different levels of water saturation. Open symbols show electrical properties measured under room-dry conditions; solid symbols show electrical properties measured after samples have been saturated with distilled water ( $\sigma_{w} \approx 4 \times 10^{-4} \mathrm{~S} / \mathrm{m}$ ). Measurement frequencies are $100 \mathrm{kHz}, 1$ MHz and 10 MHz .


Figure 5.9. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for seven sand-kaolinite mixtures at low confining pressures and room-dry conditions. The legend in the lower plot shows the clay weight fraction and porosity of each mixture.
observed dispersion in $\kappa$ and the measured conductivity of the sand-kaolinite samples, so that the samples with high clay contents and high conductivities are also the ones that show the greatest dispersion in $\boldsymbol{\kappa}$.

The results of saturating the sand-kaolinite mixtures with distilled water are also shown in Figures 5.7 and 5.8, and in Figure 5.10 (detailed frequency plot). Water saturation levels are listed in the caption on Figure 5.10; all saturation levels exceed 0.84 . The data show that when water replaces air as the pore fluid, both $\kappa$ and $\sigma_{e f}$ increase dramatically. The amount of enhancement in $\kappa$ depends strongly on clay content, conductivity and frequency; the enhancement is greater for conductive clay-rich mixtures and at lower frequencies. At 10 MHz , the highest frequency considered in this investigation, a distinct minimum is observed in the $\kappa-W_{c l}$ relationship (Figure 5.8a) at $W_{c l}=0.209$, the point corresponding to the sample with the lowest porosity and hence lowest moisture content. Similar, but less pronounced, minima are also observed at 1 MHz and 100 kHz , though the position of this minima shifts to lower clay contents (and correspondingly higher porosities and moisture contents) as frequency is decreased. At $100 \mathrm{kHz}, \kappa$ values greater than 80 are observed for mixtures comprised of more than 50 per cent kaolinite.

Figures 5.7 b and 5.8 b show that $\sigma_{e f}$ of sand-kaolinite mixtures increases two to four orders of magnitude, depending on frequency, when samples are saturated with distilled water. $\sigma_{e f}$ values between $10^{-2}$ and $10^{-3} \mathrm{~S} / \mathrm{m}$ were observed for all seven saturated samples: In addition, the observed dispersion in $\sigma_{e f}$ for the saturated samples (Figure 5.10b) is much less than that observed for the dry samples (Figure 5.9b). A slight increase in $\sigma_{e f}$ is observed with increasing clay content (Figure 5.8b), at least to the point $W_{c l}=0.372$; beyond this point, $\sigma_{e f}$ does not change very much except to become slightly more dispersive.


Figure 5.10. (a) Dielectric constant versus frequency, and (b) conductivity versus frequency, for seven water-saturated sand-kaolinite mixtures at low confining pressures. The legend in the upper plot shows the clay weight fraction, porosity and water saturation of each mixture.

### 5.3.4 Drying experiments

The results of the two drying experiments are shown in Figures 5.11 and 5.12. Figure 5.11 shows plots of $\kappa$ and $\sigma_{e f}$ versus $S_{w}$ for the sample with $W_{c l}=0.062$, while Figure 5.12 shows the equivalent data for the sample with $W_{c l}=0.373$; both samples have a porosity of 0.36. Although the two samples have the same porosity, they do not exhibit the same dielectric response as water saturation is varied. Consider first the dielectric response of the sample with low clay content (Figure 5.11). For this sample, most of the increase in $\kappa$, particularly at low frequencies, occurs at low water saturations. This is also the region where most of the dispersion in $\kappa$ is observed. The maximum $\kappa$ value measured is about 30 ; this corresponds to the data point acquired at 100 kHz at the highest water saturation.

The measured conductivity of this sample also changed dramatically at low water saturations. For instance, as $S_{w}$ increases from 0.00 to $0.20, \sigma_{e f}$ at 100 kHz increases by a factor of 1000 . The rate of change in $\sigma_{e f}$ decreases steadily with increasing saturation, so that beyond saturation levels of 0.60 there is little change in $\sigma_{e f}$ at any frequency. The magnitude of the enhancement observed at low water saturations decreases with increasing frequency, but is still significant even at 10 MHz . Dispersion in $\sigma_{e f}$ also decreases with increasing saturation; at saturation levels greater than 0.60 , there is very little frequency dependence in $\sigma_{e f}$.

The dielectric and conductivity response of the high clay content sample is quite different. As shown in Figure 5.12, there is little change in $\kappa$ except at water saturation levels above 0.60. Dispersion in $\kappa$ is small at low water saturations, but large at high water saturations; this is essentially the reverse of the findings for the low clay content sample. A direct consequence is that at full saturation the two samples have essentially the same dielectric constant at 10 MHz ( $\kappa \approx 20$ ), but very different $\kappa$ at 100 kHz ( $\kappa \approx 30$ for the low clay content sample whereas $\kappa \approx 85$ for the high clay content sample).


Figure 5.11. (a) Dielectric constant versus water saturation, and (b) conductivity versus water saturation, for a clayey sand mixture ( $W_{c l}=0.062$ ) with porosity $=0.36$. Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz .
(b)


Figure 5.12. (a) Dielectric constant versus water saturation, and (b) conductivity versus water saturation, for a sandy clay mixture ( $W_{c l}=0.373$ ) with porosity $=0.36$. Measurement frequencies are $100 \mathrm{kHz}, 1 \mathrm{MHz}$ and 10 MHz .

Figure 5.12 b shows the conductivity response of the high clay content sample. For a given frequency, $\sigma_{e f}$ remains essentially constant at low water saturations ( $S_{w}<0.40$ ) and at high water saturations ( $S_{w}>0.80$ ), but increases dramatically with increasing saturation in the mid-saturation range ( $0.40<S_{w}<0.80$ ). The magnitude of the enhancement in $\sigma_{e f}$ decreases with increasing frequency; at 100 kHz the enhancement is about 3 orders of magnitude, while at 10 MHz the enhancement is approximately 1 order of magnitude. At low water saturations, $\sigma_{e f}$ scales with frequency, while at high saturations, $\sigma_{e f}$ is essentially independent of frequency; this result is similar to the dispersion characteristics of the low clay content sample.

### 5.4 DISCUSSION

A tremendous amount of information is contained in Figures 5.2 through 5.12. These figures show how dielectric properties vary with porosity (Figures 5.3, 5.5, and 5.7), clay content (Figures 5.8) and water saturation (Figures 5.11 and 5.12) as other parameters are held constant or are systematically varied (Figure 5.2). In addition, the data show how $\kappa$ and $\sigma_{e f}$ depend upon each other and upon frequency. This is most evident when the two parameters, $\kappa$ and $\sigma_{e f}$, measured at various frequencies, are juxtaposed on the same figure. To successfully model dielectric properties, the interrelationships of all these parameters must be considered.

### 5.4.1 Volumetric, geometric and surface effects

It is generally believed that four factors combine to determine the bulk dielectric constant of a material: (1) the individual dielectric constants of the components, (2) the volume fractions of the components, (3) the geometries of the components, and (4) the electrochemical interactions between the components. For years, researchers have been trying to determine how best to mathematically incorporate these various factors into dielectric mixing models and effective medium theories. The experimental data acquired in this study provide some insight into this problem, as well as a means of testing different modeling approaches.

The effect of changing individual component properties can be seen by comparing the dielectric data for pure sand (Figure 5.3a), pure kaolinite (Figure 5.5a) and pure montmorillonite (Figure 4.7a) at a given porosity value and level of water saturation; for instance, at $\phi=0.40$ and $S_{w}=0.0$ (referenced to room-dry conditions), the measured dielectric constant values at 1 MHz for these three materials are $2.6,5.7$ and 72.3 , respectively. Likewise, changing the pore fluid from air to water, as was done in the saturation experiments in this chapter, can also have a large effect on electrical properties. For instance, compare the dielectric data for the two saturation states (open symbols versus solid symbols) for any one of the pure sand samples shown in Figure 5.3a. Changing the pore fluid from air to water results in an increase in the measured dielectric constant of the bulk material because of the difference that exists between the dielectric constants of air (1) and water ( $\sim 80$ ).

The effect of changing the volume fractions of components can be seen in many of the dielectric constant versus hydrogeologic parameter plots, since porosity, clay content and water saturation are all volumetric parameters. Consider, for example, the compaction experiment for pure sand (i.e., Figure 5.3a). For any given measurement frequency, the dielectric constant increases with compaction if the samples are dry, and decreases with compaction if the samples are water saturated; this is due to the differences in the proportions of high- $\kappa$ and low- $\kappa$ material in the mixtures.

Geometric and surface effects are also apparent in some of the data, particularly for clayrich samples at low frequencies. An example from the previous chapter is the anomalous enhancement in the dielectric constant of pure montmorillonite as it undergoes compaction (Figure 4.7). This enhancement is interpreted as being due to the establishment of critical conductive pathways through the sample by percolating clay booklets, and scaling of the $\sigma^{\prime \prime}$ term in the expression for the effective dielectric constant. Changing the surface properties or microgeometry of the clay will affect this component, and hence the frequency dependence of
$\kappa$, as can be seen by comparing the montmorillonite data in Chapter 4 with the kaolinite data in the present chapter.

### 5.4.2 Applicability of the Time Propagation model

Since the volume fraction of components comprising each mixture is known, the data acquired in this study can be used to test the applicability of different mixing formulas and effective medium theories. A complete analysis of mixing formulas is beyond the scope of this study. However, as a first test, I attempt to model the 1 MHz dielectric data from the drying experiment using the Time Propagation equation. The purpose is to explore the applicability of the modeling approach under circumstances when the surface properties of the matrix are likely to be changing.

The data that I attempt to model are the dielectric constant versus water saturation data collected at 1 MHz for the two sand-kaolinite mixtures that were dried on the bench top in experiment (4); these data are shown by the circles in Figures 5.11 and 5.12. The two samples have the same porosity ( $\phi=0.36$ ), but different clay contents, hence the dielectric constant versus water saturation data can be used to investigate the influence of texture on the relationship between $\kappa$ and volumetric moisture content $\theta_{\nu}$, where $\theta_{\nu}=\phi S_{w}$.

For a four-phase mixture of sand, clay, air and water, the Time Propagation (TP) equation can be written:

$$
\begin{equation*}
\sqrt{\kappa}=\phi\left(1-S_{w}\right) \sqrt{\kappa_{a}}+\phi S_{w} \sqrt{\kappa_{w}}+(1-\phi) C_{v} \sqrt{\kappa_{c l}}+(1-\phi)\left(1-\mathrm{Cl}_{\mathrm{v}}\right) \sqrt{\kappa_{s}} \tag{5.5}
\end{equation*}
$$

where $\phi$ is porosity, $C l_{v}$ is clay volume fraction, $S_{w}$ is water saturation, $\kappa$ is dielectric constant, and the subscripts identify the components. Additional information about this volumetric mixing model may be found in Section 3.3.3 of this thesis.

In this forward modeling exercise, values of $\phi, C l_{v}$, and $S_{w}$ are known since these parameters were directly measured in the experiment. In addition, the $\kappa$ values for air
( $\kappa_{a}=1.0006$ ) and water ( $\kappa_{w}=79.46$ ) are assumed to be known. This leaves the matrix parameters $\kappa_{s}$ and $\kappa_{c l}$ as the only parameters that must be specified before bulk $\kappa$ values can be computed. Values for these parameters were determined directly from the dielectric measurements made for the pure water-saturated sand sample with porosity equal to 0.399 , and the pure water-saturated kaolinite sample with porosity equal to 0.599 . These samples are the end-members at zero-confining pressure that were mixed in various proportions to produce the two sand-clay samples used in the drying experiment. Since the porosity and water saturation values of the end-member samples are known (i.e., measured), the TP equation can be solved directly for the matrix parameter values. The effective matrix parameter values determined in this way are: $\kappa_{s}=7.346$ and $\kappa_{c l}=50.834$ at 1 MHz . Given values for all the parameters on the right hand side of equation (5.5), the relationship between dielectric constant and water saturation can now be predicted for each of the two sand-clay mixtures involved in the drying experiment.

The results are shown in Figure 5.13. The upper plot is for the low clay content sample with $W_{c l}=0.062$, while the lower plot is for the high clay content sample with $W_{c l}=0.372$. The agreement between the TP model predictions and the experimental data is quite good for the low clay content sample over the entire water saturation range. This suggests that the relationship between dielectric constant and water saturation for this sample is predominantly controlled by volumetric factors, and that surface effects do not vary significantly with water saturation. Stated another way, the definition of the matrix parameter in this model is sufficient to explain the polarization occurring at the solid/fluid interface.

The results for the high clay content sample (Figure 5.13b) are not so promising. In this case, the agreement between the TP model and the experimental data is poor, except at the highest water saturation. The model predictions are consistently too high. This suggests that the matrix parameter value used in this model has overestimated the surface effects that occur at low water saturations. If the matrix parameter is arbitrarily decreased some amount, the TP

## Sand-Kaolinite Mixture \#1


(b)


Figure 5.13. Dielectric constant ( 1 MHz ) versus water saturation for two sand-kaolinite mixtures with the same porosity but different clay contents. (a) Sample with clay weight fraction equal to 0.062 . (b) Sample with clay weight fraction equal to 0.372 . Also shown are the TP model predictions assuming $\kappa_{s}=7.346$ and $\kappa_{c l}=50.834$.
model curve shifts down and the fit is improved somewhat. However, regardless of what matrix value is used, the TP model cannot reproduce the curvature of the measured data shown in Figure 5.13b. This suggests that the nature of the solid/fluid interface is changing as water saturation changes for this sample.

This simple modeling exercise demonstrates how surface and volumetric effects may be recognized in dielectric data. There is a clear need for development of better mathematical models of dielectric properties. Experimental data such as acquired in this study can help in the development and testing of dielectric models.

### 5.5 SUMMARY

Measurements have been made of the dielectric properties of sand-clay mixtures with known porosity, clay content and degree of compaction, as water saturation is also varied. Results show the effects of varying individual component properties, volume fractions, microgeometries, and surface properties. At high frequencies (around 10 MHz ), volumetric effects tend to dominate the dielectric response, though texture also plays a role. At low frequencies, surface effects become important. The data set is useful for testing hypotheses about petrophysical transform relationships, and for assessing the applicability of different mixing formulas. As such, it represents an important step towards development of more generally applicable effective medium theories of dielectric properties that can explain both the dielectric response and the conductivity response of a variety of geologic materials over a wide range of frequencies.

## Chapter 6 <br> Estimating hydraulic permeability from dielectric measurements

### 6.1 INTRODUCTION

Hydraulic permeability ${ }^{1}$ is a measure of a material's ability to transmit fluids; for many applications, this is the most important property of porous media. Permeability values for geologic materials span many orders of magnitude (recall Table 1.2). Clays and silts, for instance, have permeabilities ranging from $10^{-15}$ to $10^{-8} \mathrm{~cm}^{2}$, clean sands from $10^{-8}$ to $10^{-5}$ $\mathrm{cm}^{2}$, and gravels from $10^{-6}$ to $10^{-3} \mathrm{~cm}^{2}$ (Freeze and Cherry, 1979). Even within individual stratigraphic units (e.g., at the bed scale of 1-10 m), measured permeability values may vary over orders of magnitude (Hartkamp-Bakker, 1993).

The statistical distribution and spatial structure of permeability values determines, to a large extent, the nature of fluid flow and contaminant transport in the subsurface (Scheibe, 1993). Of particular importance in contamination problems is the spatial connectivity of high and low permeability zones, since these zones tend to condition flow paths and influence early and late breakthrough times (Smith and Schwartz, 1981; Journel and Alabert, 1988). The challenge in site characterization is to obtain enough permeability measurements of sufficient resolution to identify the critical pathways and barriers to flow.

Conventional methods of characterizing in situ permeability distributions, such as pump tests, slug tests and borehole flowmeter measurements, typically suffer from aliasing and/or resolution problems (Beckie, 1996). Pump tests, for instance, are generally incapable of resolving bed-scale permeability variations which can strongly influence transport behavior,

[^1]although these tests are very useful for sampling large volumes of aquifer material and determining large-scale aquifer properties. Borehole flowmeters, on the other hand, can resolve bed-scale permeability variations along the length of a well, but these instruments have a small measurement volume; if wells in a flowmeter sampling network are spaced too far apart, then critical features of the permeability field between the wells will be aliased. Slug tests suffer from the same problem. Increasing the density of wells helps to reduce the uncertainty and errors caused by aliasing, however installing and testing new wells can be very expensive.

Unlike direct hydraulic measurements, ground penetrating radar (GPR) and very early time electromagnetics (VETEM) can both efficiently sample the subsurface on large, dense, grids and resolve small-scale heterogeneities. As a result, these electromagnetic geophysical techniques may offer a practical solution to the problem of closure of measurement and network sampling scales (Beckie, 1996). What is not known is whether the heterogeneities imaged by GPR and VETEM are in any way related to permeability variations; if they are related, this would imply a relationship between dielectric properties and permeability. To my knowledge, no such relationship has ever been demonstrated. The purpose of this chapter is to investigate possible correlations between dielectric properties and permeability.

Although no hydraulic stress is imposed when making a dielectric measurement, there is reason to believe that permeability information may be extractable from dielectric data in some cases. As shown in the previous two chapters (4 and 5), dielectric properties depend upon porosity, clay content and clay mineralogy, among other factors. Clay content and clay mineralogy are related to grain size distribution and specific surface. Porosity, grain size distribution and specific surface are factors that affect permeability (as reviewed in the next section). Therefore, it is not unreasonable to expect that these parameters (i.e., porosity, grain
size distribution and specific surface) may be used as a bridge to relate dielectric constant and hydraulic permeability.

To test this idea, permeability measurements were made on some of the silica sandkaolinite clay mixtures investigated in the previous chapter (5). The relationships between permeability, dielectric constant and other petrophysical parameters are then explored using a variety of crossplots. The measured data are also compared to the predictions of three interrelated petrophysical models; these models are described in the section following the permeability review. Results show that the modeled dielectric and permeability data are in good agreement with the measured data for sand-clay mixtures. This supports the hypothesis that dielectric properties and permeability are related through their common dependence on porosity, grain size distribution and specific surface.

The dielectric and permeability models can also be used to predict the dielectric constantpermeability relationships for materials other than binary sand-clay mixtures. These more general relationships can be used as the basis for joint geophysical-hydrogeological inverse procedures such as considered by Rubin et al. (1992), Copty et al. (1993), Hyndman et al. (1994) and McKenna and Poeter (1995). The chapter concludes with a simple surface-toborehole radar field test to demonstrate the applicability of the dielectric constant-permeability transform and to highlight present limitations.

### 6.2 PERMEABILITY REVIEW

### 6.2.1 Definition and units

Permeability is defined empirically as the constant of proportionality $k$ in Darcy's law, i.e., $\quad V=-\left(k \frac{\rho g}{\mu}\right) \frac{\partial h}{\partial l}$
where $V$ is the specific discharge, $d h / d l$ is the hydraulic gradient, $\rho$ is the density of the fluid, $g$ is the gravitational constant $\left(980.7 \mathrm{~cm} / \mathrm{s}^{2}\right)$, and $\mu$ is the dynamic viscosity of the fluid. If the fluid is water, the expression in brackets $(\mathrm{k} \rho \mathrm{g} / \mu)$ is the hydraulic conductivity $K$. Permeability is a function of the porous media alone while hydraulic conductivity is a function of both the porous media and the fluid.

Dimensional analysis shows that permeability has units of area, while hydraulic conductivity has units of velocity. The units used in this thesis are $\mathrm{cm}^{2}$ for permeability and $\mathrm{cm} / \mathrm{s}$ for hydraulic conductivity. The density and viscosity of fresh water are functions of temperature and pressure. At $20^{\circ} \mathrm{C}$ and atmospheric pressure (i.e., typical laboratory conditions), $\rho=0.9982 \mathrm{~g} / \mathrm{cm}^{3}$ and $\mu=1.002 \times 10^{-2} \mathrm{~g} / \mathrm{cm}-\mathrm{s}$ (Hillel, 1980, p. 49); under these conditions, permeability in $\mathrm{cm}^{2}$ may be computed from hydraulic conductivity measurements in $\mathrm{cm} / \mathrm{s}$ by dividing $K$ by $9.770 \times 10^{4}(1 / \mathrm{cm}-\mathrm{s})$. At $10^{\circ} \mathrm{C}$ and the same pressure (i.e., typical groundwater field conditions), the $K / k$ ratio is $7.501 \times 10^{4}(1 / \mathrm{cm}-\mathrm{s})$. To transform permeability values in $\mathrm{cm}^{2}$ to their darcy equivalent (i.e., the unit generally used in the petroleum industry), multiply $k$ values in $\mathrm{cm}^{2}$ by the conversion factor $1.013 \times 10^{8}$ (darcies $/ \mathrm{cm}^{2}$ ).

### 6.2.2 Factors that affect permeability

Intuitively, it is clear that permeability depends upon both volumetric and geometric characteristics of the pore space. Important characteristics include the volume fraction, size, shape, orientation, tortuosity and connectivity of pores. Because some of these pore space parameters are difficult to measure, permeability is also commonly related to various grain space parameters including grain size distribution, grain shape distribution and mode of packing (Bear, 1972; Scheidegger, 1974). The following discussion describes how these pore and grain space parameters are related to permeability.

Effective porosity is the most obvious factor that affects permeability. It is defined as the ratio of accessible pore volume to total sample volume, and can be easily measured by gravimetric and gas expansion methods. For consolidated materials, porosity reflects primarily compaction and cementation (i.e., diagenesis factors); for unconsolidated materials, porosity reflects the packing of grains and their size and shape distributions (i.e., depositional factors). If other parameters are held constant, then porosity and permeability are positively correlated. This trend holds so long as porosity is above some minimum value called the porosity percolation threshold $\phi_{p}$ (Mavko and Nur, 1993); if porosity drops below $\phi_{p}$, then pores becomes disconnected and permeability drops to zero. Values of $\phi_{p}$ depend upon pore geometry, so different geologic materials tend to exhibit different $\phi_{p}$ values. Sedimentary rocks typically have $\phi_{p}$ values (in terms of fractional porosity) between 0.02 and 0.05 , as predicted by consolidation and cementation models (Schwartz and Kimminau, 1987). For unconsolidated materials, $\phi_{p}$ ceases to be important because bulk porosity values are generally far above the percolation threshold.

Permeability is also strongly influenced by pore size and pore shape. Unfortunately, these parameters are only well-defined if the pores have simple geometries like capillary tubes or parallel plates. For general pore geometries, one must resort to operational definitions that depend upon both the experimental method and the pore structure model used (Dullien, 1979). For example, Scheidegger (1974) defines pore size at a point as the diameter of the largest sphere which contains the point and remains wholly within the pore space. The only way to measure this diameter directly is via three-dimensional image analysis. Another method for determining pore size distributions involves inversion of capillary pressure data from mercury injection experiments (e.g., Katz and Thompson, 1986). Although the pore size distributions determined from image analysis and capillary pressure measurements are generally not identical, both methods predict the same type of relationship between pore size and
permeability, i.e., permeability decreases with decreasing pore size. Permeability also tends to decrease as the surface area of pores increases; the ratio of surface area to pore volume is a commonly used measure of pore shape.

Another factor that affects permeability is pore orientation. Pore orientation is related to permeability anisotropy. If pores are preferrentially aligned in some direction, then the permeability measured in this direction will be greater than that measured in another direction. In general, permeability is a second order tensor, though in this study it is assumed to be a scalar quantity (i.e., isotropic at the laboratory scale). Further discussion about pore orientation is contained in Section 6.3.2.

Tortuosity $T$ is a measure of both the sinuousness of flow paths and the variation in pore size along these paths. It is defined as the ratio of the effective average path length $L_{e}$ of a fluid particle and the corresponding straight distance $L$ measured along the macroscopic flow direction, i.e., $T=\left(L_{e} / L\right)$ (Suman and Ruth, 1993). [Note that some authors (e.g., Rose and Bruce, 1949) define tortuosity as the square of this ratio (i.e., $T=\left(L_{e} / L\right)^{2}$ ), though the equations these authors use to relate tortuosity to permeability take into account the proper power of this ratio; further discussion of this issue may be found in Bear (1972) and Dullien (1979).] Values of $T$ are difficult to measure directly, except in idealized network models. Most published $T$ values were determined by inverting some permeability equation given all other parameters. Using the Kozeny-Carmen equation and the $L_{e} / L$ definition, Wyllie and Spangler (1952) obtained $T$ values ranging from 1.5-2.5 for a variety of different geologic and artifical porous materials. All other things being equal, permeability decreases as tortuosity increases.

Connectivity is a measure of the number and type of pore connections. If all pores are the same size, then it is the average number of pores per junction (Fatt, 1956). If all junctions join the same number of pores, then it is the average effective pore size at these junctions. Like
tortuosity, connectivity is difficult to measure directly. For this reason, it is usually lumped into fitting parameters such as the constant $c$ in the Kozeny and Kozeny-Carmen equations (see Section 6.3.2). As connectivity increases, so too does permeability.

As stated at the beginning of this section, it is often easier to characterize the geometrical properties of porous materials using grain-based parameters than it is using pore-based parameters. For example, it has long been recognized that permeability is related in some way to grain size. As with pore size, grain size cannot be uniquely defined by a single linear dimension except for grains with simple shapes; in general, it can only be defined in terms of some method of measurement. The most common measurement techniques are sieve analysis and hydrometer analysis, although other techniques such as image analysis are gaining popularity (Morgan et al., 1991). In sieve analysis, the size of a grain (assumed to be a sphere) is defined as the side dimension of a square hole on a screen. Since natural grains are not perfect spheres, the best we can say is that we have measured some dimension of a grain that allows it to pass through a square hole. Nevertheless, this is significantly easier than trying to derive some measure of pore size.

Empirical studies have shown that permeability depends both on some representative grain size and on some measure of the spread of the overall grain size distribution. Hazen (1892) showed that permeability is related to the square of the $\mathrm{d}_{10}$ size fraction, i.e., the diameter at which 10 percent (by weight) of the grains are finer as determined by sieve analysis. In general, permeability is influenced more by the volume fraction of small-diameter grains than by the volume fraction of large-diameter grains. For materials comprised of one grain size, permeability decreases with decreasing grain size. As the grain size distribution broadens (i.e., decreased sorting), permeability also decreases. Krumbein and Monk (1943), Beard and Weyl (1973), Shepherd (1989) and Alyamani and Zekai (1993) describe various methods of relating permeability to characteristics of grain size distribution curves.

To relate grain size distributions to pore size distributions, information about grain shapes and mode of packing is required. Grain shapes affect specific surface. Materials comprised of spherical grains have low specific surface, while materials comprised of platey grains have high specific surface. The mode of packing affects both the porosity and the geometry of the pores. The effect of packing on permeability was first systematically investigated by Graton and Fraser (1935). These authors showed that for materials comprised of uniform spheres, the least compact arrangement is that of simple cubic packing; this mode of packing results in a porosity of 0.4764 . The most compact arrangement is that of pyramidal or tetrahedral packing where each sphere is touching twelve neighboring spheres; in this case, porosity is 0.2595 . Intermediate arrays of uniform spheres have porosities falling between these two extremes; a typical porosity value for a dense random sphere pack is 0.36 (Bourbie et al., 1987). In uniform packings of spheres, porosity is independent of sphere size while permeability varies with sphere size; this is evidence that there is not a one-to-one relationship between porosity and permeability. In order to accurately predict permeability values, several geometrical or textural parameters must be correctly specified.

### 6.3 PETROPHYSICAL MODELS

In this section, I describe three interrelated petrophysical models for sand-clay mixtures: (1) a microgeometrical model, (2) a permeability model, and (3) a dielectric model. The latter two models depend upon porosity and clay volume fraction, parameters that can be estimated using the microgeometrical model. An important feature of these models is that most of the parameters can be directly measured, hence the models can be tested by experiment.

### 6.3.1 Microgeometrical model

Marion et al. (1992) proposed a microgeometrical model to explain the relationships between porosity, clay content, confining pressure and seismic P-wave velocity in sand-clay mixtures. The model assumes that mixtures of sand and clay form "ideal" packings as shown in Figure 6.1. At low clay contents, clay particles fit within the pore space of the sand pack. This sort of geometry is naturally favored when the volume fraction of porous clay $C l_{p}$ is less than the inherent porosity of the sand pack $\phi_{s}$ at a given confining pressure $P_{c}$. As clay packets fill the pore space of the sand, total porosity decreases according to the relation $\phi=\phi_{s}-C l_{p}\left(1-\phi_{c l}\right)$, where $\phi_{c l}$ is the inherent porosity of the clay component at the specified confining pressure. At high clay contents, where $C l_{p}$ is greater than $\phi_{s}$, a different geometrical arrangement of sand and clay particles occurs. In this domain, clay particles form the matrix and sand grains are disconnected. As $C l_{p}$ increases, total porosity also increases, this time according to the relation $\phi=C l_{p} \phi_{C l}$, because microporous packets of clay are effectively replacing zero-porosity sand grains.

The microgeometrical model parameter $C l_{p}$ is related to clay weight fraction $W_{c l}$ and clay volume fraction $V_{c l}$ (no microporosity) through the grain densities of the sand and clay components. Transform equations are given in Chapter 4 of this thesis. These equations are based on the assumption that there is no swelling of the clay component when water is added to the mixtures. This assumption is valid for kaolinite (Lockhart, 1980b), the clay mineral used in this and the previous chapter (i.e., for all the saturation experiments). To keep things simple, I work with clay volume fractions throughout the remainder of this chapter.


Figure 6.1. Microgeometry of sand-clay mixtures at a given confining pressure. At low clay contents, the mixtures are grain supported. At high clay contents, the mixtures are matrix supported. $C l_{p}$ is the volume fraction of porous clay and $\phi_{s}$ is the porosity of the sand component as defined in the text.

### 6.3.2 Permeability model

Numerous attempts have been made over the years to relate permeability to other material parameters. Excellent summaries of this work may be found in Bear (1972) and Scheidegger (1974). A widely used permeability model is the Kozeny-Carmen equation (Kozeny, 1927; Carmen, 1956). Yin (1993) derived a form of this equation for sand-clay mixtures; this is the model that I employ to predict permeability values for sand-clay mixtures. Following is a brief development of the Kozeny-Carmen-Yin theory.

A theoretical expression for permeability in terms of volumetric and geometric pore parameters can be obtained by modeling a porous medium as a bundle of capillary tubes with prescribed cross-section and length (Kozeny, 1927). The flow through each tube is given by Hagen-Poisseuille's law which results from solving the Navier-Stokes equations. Equating the total flow through the tubes with Darcy's law (6.1), Kozeny obtained the following expression for permeability:

$$
\begin{equation*}
k=\frac{\phi^{3}}{c S_{t}^{2}} \tag{6.2}
\end{equation*}
$$

where $\phi$ is porosity, $S_{t}$ is specific surface (i.e., surface area per total volume), and $c$ is a dimensionless constant that depends on the shape and orientation of the tubes. Assuming the tubes are all oriented along the direction of flow, it can be shown that $c=2$ for circular capillaries and $c=1.5$ for flat cracks. If the tubes are randomly oriented, then some of these tubes will not support flow since they will be perpendicular to the hydraulic gradient. In the extreme case, one third of the tubes will be oriented in each orthogonal direction resulting in $c$ values that are three times as large (i.e., $c=6$ for circular capillaries and $c=4.5$ for flat cracks). In natural samples, $c$ is also affected by changes in tortuosity and pore connectivity
though the range in experimentally determined values ( $3<c<6$ ) is small for most geologic materials (Wyllie and Spangler, 1952). A good value for general use is $c=5$ (Carmen, 1956).

The specific surface parameter $S_{t}$ in Kozeny's equation (6.2) contains information about both pore size and pore volume. In order to separate these two factors, Carmen (1956) substituted the identity

$$
\begin{equation*}
S_{t}=(1-\phi) S_{s} \tag{6.3}
\end{equation*}
$$

into Kozeny's equation. The parameter $S_{S}$ (also called specific surface) is defined as the surface area per solid volume. The resulting expression for permeability:

$$
\begin{equation*}
k=\frac{\phi^{3}}{5(1-\phi)^{2} S_{S}^{2}} \tag{6.4}
\end{equation*}
$$

is known as the Kozeny-Carmen equation.
Although the Kozeny-Carmen equation can be derived from consideration of capillary tubes, it is really a statistical characterization based on the concept of hydraulic radius (Carmen, 1956). The hydraulic radius $R_{h}$ is defined as the ratio of the average cross-sectional area to the average circumference of pore channels. In bulk terms, this is equivalent to the ratio of pore volume to surface area, or, normalizing by total volume, $R_{h}=\phi / S_{t}$. Dimensional analysis shows that $R_{h}$ has units of length. It is apparent that $R_{h}$ is a characteristic length parameter that links the pore geometric properties of a real porous material with the hypothetical channels which are envisioned theoretically. In other words, $R_{h}$ represents the effective hydraulic radius of the complicated pore network (Hillel, 1980).

For granular materials, the parameter $S_{s}$ can be computed directly if grain size and shape information are available. For instance, a sphere pack comprised of $m$ size fractions, each size fraction comprised of $N_{i}$ spheres of radius $r_{i}$, has:

$$
\begin{equation*}
S_{s}=\frac{\sum_{i=1}^{m} 4 \pi r_{i}^{2} N_{i}}{\sum_{i=1}^{m} \frac{4}{3} \pi r_{i}^{3} N_{i}}=3 \sum_{i=1}^{m} \frac{V_{i}}{r_{i}} \tag{6.5}
\end{equation*}
$$

where $V_{i}$ is the volume fraction of the $i$ th component $\left(\Sigma V_{i}=1\right)$ (Bear, 1972).
Yin (1993) substituted equation (6.5) into the Kozeny-Carmen equation (6.4) and evaluated the result for two components, sand $(s)$ and clay ( $c l$ ):

$$
\begin{equation*}
k=\frac{\phi^{3}}{45(1-\phi)^{2}\left(\frac{V_{s}}{r_{s}}+\frac{V_{c l}}{r_{c l}}\right)^{2}} \tag{6.6}
\end{equation*}
$$

This is the equation that I use to predict the permeability of sand-clay mixtures (Figures 6.3, 6.4 and 6.7). The only parameters required are the effective radii of the sand and clay components, and the volume fractions of void, sand and clay. To compare with dielectric behavior, it is useful to separate these parameters into those concerned with quantifying volume fractions ( $\phi, V_{s}$ and $V_{c l}$ ) and those concerned with quantifying geometric or specific surface properties ( $r_{s}$ and $\left.r_{c l}\right)$.

### 6.3.3 Dielectric model

There are various ways to incorporate volumetric and surface information into dielectric mixing models. One approach involves explicitly modeling and then superposing interfacial and electrochemical polarization mechanisms (e.g., Lima and Sharma, 1992; Endres and Knight, 1993; Lesmes, 1993). The problem with this approach is that many of the required input parameters are difficult if not impossible to measure. A simpler, more empirical, approach involves the use of "wetted" or "effective" matrix parameters and volumetric mixing formulas (Knight and Endres, 1990). In this approach, all non-volumetric effects (such as surface and conductivity effects) are implicitly incorporated through the definition of the matrix
components. In Chapters 4 and 5, I show how this approach can be used to accurately predict the dielectric properties of both sand-montmorillonite mixtures and sand-kaolinite mixtures.

The dielectric mixing model that I use in this chapter is the same as that used in Chapter 5. The model is a four-component version of the Time Propagation equation, i.e.,

$$
\begin{equation*}
\sqrt{\kappa}=(1-\phi) V_{s} \sqrt{\kappa_{s}}+(1-\phi) V_{c l} \sqrt{\kappa_{c l}}+\phi\left(1-S_{w}\right) \sqrt{\kappa_{a}}+\phi S_{w} \sqrt{\kappa_{w}} \tag{6.7}
\end{equation*}
$$

where, in addition to the parameters already defined in this chapter, $\kappa$ is dielectric constant and $S_{w}$ is water saturation. The subscripts $s, c l, a$ and $w$ correspond to sand, clay, air and water components, respectively.

The form of equation (6.7) suggests that the bulk dielectric constant of a sand-clay mixture is a function only of the volume fractions and dielectric constants of the components. However, as stated above, surface information is also included via the definition of the matrix parameters. This is critical for establishing a link with permeability. In order to incorporate surface information, $\kappa_{s}$ and $\kappa_{c l}$ are defined to be wetted or effective parameters, not dry parameters. This definition follows from the observation that $\kappa$ of a vacuum-dry material increases dramatically with the adsorption of several monolayers of water to the internal surface of the material (Knight and Endres, 1990). The enhancement in $\kappa$ is related to the specific surface of the material; materials with high specific surface (i.e., high clay content) exhibit high $\kappa$, particularly at low frequencies where surface effects are predominant. Once several monolayers of water have been adsorbed, $\kappa$ increases gradually and predictably with increasing $S_{w}$. This suggests that surface information can be included in dielectric models simply by redefining the matrix parameters to include the $\kappa$ component due to the wetting of the surface. Accepting this, we have in equation (6.7) a model for the dielectric constant of a sand-clay mixture that is analogous to the permeability model (equation 6.6) in that both volumetric and surface information are included.

### 6.3.4 Modeling procedure and parameters

The model data shown in Figures 6.2 through 6.7 were generated as follows. First, the microgeometrical model was used to predict the relationship between porosity and clay volume fraction for a complete suite of sand-clay mixtures $\left(C l_{p}=0.00\right.$ to 1.00 , step 0.01$)$. The porosity of the sand and clay components are taken to be $\phi_{s}=0.40$ and $\phi_{c l}=0.60$, respectively; these parameter values are close to the measured values for pure uncompacted silica sand and pure uncompacted kaolinite clay.

The set of $\left(V_{c l}, \phi\right)$ values was then input to the permeability model (equation 6.6) together with the effective radii of the sand and clay components. The radius of the sand grains ( $r_{s}=$ $3.75 \times 10^{-2} \mathrm{~cm}$ ) is taken to be half the mean grain diameter determined from sieve analysis (Table 6.1), and the radius of the clay particles $\left(r_{c l}=2.25 \times 10^{-5} \mathrm{~cm}\right)$ is taken to be that which best fits the measured permeability value for the pure kaolinite clay sample (given the porosity of the sample). Although the choice of $r_{c l}$ is empirical, it is reasonable given the range of particle diameters (i.e., $1 \times 10^{-5}-4 \times 10^{-4} \mathrm{~cm}$ ) reported for kaolinite by other investigators (Hillel, 1980, p. 76).

The set of $\left(V_{c l}, \phi\right)$ values was also input to the dielectric model (equation 6.7). Predictions were made at two saturation levels, $S_{w}=0.00$ and $S_{w}=1.00$. The dielectric constant values used for the air and water components are: $\kappa_{a}=1.0006$ and $\kappa_{w}=79.4595$ (laboratory conditions of $22^{\circ} \mathrm{C}$, atmospheric pressure, $50 \%$ relative humidity) (ASTM, 1987; Marsh, 1986). The wetted or effective matrix parameters ( $\kappa_{s}$ and $\kappa_{c l}$ ) were determined from inversion of the measured dielectric data for the pure sand and pure clay end-members, given the measured porosity and water saturation values for these mixtures. Since the magnitude of surface effects is expected to vary with water saturation, different matrix parameter values were used for the two saturation states. For the dry mixtures, the matrix values at 1 MHz are $\mathrm{K}_{s}=$ 4.111 and $\kappa_{c l}=12.599$. These values are close to those reported in Olhoeft (1979a) ( $\kappa_{s}=4.5$
and $\kappa_{c l}=11.8$ ) and the Handbook of Physics and Chemistry (1986) ( $\kappa_{s}=4.10-4.34$ ) for quartz and kaolinite at 1 MHz . For the water-saturated mixtures, the matrix values at 1 MHz are $\kappa_{s}=7.346$ and $\kappa_{c l}=50.834$. These values are higher than published values because surface effects have purposely been lumped into the matrix parameter.

Using this modeling process, I generated 202 data points that span the parameter space $\left(V_{c l}, \phi, k, S_{w}, \kappa\right)$. The locus of these points form the dotted curves shown in Figures 6.2 through 6.7.

### 6.4 EXPERIMENTAL PROCEDURE

### 6.4.1 Sample preparation

The artificial samples studied in this research were created by mixing two solid components: a silica sand and a standard kaolinite clay. The sand is from Lane Mountain, Washington, and the clay ( $\mathrm{KGa}-1$ ) is from the Clay Mineral Repository at the University of Missouri. Table 6.1 lists relevant physical properties of these materials. The grain densities, and bulk sample porosities discussed later, were measured using a Helium pycnometer. The grain diameter of the sand was determined from sieve analysis ( $20-25$ mesh). The particle diameter of the clay was taken from the literature (Hillel, 1980, p. 76). The surface area of the sand was determined from nitrogen adsorption isotherms using the BET equation (Brunauer et al., 1938), and the surface area of the clay was determined using the EGME adsorption technique (Carter et al., 1965). The cation exchange capacity (CEC) of the sand was not measured but is probably very small; the CEC value listed for kaolinite was taken from the literature (van Olphen and Fripiat, 1979).

The mixtures were first blended in a beaker under room-dry conditions and then transferred to either the dielectric sample holder or the permeability measurement cell. The mass sand and mass clay needed to produce each sample were determined ahead of time using

Table 6.1. Component properties.

| Material | Mineralogy | Grain <br> Density <br> $\left[\mathrm{g} / \mathrm{cm}^{3}\right]$ | Grain <br> Diameter <br> $[\mathrm{cm}]$ | Specific <br> Surface <br> $\left[\mathrm{cm}^{2} / \mathrm{g}\right]$ | Cation <br> Exchange <br> $[\mathrm{meq} / 100 \mathrm{~g}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Sand | Quartz | 2.645 | $7 \times 10^{-2}-8 \times 10^{-2}$ | $3.9 \times 10^{2}$ | not measured |
| Clay | Kaolinite | 2.613 | $1 \times 10^{-5}-4 \times 10^{-4}$ | $2.5 \times 10^{5}$ | 2.0 |
|  |  |  | $:$ |  |  |

the mass-material property relationships developed in Chapter 4. These mass-material property relationships made it possible to produce samples with predetermined porosity, clay content and confining pressure, given the total volume of the two sample holders (approximately $6 \mathrm{~cm}^{3}$ and $76 \mathrm{~cm}^{3}$, respectively).

The samples were saturated by injecting water into the holders from the bottom Minor differences in the method used to saturate the dielectric samples and the permeability samples are described in the next two sections. The level of water saturation was determined gravimetrically.

### 6.4.2 Permeability measurements

Hydraulic permeability values for the sand-clay mixtures were determined from constant and falling-head permeameter tests. Basic principles of these tests can be found in most applied hydrogeology and soil physics texts (e.g., Freeze and Cherry, 1979; Klute and Dirksen, 1986). Most of the tests were performed by Elizabeth Brown as part of her B.Sc. thesis research (Brown, 1995).

The falling-head permeameter used in this research can measure permeability values between $1 \times 10^{-14}$ and $1 \times 10^{-6} \mathrm{~cm}^{2}$ (Elizabeth Brown, personal communication). This measurement range turns out to be adequate for all the sand-clay mixtures except the pure sand mixture which has a permeability greater than $1 \times 10^{-6} \mathrm{~cm}^{2}$. For the pure sand samples, the constant-head permeameter was used instead of the falling-head permeameter. After emplacement in the appropriate measurement cell, the samples were compacted to a volume of $\sim 76 \mathrm{~cm}^{3}$ using a plunger, partially evacuated of air, saturated from the bottom with distilled degassed water, and allowed to equilibrate for two to twenty-four hours.

For the constant-head tests, permeability values were calculated using Darcy's law. For the falling-head tests, permeability values were determined using the equation:

$$
\begin{equation*}
k=\left(\frac{\mu}{\rho g}\right) \frac{a d}{A t} \ln \left(\frac{h_{0}}{h_{1}}\right) \tag{6.8}
\end{equation*}
$$

where $a$ is the area of the standpipe, $d$ is the thickness of the sample, $A$ is the area of the sample, and $t$ is the time for the water level to drop from head $h_{O}$ to head $h_{I}$ in the standpipe. Temperatures in the laboratory ranged from 20 to $24^{\circ} \mathrm{C}$. Viscosity and density corrections were made to report all data at $22^{\circ} \mathrm{C}$. Three or more trials were averaged to determine the $k$ value for each sample.

### 6.4.3 Dielectric measurements

The electrical properties of each sand-clay mixture were measured first under room-dry conditions and then under water-saturated conditions. To saturate the samples, distilled water with a conductivity of $\sim 2 \times 10^{-4} \mathrm{~S} / \mathrm{m}(10 \mathrm{~Hz}-10 \mathrm{MHz})$ was injected through a small hole in the base of the dielectric sample holder. Using this procedure, I was able to obtain saturation levels greater than 0.80 for all the mixtures. Further details about the saturation technique may be found in Section 5.2.

Effective electrical conductivity $\sigma_{e f}$ and dielectric permittivity $\varepsilon_{e f}$ values were calculated from two-electrode measurements of the equivalent parallel conductance $G_{p}$ and capacitance $C_{p}$ of the samples using the inversion formulas:

$$
\begin{equation*}
\sigma_{e f}=\frac{G_{p} d}{A} \quad \text { and } \quad \varepsilon_{e f}=\frac{C_{p} d}{A} \tag{6.9}
\end{equation*}
$$

where $A$ and $d$ are the area and thickness of the samples, respectively. Dielectric constants were computed from $\kappa=\varepsilon_{e f} / \varepsilon_{o}$ (where $\varepsilon_{o}=8.854 \times 10^{-12} \mathrm{~F} / \mathrm{m}$ ). $C_{p}$ and $G_{p}$ were measured at 31 frequencies spaced logarithmically between 10 Hz and 10 MHz using a Hewlett Packard 4192A impedance analyzer, although for clarity only the data acquired at 1 MHz are discussed in this chapter; data acquired at other frequencies are shown in Chapter 5 and also tabulated in Appendix D. Measured $C_{p}$ and $G_{p}$ values were compensated for cable and sample holder
residuals as described in Appendix A. An error analysis is included in Appendix B. Reported dielectric constant values are accurate to within two percent. Further details about the electrical measurement system may be found in Section 4.2.4.

### 6.5 EXPERIMENTAL RESULTS

Seven artificial sand-clay mixtures were investigated. The measured properties of these mixtures are summarized in Table 6.2. Clay content is expressed both as weight fraction and volume fraction (dry material) to facilitate comparison with other experimental and theoretical studies. Because kaolinite does not swell when saturated (Lockhart, 1980b), these clay content values are also characteristic of the saturated samples. The numbers in parentheses to the right of the saturated dielectric constant values are the measured $S_{w}$ values for the saturated dielectric samples. The samples used for the permeability measurements are assumed to be $100 \%$ watersaturated.

Although the data are sparse, they span the entire lithologic range from pure sand to pure clay. Porosity values range from 0.599 (pure clay) to 0.238 (clayey sand), permeability values range from $4.4 \times 10^{-6} \mathrm{~cm}^{2}$ (pure sand) to $5.4 \times 10^{-12} \mathrm{~cm}^{2}$ (clayey sand), and dielectric constant values range from 2.62 (dry sand) to 58.5 (saturated clay). Correlations between these parameters are investigated in the next section using various crossplots. The crossplots also show the predictions generated by the microgeometrical, permeability and dielectric models.

### 6.6 DISCUSSION

### 6.6.1 Relationship between porosity and clay volume fraction

Figure 6.2 shows the predicted and observed relationships between porosity and clay volume fraction for sand-clay mixtures at zero confining pressure. The porosity of the pure sand sample is 0.399 and the porosity of the pure clay sample is 0.599 ; these porosity values

Table 6.2. Summary of measured data.

| Clay weight <br> fraction | Clay volume <br> fraction | Porosity | Permeability <br> $\left[\mathrm{cm}^{2}\right]$ | Dielectric Constant @ 1 MHz <br> Dry <br> Saturated $\left(S_{w}\right)$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 0.000 | 0.000 | 0.399 | $4.4 \times 10^{-6}$ | 2.62 | $26.5(0.99)$ |
| 0.062 | 0.063 | 0.359 | $7.5 \times 10^{-9}$ | 3.00 | $20.4(0.80)$ |
| 0.129 | 0.130 | 0.308 | $1.6 \times 10^{-10}$ | 3.51 | $21.3(0.82)$ |
| 0.209 | 0.211 | 0.238 | $5.4 \times 10^{-12}$ | 4.34 | $21.5(0.85)$ |
| 0.372 | 0.375 | 0.359 | $7.1 \times 10^{-12}$ | 4.27 | $33.9(0.90)$ |
| 0.613 | 0.615 | 0.480 | $6.4 \times 10^{-12}$ | 4.27 | $44.7(0.85)$ |
| 1.000 | 1.000 | 0.599 | $1.5 \times 10^{-11}$ | 4.08 | $58.5(0.88)$ |



Figure 6.2. Predicted and observed relationships between porosity and clay volume fraction for silica sand-kaolinite clay mixtures at zero confining pressure. The predicted values are based on the microgeometrical model for sand-clay mixtures that was proposed by Marion et al. (1992).
correspond to samples that fill but are uncompacted in the measurement cells. As $V_{c l}$ increases from 0.000 to $0.211, \phi$ decreases from 0.399 to 0.238 because clay is filling the pore space of the sand pack. As $V_{c l}$ increases from 0.211 to $1.000, \phi$ increases from 0.238 to 0.599 because microporous packets of clay are effectively replacing zero-porosity sand grains. At $V_{c l}$ equal 0.211 , a critical point or percolation threshold is observed in the ( $\left.V_{c l}, \phi\right)$ relationship. This point of minimum porosity marks the transition from grain-supported microgeometry to matrixsupported microgeometry, as depicted in Figure 6.1. At this point, the volume fraction of porous clay is equal to the inherent porosity of the sand pack (i.e., $C l_{p}=\phi_{s}$ ). The close agreement between the experimental data and the microgeometrical model data is evidence that $I$ have succeeded in synthesizing "ideal packings" of sand and clay with systematically varying hydrogeologic properties using the "physical modeling" sample preparation technique.

### 6.6.2 Permeability response

Figure 6.3 shows the relationship between porosity and permeability for the sand-clay mixtures. There is good agreement between the theoretical predictions and the measured parameter values; for the most part, measured permeability values are within an order of magnitude of the predicted values. These data also show that there is not a one-to-one relationship between porosity and permeability. The pure clay and sandy clay samples with the highest and lowest porosity ( $\phi=0.599$ and 0.238 , respectively) have about the same, relatively low, permeability ( $k \sim 10^{-11} \mathrm{~cm}^{2}$ ), while the sand sample with intermediate porosity ( $\phi=$ 0.399 ) has the highest permeability ( $k=4.4 \times 10^{-6} \mathrm{~cm}^{2}$ ). This is undoubtedly due to the effect of clay on the permeability of the mixtures.

The relationship between permeability and clay volume fraction is shown in Figure 6.4. Again, there is good agreement between the predicted and the observed data. Results show that permeability decreases five orders of magnitude from $4.4 \times 10^{-7} \mathrm{~cm}^{2}$ to $5.4 \times 10^{-12} \mathrm{~cm}^{2}$ as


Figure 6.3. Permeability versus porosity for sand-kaolinite mixtures.


Figure 6.4. Permeability versus clay volume fraction for sand-kaolinite mixtures.
$V_{c l}$ increases from 0.000 to 0.211 in the mixtures. Adding a small amount of clay to the sand pack has a small effect on porosity but a tremendous effect on permeability; this is a geometric effect. Physically, the pore-filling clay shifts the pore-size distribution to smaller values, and this, in turn, significantly decreases permeability (Neesham, 1977; Almon, 1979). Beyond the percolation threshold ( $V_{c l}>0.211$ ), permeability is relatively insensitive to clay volume fraction. The slight increase in permeability for samples with high $V_{c l}$ is due to the greater porosity of these samples.

### 6.6.3 Dielectric response

Figure 6.5 shows the predicted and observed relationships between porosity and dielectric constant for sand-clay mixtures under dry and water-saturated conditions. The open circles correspond to the dry samples, and the closed circles correspond to the saturated samples. The predicted and observed relationships agree well with each other for both levels of water saturation. The slight overprediction of dielectric constant values for the saturated samples is due to the difference between the $S_{w}$ values used in the modeling and the values achieved in the laboratory; that is, the experimental data were not $100 \%$ saturated in all cases. If the actual measured $S_{w}$ values are used in the dielectric modeling (instead of $S_{w}=1$ for all samples), then the mean absolute deviation (MAD) between the predicted and the observed $\kappa$ values (normalized with respect to the observed $\kappa$ values) for the seven saturated samples is 1.6 percent. The same prediction error for the dry samples is 2.6 percent. These average deviations are approximately equal to the measurement uncertainty.

As predicted by the dielectric model, $\kappa$ of the dry samples increases with decreasing porosity, while $\kappa$ of the saturated samples decreases with decreasing porosity. This is because the dielectric constant of water $(\sim 80)$ is much greater than that of air $(\sim 1)$. However, the relationship between $\kappa$ and porosity is not one-to-one for either the dry or the saturated
samples; instead, there is a critical point in the $\phi-\kappa$ relationship for both dry and saturated samples. For instance, there are two water-saturated samples with a porosity of 0.36 that have significantly different dielectric constants. Likewise, there are pairs of samples with the same dielectric constant that have different porosity values. This invalidates the notion that $\phi$ and $\kappa$ are uniquely related in materials containing one pore fluid, at least at low frequencies $(<10$ MHz ).

Figure 6.6 shows the relationship between clay volume fraction and dielectric constant of sand-clay mixtures. Again, there is good agreement between the predicted and observed data; the same MAD values as given above apply. The fact that both limbs of the $V_{c l}-$ K relationship (i.e., one limb corresponding to clayey sand samples and the other limb corresponding to sandy clay samples) are accurately predicted for both dry and saturated states is evidence that the dominant volumetric and surface factors that affect dielectric properties have been accounted for in the modeling (see section 6.3.3). Note that the critical point ( $V_{c l}=0.211$ ) is much better defined for the saturated data than the dry data; this is due to the greater slope of the two limbs of the $V_{c l}-\kappa$ relationship for the saturated data.

The data in Figure 6.6 also show which lithologies or clay volume fractions are likely to have the same dielectric properties, assuming zero confining pressure and the ( $V_{c l,} \phi$ ) relationship defined by the microgeometrical model. This information can be used to address questions of non-uniqueness and sensitivity in the interpretation of VETEM and GPR field data. For instance, considering the dielectric response of the dry sand-clay mixtures, it is clear that it would be very difficult to estimate accurate clay content values from VETEM measurements of very dry (e.g., desert) materials, since a few unit change in dielectric constant accounts for the entire clay content range. [Note, however, that because clayey materials tend to possess greater residual moisture contents than sandy materials, the range in dielectric constant values of unsaturated materials is often greater than that shown in Figure 6.6].

## Sand-Kaolinite Mixtures



Figure 6.5. Dielectric constant ( 1 MHz ) versus porosity for dry and water-saturated sandkaolinite mixtures. The $S_{w}$ values associated with the measured saturated samples are listed in Table 6.2. The $S_{w}$ values used in the modeling are: $S_{w}=0$ and $S_{w}=1$.


Figure 6.6. Dielectric constant ( 1 MHz ) versus clay volume fraction for dry and watersaturated sand-kaolinite mixtures. The $S_{w}$ values associated with the measured saturated samples are listed in Table 6.2. The $S_{w}$ values used in the modeling are: $S_{w}=0$ and $S_{w}=1$.

Similarly, for the saturated sand-clay mixtures, it would be difficult to differentiate lithologies in the low clay content range $\left(V_{c l}=0.3\right)$ due to the shallow slope and multivalued nature of the $V_{c l}-\kappa$ relationship in this range. Despite these practical limitations on the information content of dielectric data, the good agreement between the predicted and observed data in Figures 6.2 through 6.6 bodes well for our goal of establishing a relationship between dielectric properties and permeability.

### 6.6.4 Relationship between dielectric constant and permeability

The primary objective of this chapter is to determine whether there is a relationship between dielectric constant and permeability for sand-clay mixtures. Figure 6.7 shows a crossplot of these two parameters. As can be seen, there is good agreement between the predicted and observed data for both dry and saturated samples. This is further illustrated in Figure 6.8 where the measured permeability and dielectric data are compared, individually, to the model predictions for these parameters. The good agreement between the predicted and observed data suggests that there is indeed a relationship between dielectric constant and permeability for sand-clay mixtures.

The form of the relationship between dielectric constant and permeability depends on the level of water saturation of the sand-clay mixtures. For the dry samples, the $k$ - $\kappa$ relationship appears almost linear on a semi-log plot (logarithmic permeability). The slope of the curve is low and there is no apparent critical point. Measured dielectric constants range from 2.62 to $4.34-$-a small range. In contrast, permeability values range from $4.4 \times 10^{-6}$ to $7.1 \times 10^{-12} \mathrm{~cm}^{2}-\mathrm{a}$ difference of six orders of magnitude. The low sensitivity of $\kappa$ to changes in permeability for dry materials implies that it would be difficult to use dielectric information from the unsaturated zone to estimate permeability values.


Figure 6.7. Crossplot of dielectric constant ( 1 MHz ) and hydraulic permeability for dry and water-saturated sand-kaolinite mixtures at low confining pressures. The porosity, clay content and $S_{w}$ values associated with the measured samples are listed in Table 6.2. The equations and parameters used to produce the model curves are given in Section 6.3 of the thesis.
(a)

(b)


Figure 6.8. Comparison between predicted and measured permeability data (plot a) and dielectric data (plot b) for sand-kaolinite mixtures at low confining pressures. Dielectric data are shown for both dry (open circles) and water-saturated (solid circles) conditions. 1:1 lines are plotted to aid comparison.

When the samples are saturated with water, however, two things change in the relationship between dielectric constant and permeability. Firstly, the range in $\kappa$ values increases as shown by the spread of the data (solid circles) in Figure 6.8b; this increases the sensitivity of $\kappa$-based permeability estimates. Secondly, a critical point develops similar to that observed in the relationship between porosity and clay volume fraction. This critical point causes the relationship between dielectric constant and permeability to be multivalued over a limited range of each parameter. For instance, saturated samples with $\kappa$ values between 20 and 27 may be associated with two permeability values--one value around $10^{-11} \mathrm{~cm}^{2}$ and another value as high as $10^{-5} \mathrm{~cm}^{2}$ depending upon sand content. Although the relationship between dielectric constant and permeability for saturated samples is multivalued, there is still useful information in the dielectric response. For instance, $\kappa$ values greater than 30 are indicative of materials with low permeability (i.e., $k<2 \times 10^{-11} \mathrm{~cm}^{2}$ ). This suggests that geophysical attributes may be defined to help identify different hydrostratigraphic units.

### 6.6.5 Implications for mapping permeability in the field

The results of this laboratory study can be used in several ways in field studies. For instance, let us assume for the moment that we are investigating a field site where we know that geology consists only of sand and clayey sand, and that the $k$ - $\kappa$ relationship depicted in Figure 6.7 is valid. The limited range of lithologies means that we need only consider one limb (i.e., the limb corresponding to sandy materials) of the $k-\kappa$ relationship. Sensitivity issues not withstanding, we could then use the three integrated petrophysical models to invert dielectric data uniquely for permeability. Theoretically, this could be done for every reflector observed in every trace of a GPR or VETEM survey to produce a detailed map of permeability (continuously variable) at the site.

What happens if geology is not so cooperative and lithologies from both limbs of the $k-\kappa$ relationship are present at a site? In this case, some values of $\kappa$ will uniquely determine permeability, while other values of $\kappa$ will only limit permeability to two possible values. The most probable of these values could be determined from analysis of spatial trends. If the risk associated with uncertain permeability values is high, then additional field measurements such as well tests could be considered to resolve the ambiguity. In this way, the geophysical data could help determine future drilling and sampling locations and hence be incorporated into the hydrogeological decision making process.

Up to this point in the discussion, it has been tacitly assumed that the goal of a geophysical survey is to map the permeability field completely and continuously over a broad range of scales. Of course this goal will be difficult to achieve in most cases due to poor sensitivity of the dielectric constant-permeability relationship, non-uniqueness of inversions, etc. Fortunately, such an optimistic goal is not necessary to solve many hydrogeological problems. For instance, in contaminant transport problems, it may be sufficient simply to characterize the connectivity of high and low permeability units (Smith and Schwartz, 1981; Journel and Alabert, 1988). The petrophysical relationships between dielectric properties and permeability developed in this chapter can also be used for this purpose.

For example, suppose that $k=10^{-9} \mathrm{~cm}^{2}$ is an appropriate threshold value separating permeable from impermeable sediments at a site. Using this threshold value, one can separate Figure 6.7 into two fields. For a given level of water saturation, some dielectric constant values will be associated with permeable sediments, while other dielectric constant values will be associated with impermeable sediments. Similar associations can be made for other types of geophysical data such as the electrical conductivity data presented in Chapter 5, and the P-wave velocity data for sand-kaolinite mixtures published by Rubin et al. (1992) and Yin (1993). In this way, a set of hydrogeophysical attributes can be defined, as shown in Table 6.3. These

Table 6.3. Hydrogeophysical attributes for a hypothetical aquifer comprised of mixtures of silica sand and kaolinite clay at zero confining pressure.

| Unit | Permeability $\left[\mathrm{cm}^{2}\right]$ | Saturation | Dielectric Constant | Conductivity[1] [ $\mathrm{S} / \mathrm{m}$ ] | P-wave Velocity[2] [ $\mathrm{m} / \mathrm{s}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Permeable | $>10^{-9}$ | 0.00 (dry) | 2.6-2.8 | $1 \times 10^{-6}-5 \times 10^{-6}$ | 200-1100 |
|  |  | 1.00 (sat) | 26.5-27.0 | $1 \times 10^{-3}-2 \times 10^{-3}$ | 1600-1700 |
| Impermeable | $<10^{-9}$ | 0.00 (dry) | 2.9-4.1 | $5 \times 10^{-6}-3 \times 10^{-5}$ | 300-1400 |
|  |  | 1.00 (sat) | 24.1-67.2 | $2 \times 10^{-3}-4 \times 10^{-3}$ | 1550-1950 |

[1] From Chapter 5 of this thesis ( 1 MHz values)
[2] From Rubin et al. (1992) and Yin (1993) (1 MHz values).
hydrogeophysical attributes can be used in an indicator sense to interpret geophysical field data. For instance, referring to Table 6.3, zones of an aquifer-aquitard system that are characterized by measured dielectric constant values that are greater than 30 can be designated as impermeable zones. The connectivity of these zones can then be analyzed and incorporated into hydrogeological models using indicator geostatistical methods (Journel and Alabert, 1988).

Although some values of geophysical parameters uniquely determine whether a zone is permeable or impermeable, it is clear from Table 6.3 that no single geophysical tool can unambiguously distinguish permeable from impermeable zones in all situations. However, combinations of different measurements can often identify the gross permeability of different units. For instance, the ambiguity associated with a dielectric constant measurement of 26.5 for a particular zone is resolvable if electrical conductivity data for the zone are also available. If the conductivity is less than $2 \times 10^{-3} \mathrm{~S} / \mathrm{m}$, then the zone is permeable; otherwise, the zone is impermeable.

The petrophysical models described in Section 6.3 can also be used to predict the relationships between dielectric constant and permeability (or hydraulic conductivity) for other types of materials besides sand-clay mixtures. For example, Figure 6.9 shows the predicted relationship between dielectric constant at 10 MHz , and hydraulic conductivity at $10^{\circ} \mathrm{C}$, for a series of sediment samples with different water saturations, porosities and effective grain sizes. The equations used to generate this figure are described in Appendix C. The data which plot in the upper part of the dielectric constant field (i.e., $\kappa>15$ ) and look something like a tobaggan are the predictions for samples under fully water-saturated conditions, while the data which plot in the lower part of the dielectric constant field (i.e., $\kappa<5$ ) and look something like a ski are the predictions for samples under room-dry conditions. The slightly curved rows of " + " and " + " symbols are the predictions at a given porosity for samples with different effective grain


Figure 6.9. Predicted relationship between dielectric constant ( 10 MHz ) and hydraulic conductivity ( $10^{\circ} \mathrm{C}$ ) for samples with different porosities, effective grain sizes and levels of water saturation. The slightly curved rows of " + " and " + " symbols are the predictions at a given porosity for samples with different effective grain sizes. The diagonal columns of "o" and "." symbols are the predictions at a given effective grain size for samples with different porosities.
sizes. The diagonal columns of " 0 " and "." symbols are the predictions at a given effective grain size for samples with different porosities. Given appropriate constraints, this crossplot can be used to estimate hydraulic conductivity values from dielectric measurements made at 10 MHz .

It would be interesting to compare the crossplot predictions in Figure 6.9 to dielectric constant (i.e., 10 MHz VETEM) and hydraulic conductivity measurements made at a wellcharacterized field site. At the time of this writing, however, no such coincident VETEM and well test measurements have been published, so a true 10 MHz field comparison with the crossplot is not possible. If electrical properties do not vary significantly with frequency above 10 MHz , then the crossplot in Figure 6.9 may also be applicable to the interpretation of lowfrequency radar data. Although the validity of this conjecture is questionable and needs to be demonstrated with additional laboratory measurements above 10 MHz , the conjecture is a useful one to make, if only for illustrative purposes.

In the summer of 1995, a vertical radar profile (VRP) was collected in a well at the U.S. Geological Survey's Toxic Waste Hydrology Research Site on Cape Cod, Massachusetts (John Lane, written communication). This VRP provides a good opportunity to test the applicability of the dielectric constant-hydraulic conductivity crossplot because detailed hydraulic conductivity measurements are also available for the well. The hydraulic conductivity measurements were made using a borehole flowmeter; these measurements are described by Hess et al. (1992).

The VRP and flowmeter measurements were made in a well (FSW-452-61) that penetrates the uppermost 18 meters of an unconfined, sand and gravel, aquifer. The well was installed by a drive-and-wash technique to minimize aquifer disturbance around the screen and casing (Morin et al., 1988). The lower 12 meters of the well are screened, and the upper 6
meters are cased, with $5-\mathrm{cm}$ internal-diameter PVC. When the VRP and flowmeter measurements were made, the water table was located about 7 meters below land surface.

The VRP was conducted by recording the time it took for a radar wave to travel from a transmitting antenna located on the surface to a receiving antenna located in the well. The transmitting antenna was oriented perpendicular and radial to the well and not moved during the course of the experiment; its center was located 0.7 m from the well axis. The receiving antenna was lowered down the well in 0.5 m increments. At each offset, 32 traces were recorded and stacked. The recording time is 340.3 ns and the sampling interval is 0.3323 $\mathrm{ns} /$ sample. An ABEM RAYMAC borehole radar system with 60 MHz antennas was used for the tests; a description of this system can be found in Olsson et al. (1992).

The traveltimes of the first arrivals were picked and plotted against the corresponding antenna separations. These data are shown in Figure 6.10. The data essentially fall along two straight lines. The intersection of the two lines occurs at a transmitter-receiver separation of about seven meters and marks the point where the center of the receiving antenna enters the saturated zone. The inverse slope of the line through the open circles is a measure of the average radar-wave velocity of the unsaturated sediments, and the inverse slope of the line through the closed circles is a measure of the average radar-wave velocity of the saturated sediments. Since the loss tangent of the aquifer material is very small ( $\tan \delta \ll 1$ ), dielectric constant values can be computed from: $\kappa=\left(c_{0} / V\right)^{2}$, where $c_{0}$ is the speed of light in a vacuum $(0.2998 \mathrm{~m} / \mathrm{ns})$ and $V$ is the measured propagation velocity. The $\kappa$ values determined in this way for the unsaturated and saturated zones are 4.53 and 27.97 , respectively.

What do these dielectric constant values suggest about the hydrogeologic properties of the Cape Cod sediments? Referring to Figure 6.9, the $\kappa$ value for the saturated sediments (27.97) suggests a porosity around 0.45 , unless the effective grain size is less than 0.001 cm . Since the aquifer is comprised largely of sand and gravel, it is safe to rule out the possibility that


Figure 6.10. Time-distance plot for vertical radar profile conducted in well FSW-452-61. Open circles correspond to data from unsaturated zone. Closed circles correspond to data from saturated zone. Velocity and dielectric constant values are also listed for the two layers.
effective grain size is less than 0.001 cm for the sediments. The radar-derived porosity estimate of 0.45 is somewhat higher than porosity estimates determined by other methods. For instance, Garabedian et al. (1991) reported an effective porosity value of 0.39 based on spatial moments analysis of a large-scale natural-gradient tracer test conducted at the site.

The measured $\kappa$ value for the unsaturated zone (4.53) is slightly greater than the predicted $\kappa$ values shown in Figure 6.9 for dry sediments with porosities around 0.45 . This suggests that the average water saturation of the unsaturated zone may be greater than the water saturation associated with room-dry laboratory conditions. This would not be surprising. However, to derive quantitative estimates of the water saturation of the unsaturated zone, or the permeability of the sediments, additional information about the matrix parameter or the effective grain size of the sediments is required.

The matrix parameter can be computed given the effective grain size of the sediments. Let us assume that the median grain size by weight is an appropriate measure of effective grain size. The median grain size of the surficial sediments at the Cape Cod site is 0.05 cm (Barber, 1992). This defines a diagonal column in Figure 6.9. The intersection of this column with the porosity value 0.45 (determined by the $\kappa$ data from the saturated zone) defines a hydraulic conductivity value of $0.3 \mathrm{~cm} / \mathrm{s}$. This radar-derived estimate of hydraulic conductivity is in good agreement with hydraulic conductivity estimates derived by other methods. For instance, the geometric mean of all the flowmeter measurements in well FSW-452-61 is $0.11 \mathrm{~cm} / \mathrm{s}$ (Hess et al., 1991), and the average hydraulic conductivity value estimated from the large-scale tracer test is $0.13 \mathrm{~cm} / \mathrm{s}$ (LeBlanc et al., 1991).

Given effective grain size and the measured $\kappa$ values for the saturated and unsaturated zones, and assuming porosity is constant, the water saturation of the unsaturated zone can also be estimated from the dielectric model. Graphically, this amounts to moving along a vertical line in Figure 6.9. The average $S_{w}$ value of the unsaturated zone estimated from the VRP data
is 0.14 . This corresponds to a volumetric moisture content of 0.061 . Rudolph et al. (1996) conducted extensive TDR measurements at the Cape Cod site. The mean residual volumetric moisture content calculated by these investigators is 0.081 . Again, there is good agreement between the radar-derived hydrogeologic parameter estimates and the estimates derived from other methods.

These examples show how the dielectric constant-hydraulic conductivity crossplot may be applied to field studies. Although accurate estimates of hydrogeologic parameters can be obtained in some cases, these estimates are dependent upon reliable supporting information such as effective grain size.

Additional factors that should be considered in applying the results of this study to actual permeability mapping problems include the following. As shown in Chapter 5, partial water saturation can produce dielectric constant values between the extremes listed in Tables 6.2 and 6.3; this makes interpretation of data from the unsaturated zone more complicated. Electrical conductivity is affected by water saturation and salinity; the conductivity values listed in Table 6.3 are only valid for sand-kaolinite mixtures that are room-dry or fully-saturated with distilled water. As shown in Chapters 4 and 5, both dielectric constant and conductivity are functions of frequency (and of each other) so different petrophysical relationships or parameter values should be used in different frequency ranges. For instance, at the higher frequencies used by most GPR practitioners (e.g., 100 MHz ), I would expect the dielectric constant values in Table 6.3 to decrease somewhat (more so for clays than sands). In addition, differences in confining pressure will affect the porosity-clay content relationship, and hence other parameter relationships, in sand-clay mixtures; specifically, increased confining pressure causes the porosity minimum to shift to lower porosities and lower clay contents (Marion et al., 1992; Yin, 1993) though this effect is minor for depths less than 100 m (lithostatic pressures less than 2.26 MPa ). Other factors that need investigation are the effect of grain size, clay
mineralogy, clay morphology and surface properties (e.g., wettability) on the dielectric constant-permeability relationship.

### 6.7 SUMMARY

Laboratory measurements have been made of the porosity, clay content, permeability and dielectric constant of a suite of sand-clay (i.e., silica sand-kaolinite clay) mixtures under both dry and water-saturated conditions. The measured data are compared to the predictions of three petrophysical models: a microgeometrical model, a permeability model and a dielectric model. Results show good agreement between predicted and observed data, suggesting that permeability estimates accurate to within an order of magnitude may indeed be derived from dielectric measurements. In order to obtain such accuracy, both volumetric and geometric information must be incorporated into petrophysical models. Such petrophysical relationship can be used in ground penetrating radar and very early time electromagnetic surveys to estimate permeability values and connectivity functions in the field.

## Chapter 7

## Conclusions

Over the past decade, significant technological advancements have been made in the capabilities of electromagnetic geophysical techniques for imaging the near surface of soil and groundwater contamination sites. High performance digital radar systems are now available that can penetrate the subsurface to depths of tens of meters at resistive sites, and a new technique--very early time electromagnetics--is under development that can image the top ten meters of conductive sites. Each of these techniques is capable of sampling the subsurface over a broad range of scales for a fraction of the cost of other characterization methods. Advancements in digital instrumentation and computer technology have also stimulated significant improvements in geophysical signal processing capabilities. GPR and VETEM data can now be filtered, deconvolved, migrated and displayed in three dimensions using desktop computers, the result being even more reliable structural and stratigraphic images of the subsurface.

Although GPR and VETEM images provide valuable information about the location, size and shape of subsurface heterogeneities, hydrogeologists fundamentally require information about hydrogeologic parameter values associated with these heterogeneities. The most significant problem in environmental geophysics today is the problem of transforming geophysical data into other, more useful, forms of information such as hydrogeologic parameter estimates. The purpose of this thesis research has been to develop a better understanding of the relationships between electrical properties and hydrogeologic properties of geologic materials observed at the same scale, since these relationships are the key to quantitative integration of geophysical and hydrogeological information. This is accomplished through systematic laboratory experiments, analysis of electromagnetic theory, and petrophysical modeling.

A review of the literature (Chapter 3) revealed numerous laboratory studies of the electrical properties of geologic materials. These studies indicate that electrical properties depend on porosity, clay content, water saturation and measurement frequency, among other variables. However, there is little agreement on the specific form of electrical propertyhydrogeological property relationships due to scatter in the experimental data and apparent inconsistencies between studies regarding the relative importance of different hydrogeologic parameters in determining the electrical response of a material. These inconsistencies are difficult to reconcile due to experimental differences in sample composition, sample preparation, measurement techniques and reported parameters.

The problem of non-standardization of electrical measurement techniques and parameter naming conventions is addressed in Chapter 2. This chapter presents an analysis of electromagnetic theory as it applies to laboratory and field measurements of electrical properties. A consistent terminology is used to develop the working time-domain and frequency-domain equations associated with different measurement techniques; the development shows how the electrical parameters measured in laboratory experiments relate to both the electrical parameters measured in GPR and VETEM field experiments and to the electrical parameters appearing in Maxwell's equations. The analysis is unique in that it draws connections between the different types of parameters used by instrument designers, experimentalists, theorists and field geophysicists.

An important conclusion of the theoretical development in Chapter 2 is that all measured parameters are real "effective" parameters, not components of complex parameters that appear in most electromagnetic theories. Transformations between effective parameters and complex parameters are necessary before microscopic electromagnetic theories can be applied to the interpretation of measured macroscopic electrical properties. Measured parameters such as effective electrical conductivity and dielectric constant include contributions from both free and
bound charge carriers, and depend upon frequency. The relationships between effective conductivity and frequency, and dielectric constant and frequency, are nonlinear due to the way that in-phase and out-of-phase conduction and polarization currents combine; however, to first order, effective conductivity scales directly with angular frequency, while dielectric constant scales with the reciprocal of angular frequency.

To resolve apparent inconsistencies in the experimental data base and test various hypotheses about relationships between electrical parameters and hydrogeologic parameters, a series of laboratory experiments was conducted on well-characterized mixtures of sand, clay, air and water. A novel method was used to systematically control the porosity, clay content and effective degree of compaction of the mixtures. The method is based on a simple model of the packing geometry of sand and clay components in binary sand-clay mixtures. Using this method, suites of mixtures were prepared to vary hydrogeologic parameters individually and to simulate geologic processes such as compaction, forced imbibition, evaporative drying, and lithologic variation along the length of a depositional system. In total, the electrical and hydrogeologic properties of more than 100 mixtures were measured, making this one of the largest experimental investigations of electrical properties ever reported.

The measurements of effective electrical conductivity and dielectric constant were made over the frequency range of 100 kHz to 10 MHz . The experimental results are presented as crossplots of electrical parameters versus frequency, and as crossplots of electrical parameters versus various hydrogeologic parameters. The first set of crossplots is useful for investigating the linkage between conduction and polarization phenomena that affect measured effective electrical parameters. The second set of crossplots is useful for characterizing the relationships between electrical and hydrogeological parameters that may exist under different hydrogeological field conditions. It is argued that all electrical measurements should be
displayed in this way, if possible, to show the interdependencies of electrical and hydrogeological parameters.

The results of this study support the idea that the bulk dielectric constant of a composite material depends on the individual dielectric constants of the components, the volume fractions of components, the geometries of the components, and the electrochemical interactions between the components. For instance, the effect of changing individual component properties can be seen by comparing the measured dielectric constants of pure sand, pure kaolinite and pure montmorillonite samples with identical porosity and water saturation values.

The effect of changing the volume fractions of components is illustrated in the plots of electrical parameters versus porosity, electrical parameters versus clay volume fraction, and electrical parameters versus water saturation, since porosity, clay volume fraction and water saturation are all volumetric parameters. For instance, in the compaction experiments, it is observed that the dielectric constant increases with compaction if the samples are dry, and decreases with compaction if the samples are water-saturated, due to differences in the proportions of high- $\kappa$ and low- $\kappa$ material in the mixtures.

Geometric and surface effects are apparent in some of the pure clay and sand-clay mixtures. For instance, anomalously high dielectric constant values are observed when roomdry montmorillonite is compacted beyond a certain point. This is due to the establishment of critical conductive pathways through the sample by percolating booklets of clay particles, and scaling of the out-of-phase component of conductivity in the expression for dielectric constant.

The experimental data are also useful for testing the applicability of dielectric mixing formulas. It is shown that a simple volumetric mixing formula, the Time Propagation equation, can accurately predict the dielectric response of geologic materials provided that conductivity effects are incorporated through correct specification of matrix parameters. More
work is needed, however, to determine how to estimate matrix parameters for use in field mapping problems.

Results also show that the dielectric constant of sand-clay mixtures depends on the porosity and specific surface of the mixtures. Since porosity and specific surface are parameters that also affect permeability, there may be a functional relationship between dielectric constant and permeability that involves these parameters. To test this hypothesis, measurements of dielectric constant and permeability for a suite of sand-clay mixtures are compared to the predictions of three interrelated petrophysical models: (1) a microgeometrical model which describes the relationship between porosity and clay content in sand-clay mixtures, (2) a permeability model based on the Kozeny-Carmen equation, and (3) a dielectric model which incorporates geometric information through the use of effective matrix parameters. Results show excellent agreement between predicted and observed data. This suggests that, at least for these mixtures, permeability estimates accurate to within an order of magnitude may indeed by derived from dielectric measurements given appropriate constraints.

This is a significant finding because dielectric information can be readily obtained from inversion of ground penetrating radar and very early time electromagnetic field surveys. Although it is unlikely that the specific petrophysical relationships developed in this study will be applicable to many natural aquifers, a similar methodology could be employed in field studies to establish locally valid relationships between dielectric parameters and permeability and other hydrogeologic parameters. Such relationships could then be used as the basis for joint geophysical-hydrogeological inverse procedures to improve characterization of heterogeneous aquifers.

## References

Alharthi, A., and Lange, J., 1987, Soil water saturation: dielectric determination: Water Resour. Res., 23, 591-595.

Almon, W.R., 1979, A geologic appreciation of shaly sands: Proc., 20th Ann. Symp., Soc. of Petr. Well Log Analysts, Paper WW, 14 pp.

Alyamani, M.S., and Zekai, S., 1993, Determination of hydraulic conductivity from complete grain-size distribution curves: Ground Water, 31, 551-555.

Annan, A.P., 1993, Practical processing of GPR data: Proc., Second Government Workshop on GPR, 26-28 Oct 1993, Columbus, Ohio, 1-22.

Annan, A.P., and Cosway, S.W., 1991, Ground penetrating radar survey design: Sensors and Software, Inc., Mississauga, Ontario, 28 pp.

Arulanandan, K., and Mitchell, J̀.K., 1968, Low frequency dielectric dispersion of clayelectrolyte systems: Clay and Clay Minerals, 16, 337-351.

ASTM, 1987, Standard test methods for A-C loss characteristics and permittivity (dielectric constant) of solid electrical insulating materials: Standard D 150-87, American Society for Testing and Materials, Philadelphia, PA, 19 pp .

Balanis, C.A., 1989, Advanced engineering electromagnetics: John Wiley \& Sons.
Barber, L.B., II, 1992, Geochemical heterogeneity in a sand and gravel aquifer: Effect of sediment mineralogy and particle size on the sorption of chlorobenzenes: J. Contam. Hydrol., 9, 35-54.

Barlow, P.M., 1987, The use of temperature as a ground-water tracer in glacial outwash: M.Sc. thesis, University of Arizona.

Bear, J., 1972, Dynamics of fluids in porous media: Elsevier Science Publ. Co., Inc.
Beard, D.C., and Weyl, P.K., 1973, Influence of texture on porosity and permeability of unconsolidated sand: AAPG Bull., 57, 348-369.

Beckie, R., 1996, Measurement scale, network sampling scale and groundwater model parameters: Water Resour. Res., 32, 65-76.

Beres, M. Jr., and Haeni, F.P., 1991, Application of ground-penetrating-radar methods in hydrogeologic studies: Ground Water, 29, 375-386.

Berryman, J.G., 1995, Mixture theories for rock properties: in Ahrens, T.J., ed., Rock physics and phase relations, AGU, Wash., DC, 205-228.

Bevington, P.R., 1969, Data reduction and error analysis for the physical sciences: McGrawHill.

Birchak, J.R., Gardner, C.G., Hipp, J.E., and Victor, J.M., 1974, High dielectric constant microwave probes for sensing soil moisture: Proc. IEEE, 62, 93-98.

Bourbie, T., Coussy, O., and Zinszner, B., 1987, Acoustics of porous media: Gulf Publ. Co.
Brown, E.A., 1995, Permeability and dielectric measurements of unconsolidated materials: B.Sc. thesis, Univ. of British Columbia.

Brown, W.F., 1956, Dielectrics, in Encyclopedia of Physics, 17, Springer-Verlag Berlin.
Bruggeman, D.A.G., 1935, Berechnung verschiedener physikallischer konstanten von heterogenen substanzen: Ann. Phys., 24, 636-664.

Brunauer, S., Emmett, P.H., and Teller, E., 1938, Adsorption of gases in multimolecular layers: J. Am. Chem. Soc., 60, 309-319.

Carmen, P.C., 1956, Flow of gases through porous media: Academic Press Inc.
Casper, D.A., and Kung, K.J.S., 1993, Testing a two-dimensional seismic migration routine on ground-penetrating radar simulations: Proc., Second Government Workshop on GPR, 26-28 Oct 1993, Columbus, Ohio, 319-336.

Carter, D.L., Heilman, M.D., and Gonzalez, C.L., 1965, Ethylene glycol monoethyl ether for determining surface areas of silicate minerals: Soil Sci., 100, 356-360.

Chew, W.C., and Sen, P.N., 1982, Dielectric enhancement due to electrochemical double layer: thin double layer approximation, J. Chem. Phys., 77, 4683-4693.

Cole, K.S., and Cole, R.H., 1941, Dispersion and absorption in dielectrics: J. Chem. Phys., 9, 341-351.

Copty, N., and Rubin, Y., 1995, A stochastic approach to the characterization of lithofacies from surface seismic and well data: Water Resour. Res., 31, 1673-1686.

Copty, N., Rubin, Y., and Mavko, G., 1993, Geophysical-hydrogeological identification of field permeabilities through Bayesian updating: Water Resour. Res., 29, 2813-2825.

Daniels, D.J., Gunton, D.J., and Scott, H.F., 1988, Introduction to subsurface radar: IEE Proc. 135, F4, 278-320.

Dasberg, S., and Dalton, F.N., 1985, Time-domain reflectometry method of soil water content and electrical conductivity: Soil Sci. Soc. Am. J., 49, 293-297.

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

Debye, P., 1929, Polar molecules: Chemical Publ. Company.
Dobson, M.C., Ulaby, F.T., Hallikainen, M.T., and El-Rayes, M.A., 1985, Microwave dielectric behavior of wet soil, II, Dielectric mixing models: IEEE Trans. Geosci. Remote Sensing, GE-23, 35-46.

Drury, M.J., 1978, Frequency spectrum of the electrical properties of seawater-saturated ocean crust and oceanic island basalts: Can. J. Earth Sci., 15, 1489-1495.

Duke, S.K., 1990, Calibration of ground penetrating radar and calculation of attenuation and dielectric permittivity versus depth: M.Sc. thesis, Colorado School of Mines.

Dukhin, S.S., 1971, Dielectric properties of disperse systems: in Matijevic, E., ed., Surface and colloid science: John Wiley \& Sons, 83-165.

Dullien, F.A.L., 1979, Porous media: Academic Press Inc.
Endres, A.L., and Knight, R.J., 1993, A model for incorporating surface phenomena into the dielectric response of a heterogeneous medium: J. Colloid Interface Sci., 157, 418-425.

Fatt, I., 1956, The network model of porous media: Petroleum Trans., AIME, 207, 144-181.
Fisher, E., McMechan, G.A., and Annan, A.P., 1992, Acquisition and processing of wideaperature ground-penetrating radar data, Geophysics, 57, 495-504.

Fitterman, D.V., 1987, Examples of transient sounding for ground-water exploration in sedimentary aquifers: Ground Water, 25, 685-692.

Ford, L.H., 1949, The effect of humidity on the calibration of precision air capacitors: Proc., IOEEA, Institution of Electrical Engineers, 96, Part III, 13-16.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc.
Fuller, B.D., and Ward, S.H., 1970, Linear-system description of the electrical parameters of rocks: IEEE Trans. Geosci. Electronics, GE-8, 7-18.

Garabedian, S.P., LeBlanc, D.R., Gelhar, L.W., and Celia, M.A., 1991, Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 2, Analysis of spatial moments for a nonreactive tracer: Water Resour. Res., 27, 911-924.

Garrouch, A.A., and Sharma, M.M., 1994, The influence of clay content, salinity, stress, and wettability on the dielectric properties of brine-saturated rocks: 10 Hz to 10 MHz : Geophysics, 59, 909-917.

General Radio, 1977, Dielectric loss and permittivity measurements with GenRad precision capacitance bridges: Application Note EID-11, General Radio, Inc., Concord, MA, 16 pp.

Gerlitz, K., Knoll, M.D., Cross, M., Luzitano, R.D., and Knight, R., 1993, Processing ground penetrating radar data to improve resolution of near-surface targets: Proc., Symp. on the Appl. of Geophys. to Envir. and Eng. Probl., 18-22 April 1993, San Diego, CA, 561-574.

Graton, L.C., and Frazer, H.J., 1935, Systematic packing of spheres--with particular relation to porosity and permeability: J. Geol., 43, 785-909.

Greenhouse, J.P., Barker, J.F., Cosgrave, T.M., and Davis, J.L., 1987, Shallow stratigraphic reflections from ground penetrating radar: Research Agreement 232, Dept. of Energy, Mines and Resources, 230 pp .

Haeni, F.P., 1986, The use of electromagnetic methods to delineate vertical and lateral lithologic changes in glacial aquifers: Proc., NWWA Conf. on Surface and Borehole Geophysical Methods and Ground Water Instrumentation, 15-17 October 1986, Denver, CO, 259-282.

Hall, P.G., and Rose, M.A., 1978, Dielectric properties of water adsorbed by kaolinite clays: J. Chem. Soc. Faraday Trans., 74, 1221-1233.

Hallikainen, M.T., Ulaby, F.T., Dobson, M.C., El-Rayes, M.A., and Wu, L.K., 1985, Microwave dielectric behavior of wet soil, I, Empirical models and experimental observations: IEEE Trans. Geosci. Remote Sensing, GE-23, 25-34.

Hanai, T., 1961, Dielectric theory on the interfacial polarization for two-phase mixtures: Bull. Inst. Chem. Res., 39, 341-367.

Handbook of Physics and Chemistry, 1986, 67th ed., CRC Press, Boca Raton, Fl.
Hartkamp-Bakker, C.A., 1993, Permeability heterogeneity in cross-bedded sandstones: impact on water/oil displacement in fluvial reservoirs: Ph.D. Thesis, Delft Univ. of Tech.

Hasted, J.B., 1973, Aqueous dielectrics: Chapman and Hall.
Hazen, A., 1892, Some physical properties of sands and gravels: Massachusetts State Board of Health, Annual Report, 539-556.

Hess, K.M., Wolf, S.H., and Celia, M.A., 1992, Large-scale natural-gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 3, Hydraulic conductivity variability and calculated macrodispersivities: Water Resour. Res., 28, 2011-2027.

Hewlett-Packard, 1987, Measuring the dielectric constant of solid materials: Application Note 339-13, Hewlett-Packard, Ltd., 5 pp.

Hillel, D., 1980, Fundamentals of soil physics: Academic Press.
Hipp, J.E., 1974, Soil electromagnetic parameters as a function of frequency, soil density and soil moisture: Proc. IEEE, 62, 98-103.

Hoekstra, P., and Delaney, A., 1974, Dielectric properties of soils at UHF and microwave frequencies: J. Geophys. Res., 79, 1699-1708.

Honda, M., 1989, The impedance measurement handbook: Hewlett-Packard, Ltd.
Huggenberger, P., 1993, Radar facies: recognition of facies patterns and heterogeneities within Pleistocene Rhine gravels, NE Switzerland: in Best, J.L., and Bristow, C.S., eds., Braided rivers: Geol. Soc. Spec. Publ., 75, 163-176.

Hulsenbeck, P., 1926, German Patent 489434.

Hyndman, D.W., Harris, J.M., and Gorelick, S.M., 1994, Coupled seismic and tracer test inversion for aquifer property characterization: Water Resour. Res., 30, 1965-1977.

IEEE Standards Board, 1990, IEEE standard definitions of terms for radio wave propagation: IEEE Std. 211-1990, NY, Inst. of Elec. and Electron. Engrs., 24 pp.

Journel, A.G., and Alabert, F.G., 1988, Focusing on the spatial connectivity of extremevalued attributes: Stochastic indicator models of reservoir heterogeneities: Proc., 63rd Ann. Tech. Conf., Soc. of Petr. Eng., Houston, TX, 2-5 Oct. 1988, 621-632.

Katz, A.J., and Thompson, A.H., 1986, Quantitative prediction of permeability in porous rock: Phys. Rev. B, 34, 8179-8181.

Keller, G.V., 1988, Rock and mineral properties, in Nabighian, M.N., ed., Electromagnetic methods in applied geophysics: volume 1, theory: Soc. of Expl. Geophys., 13-51.

Keller, G.V., and Licastro, P.H., 1959, Dielectric constant and electrical resistivity of natural state cores: U.S. Geol. Surv. Bull. 1052-H, 257-285.

Kenyon, W.E., 1984, Texture effects on megaherz dielectric properties of calcite rock samples: J. Appl. Phys., 55, 3153-3159.

King, R.W.P., and Smith, G.S., 1981, Antennas in matter: M.I.T. Press.
Klein, J.D., and Sill, W.R., 1982, Electrical properties of artificial clay-bearing sandstone: Geophysics, 47, 1593-1605.

Klute, A., and Dirksen, C., 1986, Hydraulic conductivity and diffusivity, in Methods of soil analysis: Soil Sci. Soc. of Am.

Knight, R.J., 1983, The use of complex plane plots in studying the electrical response of rocks: J. Geomag. Geoelect., 35, 767-776.

Knight, R., and Endres, A., 1990, A new concept in modeling the dielectric response of sandstones: defining a wetted rock and bulk water system: Geophysics, 55, 586-594.

Knight, R.J., and Nur, A., 1987, The dielectric constant of sandstones, 60 kHz to 4 MHz : Geophysics, 52, 644-654.

Knoll, M.D., Haeni, F.P., and Knight, R.J., 1991, Characterization of a sand and gravel aquifer using ground-penetrating radar, Cape Cod, Massachusetts: in Mallard, G.E., and Aronson, D.A., eds., U.S. Geological Survey Toxic Waste Hydrology Program-Proceedings of the technical meeting, Monterey, CA, 11-15 March 1991: U.S. Geological Survey Water Resources Investigation Report 91-4034, 29-35.

Kozeny, J., 1927, Uber kapillare leitung des wassers im boden: Sitzungsber. Acad. Wiss. Wien., 136, 271-306.

Krumbein, W.C., and Monk, G.D., 1943, Permeability as a function of the size parameters of sedimentary particles: Am. Inst. Min. and Met. Eng. Tech. Pub., 1492, 153-163.

Kutrubes, D.L., 1986, Dielectric permittivity measurements of soils saturated with hazardous fluids: M.Sc. thesis, Colorado School of Mines.

Landauer, R., 1978, Electrical conductivity in inhomogeneous media: in Garland, J.C., and Tanner, D.B., eds., Electrical transport and optical properties of inhomogeneous media: Am. Inst. Phys., 2-45.

Lange, J.N., 1983, Microwave properties of saturated reservoirs: Geophysics, 48, 367-375.
LeBlanc, D.R., Garabedian, S.P., Hess, K.M., Gelhar, L.W., Quadri, R.D., Stollenwerk, K.G., and Wood, W., 1991, Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 1, Experimental design and observed tracer movement: Water Resour. Res., 27, 895-910.

Lesmes, D.P., 1993, Electrical impedance spectroscopy of sedimentary rocks: Ph.D. dissertation, Texas A\&M University.

Lichtenecker, K., and Rother, K., 1937, Physics Zeitschrift, 255.
Lima, O.A.L., and Sharma, M.M., 1992, A generalized Maxwell-Wagner theory for membrane polarization in shaly sands: Geophysics, 57, 431-440.

Lockhart, N.C., 1980a, Electrical properties and surface characteristics and structure of clays, I, swelling clays: J. Colloid Interface Sci., 74, 509-519.
-------- 1980b, Electrical properties and surface characteristics and structure of clays, II, a nonswelling clay: J. Colloid Interface Sci., 74, 520-529.

Lucius, J.E., Olhoeft, G.R., Hill, P.L., and Duke, S.K., 1989, Properties and hazards of 108 selected substances: U.S. Geol. Survey, Open File Report 89-491.

Lundien, J.R., 1971, Terrain analysis by electromagnetic means: U.S. Army Corps of Eng., Tech. Rep. 3-693.

Marion, D., Nur, A., Yin, H., and Han, D., 1992, Compressional velocity and porosity in sand-clay mixtures: Geophysics, 57, 554-563.

Marsh, K.N.; 1987, Recommended reference materials for the realization of physiochemical properties: Blackwell Sci. Publ.

Mavko, G., and Nur, A., 1993, The effect of a percolation threshold in the Kozeny-Carmen relation: Stanford Rock and Borehole Project, 53, Stanford University, Paper M.

Maxwell, J.C., 1891, A treatise on electricity and magnetism: Dover Publ. Inc.
McKenna, S.A., and Poeter, E.P., 1995, Field example of data fusion in site characterization: Water Resour. Res., 31, 3229-3240.

Morey, R.M., 1974, Continuous subsurface profiling by impulse radar: Proc. of Engineering Foundations Conference on Subsurface Explorations for Underground Excavations and Heavy Construction, Henniker, NH, 213-232.

Morgan, F.D., Rickman, D., Lesmes, D., and Samstag, F., 1991, Microgeometric quantification of sedimentary rocks by computer image analysis: a preliminary review: 61st Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 468-470.

Morin, R.H., LeBlanc, D.R., and Teasdale, W.E., 1988, A statistical evaluation of formation disturbance produced by well-casing installation methods: Ground Water, 26, 207-217.

Neasham, J.W., 1977, The morphology of dispersed clay in sandstones and its effect on sandstone shaliness, pore space and flow properties: Proc., 52nd Ann. Tech. Conf., Soc. of Petr. Eng., Denver, CO, SPE paper 6858.

Newton, R.W., 1977, Microwave remote sensing and its application to soil moisture detection: Texas A \& M Univ., Tech. Rep. RSC-81.

Nielsen, L.E., 1978, Predicting properties of mixtures: mixture rules in science and engineering: Marcel Dekker, Inc.

Okrasinski, T.A., Koerner, R.M., and Lord, A.E., Jr., 1979, Dielectric constant determination of soils at $L$ band microwave frequencies: Geotechnical Testing J., 1, 134140.

Olhoeft, G.R., 1976, Electrical properties of rocks: in Strens, R.G.J., ed., The physics and chemistry of minerals and rocks: John Wiley and Sons, Inc., 261-278.
---------- 1979a, Tables of room temperature electrical properties for selected rocks and minerals with dielectric permittivity statistics: U.S. Geol. Survey, Open File Report 79993, 24 pp .

1979b, Electrical properties: in Initial report of the petrophysics laboratory, U.S. Geol. Survey, Circular 789, 1-25.
---------- 1979c, Nonlinear electrical properties: in Neel, L., ed., Nonlinear behavior of molecules, atoms and ions in electric, magnetic or electromagnetic fields: Elsevier Science Publ. Co., Inc., 395-410.
--------- 1981, Electrical properties of rocks: in Touloukian, Y.S., Judd, W.R., and Roy, R.F., eds., Physical properties of rocks and minerals: McGraw-Hill Book Co., 257-286.
---------- 1984, Applications and limitations of ground penetrating radar: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 147-148.

1985, Low-frequency electrical properties: Geophysics, 50, 2492-2503.
1986, Electrical properties of rocks and minerals: Short course notes, 434 pp.
1987, Electrical properties from $10^{-3}$ to $10^{9} \mathrm{~Hz}$, physics and chemistry: in Banavar, J.R., Koplik, J., and Winkler, K.W., eds., Physics and chemistry of porous media II: Am. Inst. of Phys. Conf. Proc., 154, 281-298.
---------- 1992, Site characterization tools: Proc., Third Int'l Conf. on Ground Water Quality Research, 21-24 June 1992, Dallas, TX, National Center for Ground Water Research, Rice University, 29-31.

Olhoeft, G.R., and Capron, D.E., 1994, Petrophysical causes of electromagnetic dispersion: Proc., Fifth Int'l Conf. on Ground Penetrating Radar, 12-16 June 1994, Kitchener, Ontario, 145-152.

Olhoeft, G.R., and Strangway, D.W., 1974, Magnetic relaxation and the electromagnetic response parameter: Geophysics, 39, 302-311.

Olhoeft, G.R., and Strangway, D.W., 1975, Electrical properties of the first 100 meters of the moon: Earth and Planet. Sci. Lttrs., 24, 394-404.

Ollson, O., Falk, L., Forslund, O., Lundmark, L., and Sandberg, E., 1992, Borehole radar applied to the characterization of hydraulically conductive fracture zones in crystalline rock: Geophys. Prospecting, 40, 109-142.

Pellerin, L., Labson, V.F., Pfeifer, M.C., and VETEM participants, 1994, VETEM -- a very early time electromagnetic system: Proc., Symp. on the Appl. of Geophys. to Envir. and Eng. Probl., 27-31 March 1994, Boston, MA, 795-802.

Pellerin, L., Labson, V.F., Pfeifer, M.C., and VETEM participants, 1995, VETEM -- a very early time electromagnetic system - the first year: Proc., Symp. on the Appl. of Geophys. to Envir. and Eng. Probl., 23-26 April 1995, Orlando, FL, 725-731.

Poley, J. Ph., Nootenboom, J.J., and de Waal, P.J., 1978, Use of v.h.f. dielectric measurements for borehole formation analysis: The Log Analyst, 19, 8-30.

Powers, M.H., Duke, S.K., Huffmann, A.C. III, and Olhoeft, G.R., 1992, GPRMODEL: One-dimensional full waveform forward modeling of ground penetrating radar data: U.S. Geological Survey, Open File Report 92-532, 22 pp.

Roth, K., Schulin, R., Fluhler, H., and Attinger, W., 1990, Calibration of time domain reflectometry for water content measurement using a composite dielectric approach: Water Resour. Res., 26, 2267-2273.

Rubin, Y., Mavko, G., and Harris, J., 1992, Mapping permeability in heterogeneous aquifers using hydrologic and seismic data: Water Resour. Res., 28, 1809-1816.

Rudolph, D.L., Kachanoski, G.R., Celia, M.A., LeBlanc, D.R., and Stevens, J., 1996, Infiltration and solute transport experiments in unsaturated sand and gravel, Cape Cod, Massachusetts: Experimental design and overview of results: Water Resour. Res., 32, 519532.

Ruffet, C., Gueguen, Y., and Darot, M., 1991, Complex conductivity measurements and fractal nature of porosity: Geophysics, 56, 758-768.

Sander, K.A., 1994, Characterization of DNAPL movement in saturated porous media using ground penetrating radar: M.Sc. thesis, Colorado School of Mines.

Scheibe, T.D., 1993, Characterization of the spatial structuring of natural porous media and its impacts on subsurface flow and transport: Ph.D. dissertation, Stanford University.

Scheidegger, A.D., 1974, The physics of flow through porous media: Univ. of Toronto Press.
Schwartz, L.M., and Kimminau, S., 1987, Analysis of electrical conduction in the grain consolidation model: Geophysics, 52, 1402-1411.

Scott, J.J., Carroll, R.D., and Cunningham, D.R., 1967, Dielectric constant and electrical conductivity measurements of moist rock: a new laboratory method: J. Geophy. Res., 72, 5105-5115.

Sen, P.N., 1981, Relation of certain geometrical features to the dielectric anomaly of rocks: Geophysics, 46, 1714-1720.

Sen, P.N., Scala, C., and Cohen, M.H., 1981, A self similar model for sedimentary rocks with application to the dielectric constant of fused glass beads: Geophysics, 46, 781-795.

Sena, A.G., and Toksov, M.N., 1990, Simultaneous reconstruction of permittivity and conductivity for crosshole geometries: Geophysics, 55, 1302-1311.

Shen, L.C., Marouni, H., Zhang, Y.-X., Shi, X.-D., 1987, Analysis of the parallel-disk sample holder for dielectric permittivity measurement: IEEE Trans. Geosci. Remote Sensing, GE-25, 534-540.

Shen, L.C., Savre, W.C., Price, J.M., and Athavale, K., 1985, Dielectric properties of reservoir rocks at ultra-high frequencies: Geophysics, 50, 692-704.

Shepherd, R.G., 1989, Correlations of permeability and grain size: Ground Water, 27, 633638.

Sherman, M.M., 1986, The calculation of porosity from dielectric constant measurements: a study using laboratory data: The Log Analyst, 27, 15-24.
---------- 1988, A model for the frequency dependence of the dielectric permittivity of reservoir rocks: The Log Analyst, 29, 358-369.

Smith, D.G., and Jol, H.M., 1995, Ground penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments: J. Appl. Geophys., 33, 93-100.

Smith, L., and Schwartz, F.W., 1981, Mass transport 3, role of hydraulic conductivity data in prediction: Water Resour. Res., 17, 1463-1479.

Smith-Rose, R.L, 1933, The electrical properties of soils for alternating currents at radio frequencies: Proc., Royal Soc. London, 140, 359-377.

Stewart, D.C., Anderson, W.A., Grover, T.P., and Labson, V.F., 1994, Shallow subsurface mapping by electromagnetic sounding in the 300 kHz to 30 MHz range: Model studies and prototype system assessment: Geophysics, 59, 1201-1210.

Strangway, D.W., 1972, Mineral magnetism: in Mining geophysics, vol. II (theory), Soc. of Expl. Geophys., 437-445.

Stratton, J.A., 1941, Electromagnetic theory: McGraw-Hill Book Co.
Suman, R., and Ruth, D., 1993, Formation factor and tortuosity of homogeneous porous media: Transport in Porous Media, 12, 185-206.

Taherian, M.R., Kenyon, W.E., and Safinya, K.A., 1990, Measurement of the dielectric response of water-saturated rocks: Geophysics, 55, 1530-1541.

Tillard, S., and Dubois, J.C., 1995, Analysis of GPR data: wave propagation velocity determination: J. Appl. Geophys., 33, 77-91.

Tinga, W.R., Voss, W.A.G., and Bossey, D.F., 1973, Generalized approach to multiphase dielectric mixture theory: J. Appl. Phys., 44, 3897-39002.

Topp, G.C., Davis, J.L, and Annan, A.P., 1980, Electromagnetic determination of soil water content: measurement in coaxial transmission lines: Water Resour. Res., 16, 574-582.

Turner, G., 1994, Subsurface radar propagation deconvolution: Geophysics, 59, 215-223.
Turner, G., and Siggins, A.F., 1994, Constant Q attenuation of subsurface radar pulses: Geophysics, 59, 1192-1200.

Ulaby, F.T., Moore, R.K., and Fung, A.K., 1981, Microwave remote sensing, active and passive, vol. 1: Addison-Wesley Publ. Co., 456.

Ulriksen, C.P.F., 1982, Application of impulse radar to civil engineering: Ph.D. thesis, Lund Univ. of Technology.
van Beek, L.K.H., 1967, Dielectric behavior of heterogeneous systems: Progr. Dielec., 7, 69114.
van Olphen, H. and Fripiat, J.J., eds., 1979, Data handbook for clay minerals and other nonmetallic minerals: Pergamon Press, Inc.
von Hippel, A.R., 1954: Dielectrics and waves: John Wiley \& Sons.
Wagner, K.W., 1914, Erklarung der dielektrischen nachwirkungsworkange auf grund maxwellscher vortellungen: Archiv. Electrotechnik., 2, 371-387.

Wang, J.R., 1980, The dielectric properties of soil-water mixtures at microwave frequencies: Radio Sci., 15, 977-985.

Wang, J.R., and Schmugge, T.J., 1980, An empirical model for the complex dielectric permittivity of soils as a function of water content: IEEE Trans. Geosci. Remote Sensing, GE-18, 288-295.

Ward, S.H., and Hohmann, G.W., 1988, Electromagnetic theory for geophysical applications, in Nabighian, M.N., Ed., Electromagnetic methods in applied geophysics: volume 1, theory: Soc. of Expl. Geophys., 130-311.

Wharton, R.P., Hazen, G.A., Rau, R.N., and Best, D.L., 1980, Electromagnetic propagation logging: advances in technique and interpretation: Soc. of Petr. Eng., Paper 9267.

Wright, D.L., Grover, T.P., Labson, V.F., Pellerin, L., Ellefsen, K.J., and Bradley, J.A., 1995, Tomography between wells, a transient dielectric logging tool, and the very early time electromagnetic (VETEM) system: Proc., Symp. on the Appl. of Geophys. to Envir. and Eng. Probl., 23-26 April 1995, Orlando, FL, 501-510.

Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, 21, 41-70.

Wyllie, M.R.J., and Spangler, M.B., 1952, Application of electrical resistivity measurements to problem of fluid flow in porous media: Geophysics, 36, 359-403.

Yin, H., 1993, Acoustic velocity and attenuation of rocks--isotropy, intrinsic anisotropy, and stress-induced anisotropy: Ph.D. dissertation, Stanford University.

## Appendix A

## Compensation for Cable and Sample Holder Residuals

Impedance measurements always contain some systematic error. Typical sources of this error include: (1) improper calibration of the impedance analyzer, (2) residuals due to the cables (e.g., residual impedance and stray admittance), and (3) residuals due to the sample holder assembly (e.g., current leakage through the sample holder, edge capacitance and electrode polarization) (General Radio, 1977; Olhoeft, 1986; Honda, 1989). If the systematic error can be quantified and traced to a particular source, then the effective accuracy of the impedance measurements can be improved by applying one or more data corrections. Commonly used compensation techniques are described in Standard D-150 published by the American Society for Testing and Materials (ASTM, 1987) and in the application notes distributed by HewlettPackard Company (e.g., Hewlett-Packard, 1987; Honda, 1989).

To characterize the systematic error in my impedance measurements, I measured the electrical properties of some standard reference materials (air, Teflon, aqueous KCl solutions, etc.) and precision electrical components (capacitors and resistors). By connecting the electrical components to the measurement circuit at different locations, the effects of the cables could be distinguished from basic instrument inaccuracies. The results of these tests, discussed in Appendix B, suggest that the main source of error in my impedance measurements is due to the sample holder assembly. To compensate for this error, a correction was made based on the measurement of air as a standard. In addition, an open/short correction was used to compensate for the residuals of the cables. No adjustment was made to the manufacturer's internal calibration of the impedance analyzer. The purpose of this appendix is to provide further details about the cable and sample holder compensations.

## A1 CABLE COMPENSATION

The first correction that was applied is the open/short compensation (Honda, 1989). This compensation assumes that the cable residuals can be represented by the circuit shown in Figure A1. With the sample holder in place (top diagram), the impedance analyzer measures $Z_{m}$ at a given frequency. However, the desired quantity at this stage in the analysis is the impedance of the device under test $\boldsymbol{Z}_{d u t}$ (i.e., the impedance of the sample holder assembly). $Z_{m}$ includes the residual impedance ( $Z_{s}=R_{s}+i \omega L_{s}$ ) and stray admittance ( $Y_{o}=G_{o}+i \omega C_{o}$ ) of the cables. $Z_{d u t}$ can be determined from $Z_{m}$ by applying the following compensation equation:

$$
\begin{equation*}
Z_{d u t}=\frac{Z_{m}-Z_{s}}{1-Y_{o}\left(Z_{m}-Z_{s}\right)} \tag{A1}
\end{equation*}
$$

where $Y_{o}$ and $Z_{S}$ are determined from open and short measurements, respectively. The open measurement (middle diagram) is performed without the sample holder in place but with the cables in the normal measurement position. The short measurement (bottom diagram) is performed by directly connecting the two aligator clips that terminate the cables.

In practice, it is convenient to rewrite equation (A1) so that it contains only impedance or admittance terms; then, only one type of vector must be measured by the impedance analyzer. I chose to work in the admittance plane where the equivalent open/short compensation equation is:

$$
\begin{equation*}
Y_{d u t}=\frac{Y_{s} Y_{m}}{Y_{s}-Y_{m}}-Y_{o} \tag{A2}
\end{equation*}
$$

This equation was used to implement the open/short compensation at each measurement frequency. By taking the real and imaginary parts of $\boldsymbol{Y}_{d u t}$ (and dividing the imaginary part by angular frequency), the open/short-corrected $G_{p}$ and $C_{p}$ values needed for the sample holder compensation were obtained.


Figure A1. (a) Circuit model for cable residuals. (b) Open measurement circuit. (c) Short measurement circuit. $\boldsymbol{Z}_{m}$ is the measured impedance including all cable residuals. $\boldsymbol{Z}_{d u t}$ is the impedance of the device under test. $R_{s}$ and $L_{s}$ are the equivalent series resistance and inductance of the cables, respectively. $G_{o}$ and $C_{o}$ are the equivalent parallel conductance and capacitance of the cables, respectively. The open/short compensation formula based on this circuit is given in the text.

Table A1 lists the $C_{p}$ and $G_{p}$ values (between 1 kHz and 10 MHz ) that were used to construct the $\boldsymbol{Y}_{O}$ and $\boldsymbol{Y}_{S}$ vectors. Ten sets of measurements were averaged to determine these values; the variance at each frequency is negligible. The effect of the open compensation is to reduce the measured $C_{p}$ value at each frequency by about $2 \times 10^{-13} \mathrm{~F}$. For comparison, the measured $C_{p}$ values for the dry sand samples, among the least capacitative samples studied (see Appendix D), are around $1 \times 10^{-11} \mathrm{~F}$. The non-zero $G_{p}$ values ( $\pm 2 \times 10^{-8} \mathrm{~S}$ or less) in the open measurement data are a measure of the basic inaccuracy of the impedance analyzer since the true conductance of air in the wire gap is outside the measurement range of the impedance analyzer (admittance range: $1 \times 10^{-9} \mathrm{~S}<|Y|<1 \times 10^{1} \mathrm{~S}$ ). The effect of the short compensation is to change measured $C_{p}$ and $G_{p}$ values a very small amount; typical deviations are within 0.1 percent of the measured value.

## A2 SAMPLE HOLDER COMPENSATION

The second and more important correction that was applied is the sample holder compensation. This correction reduces the systematic error due to both current leakage through the acrylic sample holder and edge capacitance through the air. It does not, however, correct for electrode polarization which occurs primarily at low frequencies ( $<10 \mathrm{kHz}$ ) for conductive samples.

The need for a sample holder correction is most apparent in the measured impedance data for air, the reference material with the highest impedance. Given a sample holder with an internal diameter of 4.207 cm and an internal thickness of 0.436 cm , the expected frequencyindependent $C_{p}$ and $G_{p}$ values for air are $2.8246 \times 10^{-12} \mathrm{~F}$ and $0.0 \times 10^{-8} \mathrm{~S}$, respectively. However the values that I measured for air in this geometry are much higher. Table A2 lists the open/short compensated $C_{p}$ and $G_{p}$ values determined by averaging ten separate measurements, as well as the deviations from the expected $C_{p}$ and $G_{p}$ values. The variance of

Table A1. $C_{p}$ and $G_{p}$ values used for the open/short compensation.

| Frequency [Hz] | Open Measurement |  | Short Measurement |  |
| :---: | :---: | :---: | :---: | :---: |
|  | $C_{p}[\mathrm{~F}]$ | $G_{p}[\mathrm{~S}]$ | $C_{p}[\mathrm{~F}]$ | $G_{p}[\mathrm{~S}]$ |
| $1.000 \mathrm{E}+07$ | 2.173E-13 | -2.000E-08 | -8.250E-09 | $5.000 \mathrm{E}-03$ |
| $6.310 \mathrm{E}+06$ | $2.080 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.100E-08 | $7.000 \mathrm{E}-03$ |
| $3.981 \mathrm{E}+06$ | $2.040 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -5.320E-08 | $1.200 \mathrm{E}-02$ |
| $2.512 \mathrm{E}+06$ | $2.030 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -1.336E-07 | $2.600 \mathrm{E}-02$ |
| $1.585 \mathrm{E}+06$ | $2.024 \mathrm{E}-13$ | $3.000 \mathrm{E}-09$ | -3.400E-07 | 1:000E-01 |
| $1.000 \mathrm{E}+06$ | $2.024 \mathrm{E}-13$ | $2.000 \mathrm{E}-09$ | -8.400E-07 | $1.000 \mathrm{E}-01$ |
| $6.309 \mathrm{E}+05$ | $2.020 \mathrm{E}-13$ | $2.000 \mathrm{E}-09$ | -2.100E-06 | $2.000 \mathrm{E}-01$ |
| $3.981 \mathrm{E}+05$ | $2.030 \mathrm{E}-13$ | $1.000 \mathrm{E}-09$ | -5.200E-06 | $4.000 \mathrm{E}-01$ |
| $2.512 \mathrm{E}+05$ | $2.030 \mathrm{E}-13$ | $1.000 \mathrm{E}-09$ | -1.310E-05 | $9.500 \mathrm{E}-01$ |
| $1.585 \mathrm{E}+05$ | $2.030 \mathrm{E}-13$ | $1.000 \mathrm{E}-09$ | -2.000E-05 | $2.150 \mathrm{E}+00$ |
| $1.000 \mathrm{E}+05$ | $2.030 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -8.200E-05 | $5.600 \mathrm{E}+00$ |
| $6.310 \mathrm{E}+04$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-04 | $1.265 \mathrm{E}+01$ |
| $3.981 \mathrm{E}+04$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-04 | $2.000 \mathrm{E}+01$ |
| $2.512 \mathrm{E}+04$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-04 | $2.000 \mathrm{E}+01$ |
| $1.585 \mathrm{E}+04$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-04 | $2.000 \mathrm{E}+01$ |
| $1.000 \mathrm{E}+04$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-03 | $2.000 \mathrm{E}+01$ |
| $6.309 \mathrm{E}+03$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-03 | $2.000 \mathrm{E}+01$ |
| $3.981 \mathrm{E}+03$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-03 | $2.000 \mathrm{E}+01$ |
| $2.512 \mathrm{E}+03$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-03 | $2.000 \mathrm{E}+01$ |
| $1.585 \mathrm{E}+03$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | $-2.000 \mathrm{E}-03$ | $2.000 \mathrm{E}+01$ |
| $1.000 \mathrm{E}+03$ | $2.000 \mathrm{E}-13$ | $0.000 \mathrm{E}+00$ | -2.000E-03 | $2.000 \mathrm{E}+01$ |

Table A2. $C_{p}$ and $\boldsymbol{G}_{\boldsymbol{p}}$ values used for the example sample holder compensation.

|  | Air Measurement |  |  | Deviation from expected value |
| :--- | :---: | :---: | :---: | :---: |
|  |  |  |  |  |
| Frequency $[\mathrm{Hz}]$ | $C p[\mathrm{~F}]$ | $G_{p}[\mathrm{~S}]$ | $C p[\mathrm{~F}]$ | $G_{p}[\mathrm{~S}]$ |
|  |  |  |  |  |
|  |  |  |  |  |
| $1.000 \mathrm{E}+07$ | $5.076 \mathrm{E}-12$ | $9.169 \mathrm{E}-07$ | $2.252 \mathrm{E}-12$ | $9.169 \mathrm{E}-07$ |
| $6.310 \mathrm{E}+06$ | $5.161 \mathrm{E}-12$ | $9.991 \mathrm{E}-07$ | $2.336 \mathrm{E}-12$ | $9.991 \mathrm{E}-07$ |
| $3.981 \mathrm{E}+06$ | $5.195 \mathrm{E}-12$ | $7.997 \mathrm{E}-07$ | $2.371 \mathrm{E}-12$ | $7.997 \mathrm{E}-07$ |
| $2.512 \mathrm{E}+06$ | $5.227 \mathrm{E}-12$ | $5.699 \mathrm{E}-07$ | $2.402 \mathrm{E}-12$ | $5.699 \mathrm{E}-07$ |
| $1.585 \mathrm{E}+06$ | $5.243 \mathrm{E}-12$ | $3.670 \mathrm{E}-07$ | $2.418 \mathrm{E}-12$ | $3.670 \mathrm{E}-07$ |
| $1.000 \mathrm{E}+06$ | $5.256 \mathrm{E}-12$ | $2.480 \mathrm{E}-07$ | $2.431 \mathrm{E}-12$ | $2.480 \mathrm{E}-07$ |
| $6.309 \mathrm{E}+05$ | $5.268 \mathrm{E}-12$ | $1.680 \mathrm{E}-07$ | $2.443 \mathrm{E}-12$ | $1.680 \mathrm{E}-07$ |
| $3.981 \mathrm{E}+05$ | $5.277 \mathrm{E}-12$ | $1.090 \mathrm{E}-07$ | $2.452 \mathrm{E}-12$ | $1.090 \mathrm{E}-07$ |
| $2.512 \mathrm{E}+05$ | $5.296 \mathrm{E}-12$ | $6.900 \mathrm{E}-08$ | $2.471 \mathrm{E}-12$ | $6.900 \mathrm{E}-08$ |
| $1.585 \mathrm{E}+05$ | $5.311 \mathrm{E}-12$ | $4.600 \mathrm{E}-08$ | $2.486 \mathrm{E}-12$ | $4.600 \mathrm{E}-08$ |
| $1.000 \mathrm{E}+05$ | $5.326 \mathrm{E}-12$ | $2.900 \mathrm{E}-08$ | $2.501 \mathrm{E}-12$ | $2.900 \mathrm{E}-08$ |
| $6.310 \mathrm{E}+04$ | $5.340 \mathrm{E}-12$ | $1.900 \mathrm{E}-08$ | $2.515 \mathrm{E}-12$ | $1.900 \mathrm{E}-08$ |
| $3.981 \mathrm{E}+04$ | $5.360 \mathrm{E}-12$ | $1.400 \mathrm{E}-08$ | $2.535 \mathrm{E}-12$ | $1.400 \mathrm{E}-08$ |
| $2.512 \mathrm{E}+04$ | $5.380 \mathrm{E}-12$ | $8.000 \mathrm{E}-09$ | $2.555 \mathrm{E}-12$ | $8.000 \mathrm{E}-09$ |
| $1.585 \mathrm{E}+04$ | $5.390 \mathrm{E}-12$ | $6.000 \mathrm{E}-09$ | $2.565 \mathrm{E}-12$ | $6.000 \mathrm{E}-09$ |
| $1.000 \mathrm{E}+04$ | $5.410 \mathrm{E}-12$ | $4.000 \mathrm{E}-09$ | $2.585 \mathrm{E}-12$ | $4.000 \mathrm{E}-09$ |
| $6.309 \mathrm{E}+03$ | $5.400 \mathrm{E}-12$ | $3.000 \mathrm{E}-09$ | $2.575 \mathrm{E}-12$ | $3.000 \mathrm{E}-09$ |
| $3.981 \mathrm{E}+03$ | $5.400 \mathrm{E}-12$ | $2.000 \mathrm{E}-09$ | $2.575 \mathrm{E}-12$ | $2.000 \mathrm{E}-09$ |
| $2.512 \mathrm{E}+03$ | $5.500 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ | $2.675 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ |
| $1.585 \mathrm{E}+03$ | $5.500 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ | $2.675 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ |
| $1.000 \mathrm{E}+03$ | $5.500 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ | $2.675 \mathrm{E}-12$ | $1.000 \mathrm{E}-09$ |
|  |  |  |  |  |

the measurements is negligible at all frequencies. At 1 MHz , the relative error in both the measured $C_{p}$ value and the determined dielectric constant for air is +85 percent.

Tests on other reference materials including cyclohexane, methanol, water, Teflon, Plexiglas and Stycast, show that the absolute deviations between the open/short compensated $C_{p}$ and $G_{p}$ values, and the expected $C_{p}$ and $G_{p}$ values, are nearly constant. This indicates that the systematic sample holder error can be largely reduced simply be subtracting the deviations from the expected values.

Another way to think of this compensation is via the equivalent circuit model shown in Figure A2. The admittance of the sample holder, $\boldsymbol{Y}_{h}=G_{h}+i \omega C_{h}$, is in parallel with the admittance of the sample, $\boldsymbol{Y}_{\text {sample }}=G_{\text {sample }}+i \omega C_{\text {sample }}$, because the acrylic cylinder and the sample each bridge the gap between the electrodes. The admittance of the sample is given by:

$$
\begin{equation*}
Y_{\text {sample }}=Y_{d u t}-Y_{h}=\left(G_{d u t}-G_{h}\right)+i \omega\left(C_{\text {dut }}-C_{h}\right)=G_{\text {sample }}+i \omega C_{\text {sample }}, \tag{A3}
\end{equation*}
$$

where the terms with subscript $d u t$ represent the open/short compensated values and the terms with subscript $h$ represent the deviations or residuals due to the sample holder. The desired parameters are $G_{\text {sample }}$ and $C_{\text {sample }}$ which can be directly converted to dielectric constant and conductivity values given the geometry of the sample.

The specific $G_{h}$ and $C_{h}$ values used for this compensation were determined independently for each sample holder and measurement geometry using repeated measurements of air as a reference standard. The frequency-independent values assumed for the dielectric constant and conductivity of air are 1.0006 and 0 , respectively; these values are representative of air at $23^{\circ}$ C, standard pressure ( 101.3 kPa ) and 50 percent relative humidity (Ford, 1949; ASTM, 1987).

Appendix B contains an analysis of the error that remains after the open/short and sample holder compensations have been applied. A complete listing of all the measured and compensated admittance data for each sample is included in Appendix D.


Figure A2. Circuit model for the sample holder assembly. The terminals correspond to the point in the measurement circuit where the sample holder is connected. $\boldsymbol{Y}_{d u t}$ is the admittance of the device under test which, at this point, includes both the sample holder and the sample. The individual admittances of these components are assumed to be connected in parallel since both the acrylic cylinder and the sample span the space between the electrodes. The equivalent parallel conductance and capacitance of the holder is indicated by $G_{h}$ and $C_{h}$, respectively. The admittance of the sample is indicated by $\boldsymbol{Y}_{\text {sample }}$. The sample holder compensation formula based on this circuit is given in the text.

## Appendix B

## Error Analysis

A reported parameter value is worthless if it is not accompanied by a reliable estimate of its uncertainty. The uncertainty of a measured parameter value is due to the imprecision and inaccuracy of the measurement instrument (assuming the measurement has been performed correctly). Uncertainty in a derived parameter value is due to the propagation of measurement error through conversion formulas. Imprecision can be quantified by statistical analysis of duplicate measurements. Inaccuracy, on the other hand, is much more difficult to quantify, since it depends on the availability and measurement of reliable reference standards.

It is generally believed that systematic errors constitute the main source of uncertainty in petrophysical parameter values. Standard methods of data analysis (e.g., Bevington, 1969) generally ignore the problem of systematic errors. The emphasis in the present study is on the detection, reduction and quantification of systematic errors in the electrical data; statistical analysis of uncertainty in other parameters, and rigorous testing of petrophysical models, is postponed for later research. The purpose of this appendix is to describe the efforts made to identify sources of systematic error in the electrical measurements, and to provide rough estimates of the uncertainties of the electrical parameter values reported in Chapters 4 through 6.

To assess the precision of the impedance data and the repeatability of the measurement procedure, duplicate measurements were made on a number of precision electrical components and solid disk-shaped samples of various reference materials (Teflon, Plexiglas and Stycast HiK ). Ten to twenty measurements for each sample were used to estimate the standard deviations of $C_{p}$ and $G_{p}$ across the frequency range 10 Hz to 10 MHz . The mean $C_{p}$ and $G_{p}$ values for the standards span the range of values measured for the sand-clay mixtures. Although the
standard deviations vary with frequency and admittance, they are all less than 0.1 percent of the measured value. This indicates that the measured $C_{p}$ and $G_{p}$ values are very precise and highly repeatable. Imprecision is not a major component of the uncertainty in the data.

The basic accuracy level stated in the operating manual of the HP 4192a impedance analyzer is 0.1 percent. This value assumes that all cable and sample holder residuals are negligible. To test the accuracy of the measurement system and the effectiveness of the open/short compensation, the measured $C_{p}$ and $G_{p}$ values for the electrical components were compared to the expected values for these components. Figure B1 shows the results for five precision capacitors. The manufacturing tolerance and nominal value of each capacitor is shown on the plot. All the measured values are within the tolerance range. This is evidence that the impedance analyzer is well calibrated, that the open-short compensation is effective, and that the measurements are accurate to within the tolerance level of the components (generally two percent).

A similar analysis was performed for a series of one percent resistors with expected lowfrequency resistance values ranging from 1 to 10000 ohms. Again, all the measured values are within the tolerance of the resistor manufacturing process. The mean values for the resistors, determined by averaging the resistance data for all frequencies less than 100 kHz , fall on both sides of the expected values and show no obvious systematic trends. This is evidence that the impedance analyzer is also well calibrated to measure resistance values, and that the open/short compensation is sufficient to reduce cable residuals to less than one percent of measured values.

To investigate the effectiveness of the sample holder compensation, I made two sets of measurements on a disk-shaped Plexiglas sample. In the first set of measurements, the sample was situated inside the sample holder, while in the second set of measurements, the sample was measured without the surrounding Plexiglass cylinder. If the sample holder compensation


Figure B1. Measured equivalent parallel capacitance values for a set of precision capacitors. The expected value and tolerance of the capacitors is listed to the right of the measured data.
is perfect, then the two sets of measurements should be identical except for random error and a small residual due to edge capacitance. Figure B2 shows a comparison of the two sets of measurements after application of the sample holder compensation. The $C p$ measurements differ by less than 2 percent, and the $G p$ measurements differ by less than 14 percent (with most of the deviation occuring at lower frequencies). Without the sample holder correction, the differences are 29 percent and 38 percent, respectively. This is evidence that the sample holder compensation effectively reduces most of the systematic error caused by the sample holder.

Conversion of measured $C_{p}$ and $G_{p}$ values to dielectric constant and conductivity values introduces additional error due to the uncertainty of the sample dimensions. Error in the ratio of sample thickness to area is estimated to be $\pm 0.5$ percent. Depending upon the specific $C_{p}$ or $G_{p}$ value of the sample, and the $C_{p}$ or $G_{p}$ standard deviation, the resultant error in dielectric constant or conductivity can range from 0.5 to 5 percent. Tests on standard dielectric materials including Teflon, Plexiglass, Stycast Hi-K, cyclohexane, methanol and distilled water suggest that the uncertainty in the dielectric constant values reported in Chapters 4 through 6 is: $\pm 2$ percent of the measured value $\pm 0.1$ dielectric units. Tests on four acqueous KCl solutions ranging from 0.0001 M to 0.1 M concentration suggest that the uncertainty in conductivity values is $\pm 8$ percent of the measured value $\pm 1 \times 10^{-7} \mathrm{~S} / \mathrm{m}$.

## Plexiglas Standard



Figure B2. Two measurements of the conductance and capacitance of a Plexiglas sample. The data collected without the sample holder are shown by open circles. The data collected with the sample holder, and including the sample holder compensation, are shown by the solid circles.

## Appendix C

## Dielectric constant-hydraulic conductivity crossplot

The dielectric constant-hydraulic conductivity crossplot shown in Figure 6.8 was generated by plotting the predictions of two petrophysical models against each other. The two petrophysical models are a dielectric model and a hydraulic conductivity model.

The dielectric model is a three-component version of the Time Propagation equation, i.e.,

$$
\begin{equation*}
\sqrt{\kappa}=\phi\left(1-S_{w}\right) \sqrt{\kappa_{a}}+\phi S_{w} \sqrt{\kappa_{w}}+(1-\phi) \sqrt{\kappa_{m}} \tag{C1}
\end{equation*}
$$

where the subscripts, $a, w$ and $m$, signify air, water and matrix components, respectively. All the parameter values on the right hand side of equation (C1) are assumed to be known for the modeling. The dielectric constant of air is assumed to be 1.0006 , the value for humid air at ambient temperature and pressure conditions (Ford, 1949; ASTM, 1987). The dielectric constant of water is assumed to be 83.95 , the value for distilled water at 10 degrees C (Handbook of Physics and Chemistry, 1986); this value is also assumed to be representative of groundwater conditions (low salinity, temperatures close to 10 degrees C ) at the Cape Cod site (Barlow, 1985).

The dielectric constant of the matrix $\kappa_{m}$ at 10 MHz was calculated from the following equation:

$$
\begin{equation*}
\kappa_{m}=4.6000+\left(2.4696 \times 10^{-5}\right) S_{s}+\left(1.2226 \times 10^{-10}\right) S_{s}^{2}-\left(3.6567 \times 10^{-17}\right) S_{s}^{3} \tag{C2}
\end{equation*}
$$

which was determined by fitting a third-order polynomial to the $\left(S_{s}, \kappa_{m}\right)$ data for all the dry and water-saturated sand-clay mixtures (including both sand-kaolinite and sand-montmorillonite mixtures). These data and the polynomial fit are shown in Figure C1. The $\kappa_{m}$ values for each sand-clay mixture were determined from direct application of the Time Propagation equation as described in Chapters 4 and 5. At $10 \mathrm{MHz}, \kappa_{m}$ shows little variation with porosity and water


Figure C1. Relationship between the dielectric constant of the matrix ( 10 MHz ) and the specific surface of a material. Samples include dry sand, dry kaolinite, dry montmorillonite, dry sand-montmorillonite, dry sand-kaolinite, saturated sand, saturated kaolinite and and saturated sand-kaolinite.
saturation, but significant variation with specific surface; at lower frequencies, $\kappa_{m}$ shows significant variation with each of these parameters for the various sand-clay mixtures.

Specific surface is related to effective grain diameter by the identity:

$$
\begin{equation*}
S_{s}=6 / d_{e f f} \tag{C3}
\end{equation*}
$$

The dielectric constant estimates in Figure 6.8 result from systematically varying the porosity, water saturation and $d_{e f f}$ values in equations $(\mathrm{Cl})$ through (C3).

The model that was used to produce the hydraulic conductivity $K$ data in Figure 6.8 is the Kozeny-Carmen equation:

$$
\begin{equation*}
K=\left(\frac{\rho g}{\mu}\right) \frac{d_{e f f}^{2} \phi^{3}}{180(1-\phi)^{2}} \tag{C4}
\end{equation*}
$$

This equation follows directly from substitution of equation (C3) into equation (6.4), and then scaling by $(\rho \mathrm{g} / \mu)$. At 10 degrees $\mathrm{C}, \rho=0.9997$ and $\mu=1.307 \times 10^{-2} \mathrm{~g} / \mathrm{cm}-\mathrm{s}$. Further information about this hydraulic conductivity model can be found in Bear (1972).

## Appendix D <br> Experimental Data

Following is a tabulation of the experimental data analyzed in Chapters 4 through 6. Each page represents a different sand-clay-air-water mixture. In the leftmost box is listed the mineralogy, mass of each component, clay weight fraction, porosity, permeability and water saturation of the mixture. The dimensions of the sample are also listed at the bottom of this box. The columns to the right show the electrical data as a function of frequency. The first two columns are the raw $C p$ and $G p$ data. The next two pairs of columns show the data after open/short and sample holder compensations, respectively. These are followed by columns of data showing impedance magnitude, phase and loss tangent. Finally, in the last two columns, the computed dielectric constant and electrical conductivity data are listed.







| D: | MDO246 | Freq [ Hz$]$ | CP_m [F] | Gp_m [S] |
| :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 9.752E-12 | 6.200E-06 |
|  |  | $6.310 \mathrm{E}+06$ | $9.9208-12$ | $5.000 \mathrm{E}-0$ |
| Sample: | Sand | $3.981 \mathrm{E}+06$ | 1.003E-11 | 3.300E-06 |
| Mineralogy | Qtz | $2.512 \mathrm{t}+06$ | 1.009E-11 | 2.000E-06 |
| Ms [g] | 9.5405 | $1.585 \mathrm{~S}+06$ | 1.013E-11 | 1.340E-06 |
| Mce [g] | 0.0000 | $1.000 \mathrm{E}+06$ | 1.017E-11 | 9.100E-07 |
| Mw [g] | 0.0000 | 6.310E+05 | 1.021E-11 | 6.300E-07 |
| Wcl (dy) | 0.0000 | $3.981 \mathrm{E}+05$ | 1.025E-11 | $4.300 E-07$ |
| Porosity (dry) | 0.3990 | $2.512 \mathrm{t}+05$ | 1.0308-11 | 3.200E-07 |
| Perm [cm^2] | 4.4E-06 | $1.585 \mathrm{E}+05$ | $1.0366-11$ | $2.2880-07$ |
| Sw | 0.0000 | $1.000 E+05$ | 1.042E-11 | 1.660E-07 |
|  |  | $6.310 \mathrm{E}+04$ | 1.049E-11 | 1.270E-07 |
| Geometry: |  | $3.981 \mathrm{E}+04$ | $1.057 \mathrm{E}-11$ | 9.800E-08 |
| Diameter (cm) | 4.209 | 2.512 t 04 | $1.067 \mathrm{E}-11$ | $7.600 \mathrm{E}-88$ |
| Thickness [cm] | 31 | $1.585 \mathrm{E}+04$ | 1.079E-11 | 6.000E-08 |
|  |  | $1.000 \mathrm{E}+04$ | 1.096E-11 | $4.800 \mathrm{E}-0$ |






| Experiment ID: | MD0260 | Freg [ Hz$]$ | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_osc [S] | Cp_he [F] | Gp_hc [S] | \|Z1 [ ${ }^{\text {a }}$ | 0 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | $9.922 \mathrm{E}-12$ | $6.300 \mathrm{E}-06$ | 9.693E-12 | 6.298E-06 | 7.373E-12 | $5.581 \mathrm{E}-06$ | $2.159 \mathrm{E}+03$ | 89.3098 | 1.20E-02 | 2.561 1.717E-05 |  |
|  |  | $6.310 \mathrm{E}+06$ | 1.010E-11 | $5.100 \mathrm{E}-06$ | 9.887E-12 | 5.094E-06 | 7.482E-12 | $4.194 \mathrm{E}-06$ | $3.371 \mathrm{E}+03$ | 89.1898 | $1.41 \mathrm{E}-02$ | 2.599 | $1.290 \mathrm{E}-05$ |
| Sample: | Sand | $3.981 \mathrm{E}+06$ | $1.021 \mathrm{E}-11$ | $3.400 \mathrm{E}-06$ | 1.000E-11 | $3.398 \mathrm{E}-06$ | 7.554E-12 | $2.599 \mathrm{E}-06$ | $5.292 \mathrm{E}+$ O3 | 89.2120 | $1.38 \mathrm{E}-02$ | 2.624 | $7.993 \mathrm{E}-06$ |
| Mineralogy | Qtz | $2.512 \mathrm{E}+06$ | 1.026E-11 | $2.000 \mathrm{E}-06$ | 1.006E-11 | $2.000 \mathrm{E}-06$ | 7.577E-12 | $1.420 \mathrm{E}-06$ | $8.361 \mathrm{E}+03$ | 89.3199 | $1.19 \mathrm{E}-02$ | 2.632 | $4.367 \mathrm{E}-06$ |
| Ms [g] | 9.2902 | $1.585 \mathrm{E}+06$ | $1.031 \mathrm{E}-11$ | 1.370E-06 | 1.010E-11 | $1.367 \mathrm{E}-06$ | 7.607E-12 | 9.799E-07 | $1.320 \mathrm{E}+04$ | 89.2589 | $1.29 \mathrm{E}-02$ | 2.643 | $3.014 \mathrm{E}-06$ |
| MCl [g] | 0.0000 | $1.000 \mathrm{E}+06$ | $1.035 \mathrm{E}-11$ | 9.200E-07 | 1.014E-11 | $9.180 \mathrm{E}-07$ | 7.636E-12 | $6.600 \mathrm{E}-07$ | $2.084 E+04$ | 89.2119 | 1.38E-02 | 2.653 | 2.030E-06 |
| Mw [g] | 0.0000 | $6.310 E+05$ | 1.039E-11 | $6.300 \mathrm{E}-07$ | 1.019E-11 | $6.280 \mathrm{E}-07$ | 7.665E-12 | $4.500 \mathrm{E}-07$ | 3.291E+04 | 89.1516 | $1.48 \mathrm{E}-02$ | 2.663 | $1.384 \mathrm{E}-06$ |
| Wcl (dry) | 0.0000 | $3.981 \mathrm{E}+05$ | 1.043E-11 | $4.400 \mathrm{E}-07$ | 1.023E-11 | $4.390 \mathrm{E}-07$ | $7.695 \mathrm{E}-12$ | 3.200E-07 | $5.195 \mathrm{E}+04$ | 89.0475 | $1.66 \mathrm{E}-02$ | 2.673 | 9.843E-07 |
| Porosity (dry) | 0.4119 | $2.512 \mathrm{E}+05$ | 1.048E-11 | $3.100 \mathrm{E}-07$ | 1.028E-11 | $3.090 \mathrm{E}-07$ | 7.725E-12 | $2.330 \mathrm{E}-07$ | $8.201 \mathrm{E}+04$ | 88.9052 | $1.91 \mathrm{E}-02$ | 2.684 | $7.167 \mathrm{E}-07$ |
| Perm [cm^2] |  | $1.585 E+05$ | $1.054 \mathrm{E}-11$ | 2.250E-07 | 1.033E-11 | $2.240 \mathrm{E}-07$ | 7.765E-12 | 1.720E-07 | $1.293 \mathrm{E}+05$ | 88.7257 | 2.22E-02 | 2.698 | $5.291 \mathrm{E}-07$ |
| Sw | 0.0000 | $1.000 \mathrm{E}+05$ | 1.060E-11 | 1.620E-07 | 1.039E-11 | 1.620E-07 | 7.810E-12 | 1.280E-07 | $2.037 \mathrm{E}+05$ | 88.5058 | 2.61E-02 | 2.713 | 3.937E-07 |
|  |  | $6.310 \mathrm{E}+04$ | $1.067 \mathrm{E}-11$ | $1.220 \mathrm{E}-07$ | $1.047 \mathrm{E}-11$ | $1.220 \mathrm{E}-07$ | $7.865 \mathrm{E}-12$ | $1.000 \mathrm{E}-07$ | $3.206 E+05$ | 88.1630 | $3.21 \mathrm{E}-02$ | 2.732 | $3.076 \mathrm{E}-07$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 1.075E-11 | 9.400E-08 | 1.055E-11 | $9.400 \mathrm{E}-08$ | 7.925E-12 | $7.900 \mathrm{E}-08$ | $5.041 \mathrm{E}+05$ | 87.7178 | 3.99E-02 | 2.753 | 2.430E-07 |
| Diameter [cm] | 4.209 | $2.512 \mathrm{E}+04$ | 1.084E-11 | 7.2008-08 | 1.064E-11 | $7.200 \mathrm{E}-08$ | 7.995E-12 | 6.200E-08 | 7.916E+05 | 87.1870 | $4.91 \mathrm{E}-02$ | 2.778 | $1.907 \mathrm{E}-07$ |
| Thickness [cm] | 0.428 | $1.585 \mathrm{E}+04$ | $1.097 \mathrm{E}-11$ | $5.600 \mathrm{E}-08$ | $1.077 \mathrm{E}-11$ | $5.600 \mathrm{E}-08$ | $8.115 \mathrm{E}-12$ | $4.900 \mathrm{E}-08$ | $1.235 \mathrm{E}+06$ | 86.5300 | $6.06 \mathrm{E}-02$ | 2.819 | 1.507E-07 |
|  |  | $1.000 \mathrm{E}+04$ | $1.112 \mathrm{E}-11$ | $4.500 \mathrm{E}-08$ | 1.092E-11 | $4.500 \mathrm{E}-08$ | 8.245E-12 | $4.100 \mathrm{E}-08$ | $1.924 \mathrm{E}+06$ | 85.4748 | 7.91E-02 | 2.864 | $1.261 \mathrm{E}-07$ |






| Experiment ID: | MD0314 | Freq [ Hz ] | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_ose [S] | Cp_he [F] | Gp_hc [S] | [ Z [ 0 ] | 9 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.762E-11 | $1.734 \mathrm{E}-04$ | $1.737 \mathrm{E}-11$ | 1.727E-04 | 1.507E-11 | $1.719 \mathrm{E}-04$ | 1.039E+03 | 79.7057 | 1.82E-01 | 5.294 |  |
|  |  | 6.310 E+06 | $1.853 \mathrm{E}-11$ | $1.226 \mathrm{E}-04$ | 1.831E-11 | 1.224E-04 | 1.592E-11 | 1.215E-04 | $1.556 \mathrm{E}+03$ | 79.1048 | $1.92 \mathrm{E}-01$ | 5.593 | 3.779E-04 |
| Sample: | Clay | $3.981 \mathrm{E}+06$ | $1.937 \mathrm{E}-11$ | 8.900E-05 | 1.916E-11 | $8.893 \mathrm{E}-05$ | 1.673E-11 | $8.813 \mathrm{E}-05$ | $2.339 \mathrm{E}+03$ | 78.1055 | $2.11 \mathrm{E}-01$ | 5.877 | 2.742E-04 |
| Mineralogy | Mont | $2.512 \mathrm{E}+06$ | 2.022E-11 | $6.700 \mathrm{E}-05$ | $2.001 \mathrm{E}-11$ | 6.698E-05 | 1.756E-11 | 6.642E-05 | $3.509 \mathrm{E}+03$ | 76.5231 | $2.40 \mathrm{E}-01$ | 6.169 | 2.066E-04 |
| Ms [g] | 0.0000 | 1.585E+06 | 2.115E-11 | $5.210 \mathrm{E}-05$ | 2.095E-11 | 5.209E-05 | 1.848E-11 | $5.171 \mathrm{E}-05$ | $5.232 \mathrm{E}+03$ | 74.3016 | $2.81 \mathrm{E}-01$ | 6.491 | 1.609E-04 |
| Mc1 [g] | 4.3200 | 1.000E+06 | 2.224E-11 | $4.180 \mathrm{E}-05$ | 2.204E-11 | $4.180 \mathrm{E}-05$ | $1.955 \mathrm{E}-11$ | $4.155 \mathrm{E}-05$ | $7.710 \mathrm{E}+03$ | 71.3157 | 3.38E-01 | 6.870 | 1.292E-04 |
| Mw [g] | 0.0000 | $6.310 \mathrm{E}+05$ | 2.352E-11 | 3.447E-05 | 2.332E-11 | 3.447E-05 | 2.082E-11 | 3.429E-05 | $1.119 \mathrm{E}+04$ | 67.4443 | $4.15 \mathrm{E}-01$ | 7.316 | 1.067E-04 |
| Wcl (dry) | 1.0000 | $3.981 \mathrm{E}+05$ | 2.511E-11 | 2.905E-05 | 2.491E-11 | $2.905 \mathrm{E}-05$ | 2.239E-11 | 2.893E-05 | $1.586 \mathrm{E}+04$ | 62.6856 | 5.16E-01 | 7.868 | $8.999 \mathrm{E}-05$ |
| Porosity (dry) | 0.6973 | 2.512E+05 | 2.709E-11 | $2.497 \mathrm{E}-05$ | 2.689E-11 | $2.497 \mathrm{E}-05$ | 2.436E-11 | $2.489 \mathrm{E}-05$ | $2.183 \mathrm{E}+04$ | 57.0803 | 6.47E-01 | 8.559 | 7.743E-05 |
| Perm [cm^2] |  | 1.585E+05 | 2.960E-11 | $2.183 \mathrm{E}-05$ | 2.940E-11 | $2.183 \mathrm{E}-05$ | 2.686E-11 | $2.178 \mathrm{E}-05$ | $2.899 E+04$ | 50.8433 | $8.14 \mathrm{E}-01$ | 9.435 | 6.775E-05 |
| Sw | 0.0000 | 1.000E+05 | 3.289E-11 | 1.940E-05 | 3.269E-11 | 1.940E-05 | 3.013E-11 | $1.937 \mathrm{E}-05$ | $3.693 \mathrm{E}+04$ | 44.3462 | $1.02 \mathrm{E}+00$ | 10.585 | $6.025 \mathrm{E}-05$ |
|  |  | $6.310 \mathrm{E}+04$ | $3.740 \mathrm{E}-11$ | $1.750 \mathrm{E}-05$ | 3.720E-11 | 1.750E-05 | 3.462E-11 | 1.748E-05 | 4.500E+04 | 38.1445 | $1.27 \mathrm{E}+00$ | 12.164 | 5.437E-05 |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 4.390E-11 | 1.599E-05 | 4.370E-11 | 1.599E-05 | 4.110E-11 | 1.597E-05 | $5.264 \mathrm{E}+04$ | 32.7658 | $1.55 \mathrm{E}+00$ | 14.441 | $4.969 \mathrm{E}-05$ |
| Diameter [cm] | 4.205 | 2.512E+04 | 5.460E-11 | 1.471 E-05 | 5.440E-11 | 1.471 E-05 | 5.178E-11 | $1.470 \mathrm{E}-05$ | $5.946 \mathrm{E}+04$ | 29.0731 | $1.80 \mathrm{E}+00$ | 18.193 | $4.573 \mathrm{E}-05$ |
| Thickness [ cm ] | 0.432 | $1.585 \mathrm{E}+04$ | 7.340E-11 | $1.353 \mathrm{E}-05$ | 7.320E-11 | $1.353 \mathrm{E}-05$ | 7.056E-11 | $1.352 \mathrm{E}-05$ | $6.562 \mathrm{E}+04$ | 27.4575 | $1.92 \mathrm{E}+00$ | 24.791 | $4.207 \mathrm{E}-05$ |
|  |  | $1.000 E+04$ | 1.081E-10 | $1.225 \mathrm{E}-05$ | 1.079E-10 | 1.225E-05 | 1.052E-10 | $1.225 \mathrm{E}-05$ | $7.186 \mathrm{E}+04$ | 28.3704 | $1.85 \mathrm{E}+00$ | 36.975 | 3.809E-05 |



| Experiment ID: | MD0320 | Freg [ Hz$]$ | Cp_m [F] | Gp_m [S] | Cp_ose [F] | Gp_osc [S] | Cp_hc [F] | Gp_he [S] | 121 [ 2 ] | 0 [deg] | Loss Tan | DleiConstant | Cond [S/m] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 4.009E-11 | 1.259E-03 | $3.973 \mathrm{E}-11$ | 1.247E-03 | $3.743 \mathrm{E}-11$ | $1.246 \mathrm{E}-03$ | 3.757E+02 | 62.0840 | $5.30 \mathrm{E}-01$ | 13.151 | $3.876 \mathrm{E}-03$ |
|  |  | $6.310 \mathrm{E}+06$ | 4.520E-11 | $9.860 \mathrm{E}-04$ | 4.493E-11 | $9.818 \mathrm{E}-04$ | 4.254E-11 | $9.809 \mathrm{E}-04$ | $5.126 \mathrm{E}+02$ | 59.8168 | 5.82E-01 | 14.945 | $3.051 \mathrm{E}-03$ |
| Sample: | Clay | $3.981 \mathrm{E}+06$ | 5.070E-11 | $7.880 \mathrm{E}-04$ | S.047E-11 | 7.865E-04 | 4.804E-11 | 7.857E-04 | $6.966 \mathrm{E}+02$ | 56.8193 | $6.54 \mathrm{E}-01$ | 16.876 | $2.444 \mathrm{E}-03$ |
| Mineralogy | Mont | $2.512 \mathrm{E}+06$ | 5.684E-11 | $6.457 \mathrm{E}-04$ | 5.663E-11 | $6.451 \mathrm{E}-04$ | 5.417E-11 | $6.446 \mathrm{E}-04$ | 9.339E+02 | 52.9864 | 7.54E-01 | 19.032 | 2.005E-03 |
| Ms [g] | 0.0000 | 1.58SE+06 | $6.406 \mathrm{E}-11$ | $5.414 \mathrm{E}-04$ | $6.385 \mathrm{E}-11$ | 5.412E-04 | 6.139E-11 | 5.408E-04 | $1.225 E+03$ | 48.5002 | 8.85E-01 | 21.566 | 1.682E-03 |
| Mcl [g] | 6.4798 | $1.000 \mathrm{E}+06$ | $7.266 \mathrm{E}-11$ | 4.652E-04 | 7.246E-11 | $4.651 \mathrm{E}-04$ | 6.997E-11 | $4.649 \mathrm{E}-04$ | $1.563 \mathrm{E}+03$ | 43.4037 | $1.06 \mathrm{E}+00$ | 24.584 | $1.446 \mathrm{E}-03$ |
| Mw [g] | 0.0000 | $6.310 \mathrm{E}+05$ | $8.310 \mathrm{E}-11$ | $4.087 \mathrm{E}-04$ | 8.290E-11 | $4.087 \mathrm{E}-04$ | $8.041 \mathrm{E}-11$ | $4.085 \mathrm{E}-04$ | $1.930 \mathrm{E}+03$ | 37.9667 | $1.28 \mathrm{E}+00$ | 28.249 | $1.271 \mathrm{E}-03$ |
| Wct (dry) | 1.0000 | $3.981 \mathrm{E}+05$ | 9.610E-11 | $3.662 \mathrm{E}-04$ | 9.590E-11 | $3.662 \mathrm{E}-04$ | 9.339E-11 | $3.661 \mathrm{E}-04$ | $2.303 \mathrm{E}+03$ | 32.5428 | $1.57 \mathrm{E}+00$ | 32.809 | $1.139 \mathrm{E}-03$ |
| Porosity (dry) | 0.5475 | 2.512E+05 | 1.125E-10 | $3.336 \mathrm{E}-04$ | $1.123 \mathrm{E}-10$ | $3.336 \mathrm{E}-04$ | 1.098E-10 | 3.335E-04 | $2.661 \mathrm{E}+03$ | 27.4507 | $1.93 \mathrm{E}+00$ | 38.567 | $1.037 \mathrm{E}-03$ |
| Perm [cm^2] | 0.0000 | $1.585 \mathrm{E}+05$ | 1.340E-10 | 3.084E-04 | $1.338 \mathrm{E}-10$ | $3.084 \mathrm{E}-04$ | 1.313E-10 | 3.083E-04 | $2.986 \mathrm{E}+03$ | 22.9727 | $2.36 \mathrm{E}+00$ | 46.115 | 9.592E-04 |
| Sw |  | $1.000 \mathrm{E}+05$ | 1.633E-10 | $2.883 \mathrm{E}-04$ | $1.631 \mathrm{E}-10$ | 2.883E-04 | 1.605E-10 | $2.883 \mathrm{E}-04$ | $3.274 \mathrm{E}+03$ | 19.2860 | 2.86E+00 | 56.402 | $8.967 \mathrm{E}-04$ |
|  |  | $6.310 \mathrm{E}+04$ | 2.050E-10 | $2.719 \mathrm{E}-04$ | $2.048 \mathrm{E}-10$ | $2.719 \mathrm{E}-04$ | 2.022E-10 | 2.719E-04 | $3.528 E+03$ | 16.4297 | $3.39 E+00$ | 71.048 | 8.457E-04 |
| Geometry: |  | $3.981 E+04$ | 2.680E-10 | $2.579 \mathrm{E}-04$ | $2.678 \mathrm{E}-10$ | 2.579E-04 | 2.652E-10 | 2.579E-04 | $3.755 \mathrm{E}_{+03}$ | 14.4261 | $3.89 E+00$ | 93.175 | 8.022E-04 |
| Diameter [cm] | 4.205 | $2.512 \mathrm{E}+04$ | 3.690E-10 | $2.456 \mathrm{E}-04$ | 3.688E-10 | $2.456 \mathrm{E}-04$ | 3.662E-10 | $2.456 \mathrm{E}-04$ | $3.964 E+03$ | 13.2426 | $4.25 E+00$ | 128.655 | $7.640 \mathrm{E}-04$ |
| Thickness [ cm ] | 0.432 | $1.585 \mathrm{E}+04$ | 5.390E-10 | $2.339 \mathrm{E}-04$ | 5.388E-10 | $2.339 E-04$ | 5.362E-10 | $2.339 \mathrm{E}-04$ | $4.168 \mathrm{E}+03$ | 12.8593 | $4.38 \mathrm{E}+00$ | 188.376 | $7.276 \mathrm{E}-04$ |
|  |  | $1.000 \mathrm{E}+04$ | 8.330E-10 | 2.222E-04 | 8.328E-10 | 2.222E-04 | 8.302E-10 | 2.222E-04 | $4.381 E+03$ | 13.2109 | $4.26 \mathrm{E}+00$ | 291.655 | $6.912 \mathrm{E}-04$ |






| Experiment ID: | MD0330 | Freq [ Hz ] | $\mathrm{Cp}_{\text {_m }}[\mathrm{F}]$ | Gp_m [S] | CP_Osc [F]. | Gp_osc [S] | CP_hc [F] | Gp_hc [S] | \|z1 [ $\Omega$ ] | 0 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.302E-10 | 5.247E-03 | 1.288E-10 | 5.084E-03 | $1.265 \mathrm{E}-10$ | 5.083E-03 | $1.060 \mathrm{E}+02$ | 57.3892 | 6.40E-01 | 44.428 1.581E-02 |  |
|  |  | $6.310 \mathrm{E}+06$ | 1.528E-10 | 3.859E-03 | 1.519E-10 | 3.803E-03 | 1.496E-10 | 3.802E-03 | $1.420 E+02$ | 57.3280 | $6.41 \mathrm{E}-01$ | 52.543 | $1.183 \mathrm{E}-02$ |
| Sample: | Clay | $3.981 \mathrm{E}+0$ | 1.777E-10 | 2.890E-03 | 1.772E-10 | 2.871 E-03 | 47E | $2.870 \mathrm{E}-03$ | $1.913 \mathrm{E}+$ | 56.7097 | $6.57 \mathrm{E}-01$ | 1.38 | .928E-03 |
| Mineralogy | Mont | $2.512 \mathrm{E}+0$ | 2.057E-10 | 2.205E-03 | 2.053E-10 | $2.198 \mathrm{E}-03$ | 2.029E- | $2.198 \mathrm{E}-03$ | $2.575 \mathrm{E}+02$ | 55.5366 | $6.86 \mathrm{E}-01$ | 71.277 | 6.836E-03 |
| Ms [g] | 0.0000 | 1.5 | 2.374E-10 | $1.717 \mathrm{E}-03$ | 2.371 E-10 | 715E-03 | 2.347 E | $1.714 \mathrm{E}-03$ | 3.451 E | 53.7368 | $7.34 \mathrm{E}-01$ | 82.44 | 5.332E-03 |
| Mcl [g] | 10.8 | 1.000 | 2.734 | 1.369E-03 | 2.732E-10 | 368E-03 | $2.707 \mathrm{E}-10$ | $1.368 \mathrm{E}-03$ | 4.582E+ | 51.1916 | 8.04E-01 | 95.09 | $4.255 \mathrm{E}-03$ |
| Mw [g] | 0.000 | 310 E | 140E-10 | 120E-03 | 138E-10 | 120E-03 | $113 \mathrm{E}-$ | 19E-0 | $6.002 \mathrm{E}+$ | 47.7883 | $9.07 \mathrm{E}-01$ | 109.36 | 3.482E-03 |
| WCl (dry) | 1.0000 | $3.981 \mathrm{E}+0$ | $3.610 \mathrm{E}-10$ | 430E-04 | 3.608E-1 | $9.429 \mathrm{E}-04$ | 583E-10 | 427E-0 | 7.688 E | 43.550 | 1.05E+00 | 125.8 | 2.933E-03 |
| Porosity (dry) | 0.2434 | $2.512 \mathrm{E}+05$ | $4.156 \mathrm{E}-10$ | 8.177E-0 | $4.154 \mathrm{E}-10$ | $8.176 \mathrm{E}-04$ | $4.129 \mathrm{E}-1$ | 176E-0 | 9.565 E | 38.5561 | $1.25 E+0$ | 145.05 | .543E-03 |
| Perm [cm^2] |  | 1.585E+05 | $4.833 \mathrm{E}-10$ | $7.264 \mathrm{E}-04$ | $4.831 \mathrm{E}-10$ | $7.264 \mathrm{E}-04$ | $4.806 \mathrm{E}-1$ | $7.263 \mathrm{E}-0$ | $1.150 \mathrm{E}+$ | 33.3806 | $1.52 \mathrm{E}+0$ | 168.83 | 2.259E-03 |
| Sw |  | 1.000E+05 | $5.714 \mathrm{E}-10$ | $6.586 \mathrm{E}-04$ | 5.712E-10 | $6.586 \mathrm{E}-04$ | 5.686E-1 | 6.586E-0 | 1.335E+ | 28.4815 | $1.84 \mathrm{E}+00$ | 199.78 | 2.049E-03 |
|  |  | $6.310 \mathrm{E}+0$ | 6.920E-10 | $6.054 \mathrm{E}-0$ | 6.918E-10 | $6.054 \mathrm{E}-04$ | 6.892E-1 | $6.054 \mathrm{E}-0$ | $1.506 \mathrm{E}+$ | 24.2925 | $2.22 \mathrm{E}+00$ | 242.14 | 1.883E-03 |
| Geometry: |  | $3.981 \mathrm{E}+0$ | 8.650E-10 | $5.619 \mathrm{E}-04$ | 8.648E-10 | $5.619 \mathrm{E}-04$ | 8.622E-10 | $5.619 \mathrm{E}-0$ | $1.662 \mathrm{E}+03$ | 20.9991 | $2.61 \mathrm{E}+00$ | 302.926 | $1.748 \mathrm{E}-03$ |
| Diameter [cm] | 4.205 | $2.512 \mathrm{E}+04$ | 1.122E-09 | $5.231 \mathrm{E}-04$ | 1.122E-09 | $5.231 \mathrm{E}-04$ | 1.119E-09 | $5.231 \mathrm{E}-04$ | $1.811 \mathrm{E}+03$ | 18.6596 | $2.96 \mathrm{E}+00$ | 393.219 | 1.627E-03 |
| Thickness [cm] | 0.432 | 1.585E+04 | 1.513E-09 | 4.898E-04 | 1.513E-09 | $4.898 \mathrm{E}-04$ | 1.510E-09 | 4.898 | $1.952 \mathrm{E}+03$ | 17.0694 | 3.26E+00 | 530.596 | 1.524E-03 |
|  |  | $1.000 E+04$ | 2.122E-0 | 4.591 E | 2.122E-09 | 4.591E-04 | 2.119E-09 | $4.591 \mathrm{E}-0$ | $2.092 E+03$ | 16.1738 | 3.45E+ | 744.52 | 1.428 E |



| Experiment ID: | MD0334 | Freq [ Hz ] | Cp_m [F] | Gp_m[S] | Cp_osc [F] | Gp_ose [S] | Cp_he [F] | Gp_hc [S] | IZ1 [ $\Omega$ ] | 6 [deg] | Loss Tan | DlelConstant | Cond [S/m] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 1.370E-11 | $5.310 \mathrm{E}-05$ | 1.346E-11 | 5.293E-05 | $1.116 \mathrm{E}-11$ | $5.221 \mathrm{E}-05$ | $1.423 \mathrm{E}+03$ | 85.7402 | 7.45E-02 | 3.920 | 1.624E-04 |
|  |  | $6.310 \mathrm{E}+06$ | $1.411 \mathrm{E}-11$ | $3.810 \mathrm{E}-05$ | $1.389 \mathrm{E}-11$ | $3.805 \mathrm{E}-05$ | 1.151E-11 | $3.715 \mathrm{E}-05$ | $2.185 \mathrm{E}+03$ | 85.3443 | $8.14 \mathrm{E}-02$ | 4.042 | $1.156 \mathrm{E}-04$ |
| Sample: | Sand\&Clay | 3.981E+06 | $1.446 \mathrm{E}-11$ | $2.700 \mathrm{E}-05$ | $1.425 \mathrm{E}-11$ | $2.698 \mathrm{E}-05$ | 1.182E-11 | 2.618E-05 | $3.369 E+03$ | 84.9392 | 8.86E-02 | 4.153 | $8.145 \mathrm{E}-05$ |
| Mineralogy | Qtz\&Mont | $2.512 \mathrm{E}+06$ | $1.476 \mathrm{E}-11$ | $1.930 \mathrm{E}-05$ | $1.456 \mathrm{E}-11$ | $1.930 \mathrm{E}-05$ | 1.210E-11 | 1.874E-05 | $5.211 \mathrm{E}+03$ | 84.3975 | 9.81E-02 | 4.252 | 5.828E-05 |
| Ms [g] | 9.5388 | $1.585 \mathrm{E}+06$ | 1.507E-11 | $1.450 \mathrm{E}-05$ | $1.487 \mathrm{E}-11$ | $1.450 \mathrm{E}-05$ | 1.240E-11 | $1.412 \mathrm{E}-05$ | 8.048E+03 | 83.4759 | $1.14 \mathrm{E}-01$ | 4.356 | 4.392E-05 |
| Mcl [g] | 1.1438 | $1.000 \mathrm{E}+06$ | 1.543E-11 | $1.104 \mathrm{E}-05$ | 1.523E-11 | $1.104 \mathrm{E}-05$ | 1.275E-11 | 1.079E-05 | $1.237 \mathrm{E}+04$ | 82.3280 | $1.35 \mathrm{E}-01$ | 4.479 | $3.356 \mathrm{E}-05$ |
| Mw [g] | 0.0000 | $6.310 E+05$ | 1.587E-11 | 8.560E-06 | 1.567E-11 | 8.558E-06 | $1.317 \mathrm{E}-11$ | 8.380E-06 | $1.891 \mathrm{E}+04$ | 80.8845 | 1.60E-01 | 4.628 | $2.607 \mathrm{E}-05$ |
| WCl (dry) | 0.1071 | $3.981 \mathrm{E}+05$ | $1.639 \mathrm{E}-11$ | $6.750 \mathrm{E}-06$ | $1.619 \mathrm{E}-11$ | $6.749 \mathrm{E}-06$ | $1.367 \mathrm{E}-11$ | $6.630 \mathrm{E}-06$ | $2.870 \mathrm{E}+04$ | 79.0300 | $1.94 \mathrm{E}-01$ | 4.804 | $2.062 \mathrm{E}-05$ |
| Porosity (dry) | 0.3208 | $2.512 \mathrm{E}+05$ | $1.703 \mathrm{E}-11$ | 5.390E-06 | $1.683 \mathrm{E}-11$ | 5.389E-06 | $1.430 \mathrm{E}-11$ | $5.313 \mathrm{E}-06$ | $4.312 \mathrm{E}+04$ | 76.7550 | 2.35E-01 | 5.025 | $1.653 \mathrm{E}-05$ |
| Perm [cm^2] |  | $1.585 \mathrm{E}+05$ | 1.782E-11 | $4.350 \mathrm{E}-06$ | $1.762 \mathrm{E}-11$ | $4.349 \mathrm{E}-06$ | 1.508E-11 | $4.298 \mathrm{E}-06$ | $6.404 E+04$ | 74.0243 | $2.86 \mathrm{E}-01$ | 5.297 | 1.337E-05 |
| Sw | 0.0000 | $1.000 \mathrm{E}+05$ | 1.880E-11 | 3.549E-06 | 1.860E-11 | 3.549E-06 | $1.604 \mathrm{E}-11$ | $3.516 \mathrm{E}-06$ | 9.370E+04 | 70.7654 | 3.49E-01 | 5.635 | $1.094 \mathrm{E}-05$ |
|  |  | $6.310 \mathrm{E}+04$ | 2.004E-11 | 2.923E-06 | $1.984 \mathrm{E}-11$ | $2.923 \mathrm{E}-06$ | $1.726 \mathrm{E}-11$ | $2.901 \mathrm{E}-06$ | $1.345 E+05$ | 67.0297 | 4.24E-01 | 6.065 | $9.024 \mathrm{E}-06$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | $2.158 \mathrm{E}-11$ | $2.434 \mathrm{E}-06$ | $2.138 \mathrm{E}-11$ | $2.434 \mathrm{E}-06$ | $1.878 \mathrm{E}-11$ | $2.419 \mathrm{E}-06$ | 1.892E+05 | 62.7590 | $5.15 \mathrm{E}-\mathrm{O} 1$ | 6.599 | 7.525E-06 |
| Diameter [cm] | 4.205 | $2.512 \mathrm{E}+04$ | $2.356 \mathrm{E}-11$ | 2.046E-06 | $2.336 \mathrm{E}-11$ | $2.046 \mathrm{E}-06$ | 2.074E-11 | $2.036 \mathrm{E}-06$ | $2.594 E+05$ | 58.1234 | $6.22 \mathrm{E}-01$ | 7.288 | $6.333 \mathrm{E}-06$ |
| Thickness [cm] | 0.432 | 1.585E+04 | 2.605E-11 | 1.739E-06 | 2.585E-11 | $1.739 \mathrm{E}-06$ | $2.321 \mathrm{E}-11$ | 1.732E-06 | $3.462 \mathrm{E}+05$ | 53.1581 | $7.49 \mathrm{E}-01$ | 8.156 | $5.388 \mathrm{E}-06$ |
|  |  | $1.000 \mathrm{E}+04$ | 2.924E-11 | 1.493E-06 | 2.904E-11 | $1.493 \mathrm{E}-06$ | $2.638 \mathrm{E}-11$ | $1.488 \mathrm{E}-06$ | $4.489 \mathrm{E}+05$ | 48.0889 | 8.98E-01 | 9.269 | 4.629E-06 |























| Experiment ID: | MD0506 | Freq [ Hz ] | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_osc [S] | Cp_hc [F] | Gp_he [S] | \|21 [ 0 ] | 6 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 4.887E-11 | $9.900 \mathrm{E}-04$ | $4.840 \mathrm{E}-11$ | $9.783 \mathrm{E}-04$ | $4.598 \mathrm{E}-11$ | $9.775 \mathrm{E}-04$ | 3.279E+02 | 71.3062 | 3.38E-01 | $18.1943 .425 \mathrm{E}-03$ |  |
|  |  | $6.310 \mathrm{E}+$ | . 010 | 580E-04 | $4.980 \mathrm{E}-1$ | 9.534E-04 | $4.730 \mathrm{E}-1$ | $9.525 E-04$ | 4.755E+02 | 63.0709 | $5.08 \mathrm{E}-01$ | 8.716 | -03 |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+0$ | $5.120 \mathrm{E}-11$ | 280E-04 | 5.097E-11 | $9.262 \mathrm{E}-04$ | $4.844 \mathrm{E}-1$ | $9.255 \mathrm{E}-04$ | $6.559 \mathrm{E}+$ | 52.6243 | 7.64E-01 | 9.16 | .242E-03 |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 5.240E-11 | $9.040 \mathrm{E}-04$ | 5.220E-11 | 9.033E-04 | 4.964E-11 | $9.028 \mathrm{E}-0$ | $8.366 \mathrm{E}+{ }^{\text {2 }}$ | 40.9501 | $1.15 \mathrm{E}+00$ | 9.64 | .163E-03 |
| Ms [g] | 10.7644 | 1.585E+06 | 5.355E-11 | $8.877 \mathrm{E}-04$ | 5.336E-11 | 8.874E-04 | $5.078 \mathrm{E}-1$ | $8.871 \mathrm{E}-04$ | $9.793 \mathrm{E}+0$ | 29.6865 | $1.75 \mathrm{E}+00$ | 20.09 | 3.108E-03 |
| Mcl [g] | 0.7088 | $1.000 E_{+06}$ | 5.505E-11 | 8.747E-04 | 5.487E-11 | 8.746E-04 | 5.227E-11 | $8.744 \mathrm{E}-04$ | $1.071 \mathrm{E}+03$ | 20.5886 | $2.66 \mathrm{E}+00$ | 20.68 | 3.063E-03 |
| Mw [g] | 2.0393 | $6.310 \mathrm{E}+05$ | 5.690E-11 | $8.653 \mathrm{E}-04$ | 5.672E-11 | 653 | 5.411 E | 8.651 E | 1.122 E | 13.9266 | 4.03 L | 1.4 | . 03 |
| WCl (dry) | 0.0618 | $3.981 \mathrm{E}+0$ | 5.950E-11 | $8.581 \mathrm{E}-04$ | 932 | 8.581E-04 | .670E | $8.580 \mathrm{E}-$ | 1.150 E | 9.3866 | $6.05 E$ | 22.436 | 3.006E-03 |
| Porosity (dry) | 0.3568 | $2.512 \mathrm{E}+05$ | 6.320E-11 | 1 E - | .302E- | 1E-4 | 6.039 E | 8.520 E - | 1.166 E | 6.38 | 8.94 E | 23.895 | 985E-03 |
| Perm [cm^2] | 7.5E-09 | 1.58 | $6.860 \mathrm{E}-1$ | $8.470 \mathrm{E}-0$ | 6.843E-1 | $8.470 \mathrm{E}-0$ | $6.579 \mathrm{E}-1$ | $8.470 \mathrm{E}-\mathrm{O}$ | 1.177E+03 | 4.423 | $1.29 \mathrm{E}+0$ | 6.03 | 2.967E-03 |
| Sw | 0.8461 | 1.000E+05 | $7.710 \mathrm{E}-11$ | $8.424 \mathrm{E}-04$ | 7.692E-11 | $8.424 \mathrm{E}-04$ | $7.426 \mathrm{E}-1$ | $8.424 \mathrm{E}-0$ | $\begin{gathered} 1.185 E+03 \\ 1.192 E+03 \end{gathered}$ | 3.1703 | $1.81 \mathrm{E}+01$ | 29.38 | 2.951 E-03 |
|  |  | $310 \mathrm{E}+0$ | $9.000 \mathrm{E}-1$ | $8.382 \mathrm{E}-0$ | $8.982 \mathrm{E}-1$ | 8.382 | 8.714 E | $8.382 \mathrm{E}-0$ |  | 2.360 | $2.43 \mathrm{E}+0$ | 4.48 | 2.93 |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 1.100E-10 | 34 | $1.098 \mathrm{E}-1$ | 8.341 | 1.072E-10 | 8.341E-04 | $\begin{aligned} & 1.198 E+03 \\ & 1.204 E+03 \end{aligned}$ | 1.8406 | $3.11 \mathrm{E}+01$ | 2.400 | .922E-03 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 420E-10 | $8.300 \mathrm{E}-04$ | 1.419E-10 | $8.300 \mathrm{E}-04$ | 1.392E-10 | $8.300 \mathrm{E}-04$ |  | 1.5161 | 3.78E+01 | 55.075 | 2.908E-03 |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 1.940E-10 | 8.259 | 1.940E-10 | $8.259 \mathrm{E}-04$ | 1.912E-10 | $8.259 \mathrm{E}-$ | $1.210 \mathrm{E}+03$ | 1.3210 | $4.34 \mathrm{E}+01$ | 75.673 | 2.894E-03 |
|  |  | $1.000 \mathrm{E}+04$ | 2.790E-10 | 8.219E-0 | 2.789E-10 | 8.219E-04 | 2.761E-10 | 8.219E-04 | $1.216 \mathrm{E}+03$ | 1.2093 | $4.74 \mathrm{E}+01$ | 109.26 | 2.879E |


| Experiment ID: | MD0507 | Freq[ Hz$]$ | Cp_m [F] | Gp_m [S] | Cp_ose [F] | Gp_osc [S] | Cp_he [F] | Gp_he [S] | [2] [0] | 0 [deg] | Loss Tan | 18.037 3.397E-03 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 4.847E-11 | $9.820 \mathrm{E}-04$ | $4.800 \mathrm{E}-11$ | 9.705E-04 | 4.558E-11 | 9.697E-04 | $3.307 \mathrm{E}+02$ | 71.2953 | 3.39E-01 |  |  |
|  |  | $6.310 \mathrm{E}+06$ | 4.970E-11 | $9.510 \mathrm{E}-04$ | 4.940E-11 | $9.465 E-04$ | 4.690E-11 | $9.456 \mathrm{E}-04$ | 4.794E+02 | 63.0441 | 5.09E-01 | 18.558 | $3.313 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | $5.080 \mathrm{E}-11$ | 9.220E-04 | 5.057E-11 | 9.202E-04 | 4.804E-11 | 9.195E-04 | $6.609 \mathrm{E}+02$ | 52.5743 | 7.65E-01 | 19.007 | $3.222 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | 2.512E+06 | $5.200 \mathrm{E}-11$ | $8.980 \mathrm{E}-04$ | $5.180 \mathrm{E}-11$ | $8.973 \mathrm{E}-04$ | 4.924E-11 | $8.968 \mathrm{E}-04$ | $8.427 \mathrm{E}+02$ | 40.9094 | $1.15 \mathrm{E}+00$ | 19.482 | 3.142E-03 |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 5.316E-11 | 8.812E-04 | 5.297E-11 | 8.809E-04 | 5.039E-11 | 8.806E-04 | $9.867 \mathrm{E}+02$ | 29.6776 | $1.75 \mathrm{E}+00$ | 19.939 | $3.085 \mathrm{E}-03$ |
| Mcl [g] | 0.7088 | $1.000 \mathrm{E}+06$ | 5.465E-11 | 8.683E-04 | 5.447E-11 | 8.682E-04 | 5.187E-11 | $8.680 \mathrm{E}-04$ | $1.079 \mathrm{E}+03$ | 20.5822 | $2.66 \mathrm{E}+00$ | 20.526 | $3.041 \mathrm{E}-03$ |
| Mw [g] | 2.0263 | $6.310 \mathrm{E}+05$ | 5.650E-11 | 8.587E-04 | 5.632E-11 | 8.587E-04 | 5.371E-11 | 8.585E-04 | $1.131 \mathrm{E}+03$ | 13.9297 | 4.03E+00 | 21.252 | $3.008 \mathrm{E}-03$ |
| Wcl (dry) | 0.0618 | $3.981 \mathrm{E}+05$ | 5.910E-11 | $8.515 \mathrm{E}-04$ | 5.892E-11 | 8.515E-04 | 5.630E-11 | 8.514E-04 | $1.159 \mathrm{E}+03$ | 9.3925 | 6.05E+00 | 22.277 | $2.983 \mathrm{E}-03$ |
| Porosity (dry) | 0.3568 | 2.512E+05 | 6.280E-11 | $8.456 \mathrm{E}-04$ | 6.262E-11 | 8.456E-04 | 5.999E-11 | 8.455E-04 | 1.175E+03 | 6.3891 | 8.93E+00 | 23.736 | $2.962 \mathrm{E}-03$ |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | 6.820E-11 | 8.405E-04 | $6.803 \mathrm{E}-11$ | $8.405 \mathrm{E}-04$ | 6.539E-11 | $8.405 \mathrm{E}-04$ | $1.186 \mathrm{E}+03$ | 4.4301 | $1.29 E+01$ | 25.873 | 2.944E-03 |
| Sw | 0.8407 | $1.000 \mathrm{E}+05$ | 7.660E-11 | $8.359 \mathrm{E}-04$ | 7.642E-11 | $8.359 \mathrm{E}-04$ | 7.376E-11 | 8.359E-04 | $1.195 E+03$ | 3.1734 | 1.80E+01 | 29.184 | $2.928 \mathrm{E}-03$ |
|  |  | $6.310 \mathrm{E}+04$ | $9.000 \mathrm{E}-11$ | $8.317 \mathrm{E}-04$ | 8.982E-11 | $8.317 \mathrm{E}-04$ | 8.714E-11 | $8.317 \mathrm{E}-04$ | $1.201 \mathrm{E}+03$ | 2.3786 | $2.41 \mathrm{E}+01$ | 34.480 | $2.914 \mathrm{E}-03$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | $1.100 \mathrm{E}-10$ | 8.275E-04 | 1.098E-10 | $8.275 \mathrm{E}-04$ | 1.072E-10 | 8.275E-04 | $1.208 \mathrm{E}+03$ | 1.8553 | $3.09 \mathrm{E}+01$ | 42.400 | $2.899 \mathrm{E}-03$ |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 1.420E-10 | 8.234E-04 | $1.419 \mathrm{E}-10$ | 8.234E-04 | 1.392E-10 | $8.234 \mathrm{E}-04$ | $1.214 \mathrm{E}+03$ | 1.5282 | 3.75E+01 | 55.075 | $2.885 \mathrm{E}-03$ |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 1.930E-10 | 8.194E-04 | 1.930E-10 | $8.194 \mathrm{E}-04$ | 1.902E-10 | $8.194 \mathrm{E}-04$ | $1.220 \mathrm{E}+03$ | 1.3245 | $4.33 \mathrm{E}+01$ | 75.276 | 2.871 E-03 |
|  |  | $1.000 \mathrm{E}+04$ | 2.750E-10 | 8.154E-04 | 2.749E-10 | 8.154E-04 | 2.721E-10 | $8.154 \mathrm{E}-04$ | $1.226 \mathrm{E}+03$ | 1.2013 | $4.77 E+01$ | 107.677 | 2.857E-03 |


| Experiment ID: | MDO508 | Freq [ $\mathrm{Hz}^{\text {] }}$ | $\mathrm{CP}_{\text {P }} \mathrm{m}[\mathrm{F}]$ | Gp_m [S] | Cp_ose [ [f] | Gp_ose [S] | CP_hc [F] | Gp_hc [S] | [Z] [ 0 ] | 6.10 deg ] | Loss Tan | DielConstant | Cond [ $5 / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | $4.776 \mathrm{E}-11$ | 9.430E-04 | 4.730E-11 | $9.321 \mathrm{E}-04$ | 4.488E-11 | $9.314 \mathrm{E}-04$ | 3.367E+02 | 71.7230 | $3.30 \mathrm{E}-01$ | 17.758 |  |
|  |  | $6.310 \mathrm{E}+0$ | $4.900 \mathrm{E}-1$ | $9.110 \mathrm{E}-04$ | $4.870 \mathrm{E}-$ | $9.067 \mathrm{E}-04$ | $4.620 \mathrm{E}-1$ | 9.058E-04 | 4.894E+02 | 63.6854 | $4.95 \mathrm{E}-01$ | 18.281 | 3.174E-03 |
| ple: | Sand-Clay | $3.981 \mathrm{E}+0$ | 5.010E-11 | 8.820E-04 | $4.987 \mathrm{E}-1$ | $8.803 \mathrm{E}-04$ | $4.734 \mathrm{E}-1$ | $8.796 \mathrm{E}-0$ | 6.779E+ | 53.3913 | $7.43 \mathrm{E}-01$ | 18.73 | .082E-03 |
| Mineralogy | Qtz-Kao | $2.512 \mathrm{E}+0$ | 5.130E-11 | $8.590 \mathrm{E}-04$ | 5.110E-11 | $8.583 \mathrm{E}-04$ | 4.853E-11 | $8.578 \mathrm{E}-0$ | $8.695 \mathrm{E}+0$ | 41.7637 | $1.12 \mathrm{E}+00$ | 19.20 | .005E-03 |
| Ms [9] | 10.7644 | $1.585 \mathrm{E}+06$ | $5.241 \mathrm{E}-11$ | 8.422E-04 | 5.222E-11 | 8.419E-04 | 4.964E-11 | $8.416 \mathrm{E}-04$ | $1.025 \mathrm{E}+03$ | 30.4288 | 1.70E+00 | 19.64 | $2.948 \mathrm{E}-03$ |
| Mci (g] | 0.7088 | $1.000 E+06$ | 5.389E-11 | 8.293E-04 | 5.371E-11 | 8.292E-04 | 5.111E-11 | 8.290E-04 | $1.125 E+03$ | 21.1768 | $2.58 \mathrm{E}+00$ | 20.224 | $2.904 \mathrm{E}-03$ |
| Mw (g) | 2.0014 | $6.310 \mathrm{E}+05$ | 5.580E-11 | $8.199 \mathrm{E}-04$ | 5.562E-11 | $8.199 \mathrm{E}-04$ | 5.301E-11 | $8.197 E-04$ | $1.182 \mathrm{E}+03$ | 14.3792 | $3.90 \mathrm{E}+00$ | 20.974 | 2.872E-03 |
| WCl (aty) | 0.0618 | $3.981 \mathrm{E}+05$ | 5.820E-11 | $8.128 \mathrm{E}-04$ | 5.802E-11 | 8.128E-04 | $5.540 \mathrm{E}-1$ | $8.127 \mathrm{E}-04$ | $1.213 \mathrm{E}+$ | 9.6767 | $5.86 \mathrm{E}+00$ | 21.920 | 2.847E-03 |
| Porosity (dy) | 0.3568 | $2.512 \mathrm{E}+05$ | 6.180E-11 | 071E-04 | 6.162E-11 | $8.071 \mathrm{E}-04$ | 5.899E-11 | $8.070 \mathrm{E}-04$ | 1.231 E | 6.5804 | $8.67 \mathrm{E}+$ | 3.3 | .827E-03 |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | 6.710E-11 | 8.021 E-04 | 6.693E-11 | $8.021 \mathrm{E}-04$ | 6.428E-11 | $8.021 \mathrm{E}-0$ | 1.243 E | 4.5634 | $1.25 E+01$ | 25.4 | 2.810E-03 |
| Sw | 0.830 | $1.000 \mathrm{E}+0$ | 7.520E-11 | $7.976 \mathrm{E}-04$ | 7.502E-11 | $7.976 \mathrm{E}-\mathrm{O}$ | 7.236E-11 | $7.976 \mathrm{E}-04$ | $1.252 \mathrm{E}+$ | 3.2624 | 1.75E+01 | 28.630 | 2.794E-03 |
|  |  | $6.310 \mathrm{E}+04$ | 8.800E-11 | $7.935 \mathrm{E}-04$ | 8.782E-11 | 7.935 | $8.514 \mathrm{E}-11$ | $7.935 \mathrm{E}-04$ | 1.259 E | 2.4357 | $2.35 \mathrm{E}+01$ | 33.688 | $2.780 \mathrm{E}-03$ |
| Geome |  | 3.981E+04 | 1.070E-10 | $7.895 \mathrm{E}-04$ | 1.068E-10 | 7.895E-04 | 1.042E-10 | $7.895 \mathrm{E}-04$ | 1.266 E | 1.8950 | $3.03 \mathrm{E}+01$ | 41.211 | 2.766E-03 |
| Diameter (cm) | 4.207 | 2.512E+04 | 1.380E-10 | 7.855E-04 | 1.379E-10 | 7.855E-04 | 1.352E-10 | 7.855E-04 | $1.273 \mathrm{E}+03$ | 1.5558 | $3.68 \mathrm{E}+01$ | 53.488 | 2.752E-03 |
| Thickness (cm) | 0.487 | $1.585 \mathrm{E}+04$ $1.000 E+04$ | 1.880E-10 2.680E-10 | $7.817 \mathrm{E}-04$ <br> $7.778 \mathrm{E}-04$ | 1.880E-10 2.679E-10 | 7.817E-04 <br> 7.778E-04 | $1.852 \mathrm{E}-10$ $2.651 \mathrm{E}-10$ | 7.817E-04 7.778E-04 | $1.279 E+03$ | $1.3517$ | $4.24 E+01$ | $73.292$ $104.905$ | $2.739 E-03$ $2.725 E-03$ |


| Experiment ID: | MD0509 | Freg[ Hz ] | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_osc [S] | Cp_hc [F] | Gp_hc [S] | \|Z1 [ 0 ] | 0 [deg] | Loss Tan | DielConstant | Cond [S/m] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | $4.699 \mathrm{E}-11$ | $9.130 \mathrm{E}-04$ | $4.653 \mathrm{E}-11$ | 9.026E-04 | $4.412 \mathrm{E}-11$ | $9.019 \mathrm{E}-04$ | $3.431 \mathrm{E}+02$ | 71.9777 | 3.25E-01 | 17.457 | $3.160 \mathrm{E}-03$ |
|  |  | $6.310 E+06$ | 4.820E-11 | $8.830 \mathrm{E}-04$ | $4.791 \mathrm{E}-11$ | 8.789E-04 | 4.540E-11 | 8.780E-04 | $4.993 \mathrm{E}+02$ | 63.9972 | $4.88 \mathrm{E}-01$ | 17.966 | $3.076 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | $4.940 \mathrm{E}-11$ | 8.540E-04 | 4.917E-11 | $8.524 \mathrm{E}-04$ | 4.664E-11 | $8.517 \mathrm{E}-04$ | 6.923E+02 | 53.8662 | 7.30E-01 | 18.453 | $2.984 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | 2.512E+06 | 5.050E-11 | 8.300E-04 | 5.030E-11 | $8.294 \mathrm{E}-04$ | 4.773E-11 | 8.288E-04 | $8.928 \mathrm{E}+02$ | 42.2684 | $1.10 \mathrm{E}+00$ | 18.887 | 2.904E-03 |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 5.169E-11 | $8.137 \mathrm{E}-04$ | 5.150E-11 | $8.135 \mathrm{E}-04$ | 4.892E-11 | $8.131 \mathrm{E}-04$ | $1.055 \mathrm{E}+03$ | 30.9266 | $1.67 \mathrm{E}+00$ | 19.356 | $2.849 \mathrm{E}-03$ |
| Mcl [g] | 0.7088 | $1.000 E+06$ | 5.317E-11 | 8.007E-04 | 5.298E-11 | 8.006E-04 | 5.039E-11 | 8.004E-04 | $1.162 \mathrm{E}+03$ | 21.5831 | $2.53 \mathrm{E}+00$ | 19.939 | $2.804 \mathrm{E}-03$ |
| Mw [g] | 1.9754 | $6.310 \mathrm{E}+05$ | $5.500 \mathrm{E}-11$ | 7.914E-04 | 5.482E-11 | $7.914 \mathrm{E}-04$ | $5.221 \mathrm{E}-11$ | 7.912E-04 | $1.223 \mathrm{E}+03$ | 14.6594 | $3.82 \mathrm{E}+00$ | 20.657 | 2.772E-03 |
| Wcl (dyy) | 0.0618 | $3.981 \mathrm{E}+05$ | $5.750 \mathrm{E}-11$ | 7.842E-04 | 5.732E-11 | $7.842 \mathrm{E}-04$ | 5.470E-11 | $7.841 \mathrm{E}-04$ | $1.256 \mathrm{E}+03$ | 9.8983 | $5.73 \mathrm{E}+00$ | 21.643 | 2.747E-03 |
| Porosity (dry) | 0.3568 | $2.512 \mathrm{E}+05$ | $6.100 \mathrm{E}-11$ | $7.785 \mathrm{E}-04$ | 6.082E-11 | $7.785 \mathrm{E}-04$ | 5.819E-11 | 7.784E-04 | $1.276 \mathrm{E}+03$ | 6.7281 | $8.48 \mathrm{E}+00$ | 23.023 | $2.727 \mathrm{E}-03$ |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | $6.610 \mathrm{E}-11$ | $7.736 \mathrm{E}-04$ | 6.593E-11 | $7.736 \mathrm{E}-04$ | 6.328E-11 | 7.736E-04 | $1.288 \mathrm{E}+03$ | 4.6573 | $1.23 \mathrm{E}+01$ | 25.039 | $2.710 \mathrm{E}-03$ |
| Sw | 0.8195 | $1.000 \mathrm{E}+05$ | 7.410E-11 | $7.692 \mathrm{E}-04$ | 7.392E-11 | 7.692E-04 | 7.125E-11 | 7.692E-04 | $1.298 E+03$ | 3.3312 | $1.72 \mathrm{E}+01$ | 28.194 | $2.695 \mathrm{E}-03$ |
|  |  | $6.310 E+04$ | $8.600 \mathrm{E}-11$ | $7.651 \mathrm{E}-04$ | 8.582E-11 | $7.651 \mathrm{E}-04$ | 8.314E-11 | 7.651E-04 | $1.306 \mathrm{E}+03$ | 2.4667 | 2.32E+01 | 32.896 | $2.680 \mathrm{E}-03$ |
| Geometry: |  | $3.981 E+04$ | 1.050E-10 | 7.612E-04 | 1.048E-10 | $7.612 \mathrm{E}-04$ | $1.021 \mathrm{E}-10$ | $7.612 \mathrm{E}-04$ | $1.313 \mathrm{E}+03$ | 1.9226 | 2.98E+01 | 40.419 | $2.667 \mathrm{E}-03$ |
| Diameter [cm] | 4.207 | 2.512E+04 | 1.350E-10 | $7.573 \mathrm{E}-04$ | 1.349E-10 | $7.573 \mathrm{E}-04$ | 1.322E-10 | $7.573 \mathrm{E}-04$ | $1.320 \mathrm{E}+03$ | 1.5779 | $3.63 \mathrm{E}+01$ | 52.299 | $2.653 \mathrm{E}-03$ |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 1.840E-10 | 7.536E-04 | 1.839E-10 | $7.536 \mathrm{E}-04$ | 1.812E-10 | $7.536 \mathrm{E}-04$ | $1.327 \mathrm{E}+03$ | 1.3718 | $4.18 \mathrm{E}+01$ | 71.705 | $2.640 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | 2.620E-10 | $7.498 \mathrm{E}-04$ | 2.619E-10 | $7.498 \mathrm{E}-04$ | 2.591E-10 | $7.498 \mathrm{E}-04$ | $1.333 \mathrm{E}+03$ | 1.2439 | $4.61 E+01$ | 102.528 | 2.627E-03 |









| Experiment ID: | MD0517 | Freg [ Hz$]$ | Cp_m [F] | Gp_m [S] | CP_osc [F] | Gp_ose[S] | Cp_hc [F] | Gp_hc [S] | \|Z1 [ 0 ] | 6 [deg] | Loss Tan | Dielcon | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | $2.311 \mathrm{E}-11$ | $4.460 \mathrm{E}-04$ | 2.284E-11 | 4.435E-04 | 2.042E-11 | $4.428 \mathrm{E}-04$ | 7.368E+02 | 70.9583 | 3.45E-01 | $8.079 \quad 1.551 \mathrm{E}-03$ |  |
|  |  | $6.310 \mathrm{E}+06$ | 2.426E-11 | 4.264E-04 | 2.403E-11 | 4.254E-04 | 2.153E-11 | $4.245 \mathrm{E}-04$ | $1.049 \mathrm{E}+03$ | 63.5541 | 4.97E-01 | 8.51 | .487E-03 |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 572E-11 | 3.962E-04 | $2.551 \mathrm{E}-11$ | 3.958E-04 | 2.297E-11 | $3.951 \mathrm{E}-04$ | $1.434 \mathrm{E}+$ | 55.4867 | $6.88 \mathrm{E}-01$ | . 09 | 384E-03 |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 2.765E-11 | 3.654E-04 | 2.745E-11 | 2E-04 | $2.488 \mathrm{E}-11$ | $3.647 \mathrm{E}-$ | 1.866 E | 47.1130 | $9.29 \mathrm{E}-01$ | 9.84 | .278E-03 |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 3.001E-11 | -4 | 2.981 E | $3.366 \mathrm{E}-04$ | $2.723 \mathrm{E}-11$ | 3.363 E | $2.315 \mathrm{E}+$ | 38.8780 | 1.24E+00 | 10.774 | $1.178 \mathrm{E}-03$ |
| Mcl [g] | 0.7088 | 1.000E+06 | 3.256E-11 | 3.129E-04 | 3.236E-11 | $3.129 \mathrm{E}-04$ | 2.977E-1 | $3.126 E-04$ | $2.745 \mathrm{E}+0$ | 30.8884 | $1.67 \mathrm{E}+00$ | 11.778 | $1.095 \mathrm{E}-03$ |
| Mw [g] | 1.0 | 6.310E+ | E-1 | 957E-04 | $3.490 \mathrm{E}-1$ | 957E-04 | 3.229E-1 | $2.955 \mathrm{E}-0$ | $3.105 \mathrm{E}+$ | 23.4208 | $2.31 \mathrm{E}+00$ | 12.77 | .035E-0 |
| WCl (dry) | 0.061 | 3.981 E | 750E-1 | 844E-04 | .730E- | $2.844 \mathrm{E}-04$ | 3.468E- | $2.843 \mathrm{E}-0$ | $3.364 \mathrm{E}+3$ | 16.9697 | $3.28 \mathrm{E}+00$ | 13.72 | .960E-04 |
| Porosity (dry) | 0.356 | 2.512 E | 000 | .775E-04 | 3.980 E | $2.775 \mathrm{E}-0$ | $3.717 \mathrm{E}-1$ | $2.774 \mathrm{E}-0$ | $3.527 \mathrm{E}+0$ | 11.9393 | $4.73 \mathrm{E}+00$ | 14.70 | .720E-04 |
| Perm [cm^2] | 7.5E-0 | $1.585 \mathrm{E}+{ }^{\text {c }}$ | $4.320 \mathrm{E}-11$ | $2.729 \mathrm{E}-0$ | $4.300 \mathrm{E}-1$ | $2.729 \mathrm{E}-0$ | 4.036E-1 | $2.729 \mathrm{E}-0$ | 3.626E | 8.3785 | 9.64E+00 | 17.623 | $9.448 \mathrm{E}-04$ |
| Sw | 0.4282 | $1.000 \mathrm{E}+0$ | $4.740 \mathrm{E}-1$ | $2.697 \mathrm{E}-04$ | $4.720 \mathrm{E}-11$ | 2.697E-04 | 4.454E-11 | $2.697 \mathrm{E}-04$ | $3.688 \mathrm{E}+$ | $\begin{aligned} & 5.9245 \\ & 4.3378 \end{aligned}$ |  |  |  |
|  |  | 6.310 | 400 | $2.672 \mathrm{E}-04$ | 5.380E-11 | 2.672E-04 | 5.112E-11 | $2.672 \mathrm{E}-04$ | $3.732 \mathrm{E}+03$ |  | $1.32 \mathrm{E}+01$ | 20.228 | $9.360 \mathrm{E}-04$ |
| ometry |  | $3.981 \mathrm{E}+0$ | 6.300E-11 | $2.650 \mathrm{E}-04$ | $6.281 \mathrm{E}-11$ | $2.650 \mathrm{E}-04$ | 6.011E-11 | $2.650 \mathrm{E}-04$ | $3.768 \mathrm{E}+03$ | 3.2478 | $1.76 \mathrm{E}+01$ | 23.786 | 9.284E-04 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 7.700E-11 | $2.630 \mathrm{E}-04$ | 7.681E-11 | $2.630 \mathrm{E}-04$ | 7.410E-11 | $2.630 \mathrm{E}-04$ | $3.799 \mathrm{E}+03$ | 2.5462 | $2.25 \mathrm{E}+01$ | 29.320 | 9.214E-04 |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 1.000E-10 | 2.61 | 9.982E-11 | $2.611 \mathrm{E}-04$ | 9.709E-11 | $2.611 \mathrm{E}-04$ | $3.827 \mathrm{E}+03$ | 2.1206 | $2.70 \mathrm{E}+01$ | 38.4 | 9.14 |
|  |  | $1.000 \mathrm{E}+04$ | 1.350E-1 | 2.594E | 1.348E-10 | 2.594 E | 1.321E-10 | $2.594 \mathrm{E}-04$ | $3.853 \mathrm{E}+03$ | 1.8321 | 3.13E+ | 52.25 | 9.08 |


| Experiment ID: | MD0518 | Freq [ Hz$]$ | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_osc [S] | CP_he [F] | Gp_he [S] | \|21 [ 01 | 6 [deg] | Loss Tan | DielConstant | $\frac{\text { Cond }[\mathrm{S} / \mathrm{m}]}{1.395 \mathrm{E}-03}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 2.112E-11 | 4.010E-04 | 2.085E-11 | 3.990E-04 | $1.844 \mathrm{E}-11$ | 3.982E-04 | $8.163 \mathrm{E}+02$ | 71.0291 | 3.44E-01 |  |  |
|  |  | 6.310E+06 | 2.230E-11 | 3.819E-04 | 2.207E-11 | 3.811E-04 | 1.957E-11 | 3.802E-04 | $1.157 \mathrm{E}+03$ | 63.8949 | $4.90 \mathrm{E}-01$ | 7.744 | $1.332 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 2.387E-11 | 3.522E-04 | 2.366E-11 | 3.519E-04 | 2.112E-11 | 3.512E-04 | $1.576 \varepsilon+03$ | 56.3890 | 6.65E-01 | 8.358 | 1.230E-03 |
| Mineralogy | Qtz-Ka0! | 2.512E+06 | $2.613 \mathrm{E}-11$ | 3.206E-04 | 2.593E-11 | 3.205E-04 | 2.336E-11 | 3.199E-04 | $2.049 \varepsilon+03$ | 49.0473 | $8.68 \mathrm{E}-01$ | 9.243 | $1.121 \mathrm{E}-03$ |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 2.925E-11 | 2.887E-04 | 2.905E-11 | 2.886E-04 | 2.647E-11 | 2.883E-04 | $2.560 \mathrm{E}+03$ | 42.4334 | $1.09 \mathrm{E}+00$ | 10.472 | $1.010 \mathrm{E}-03$ |
| Mcl [g] | 0.7088 | 1.000E+06 | 3.313E-11 | 2.587E-04 | 3.293E-11 | 2.587E-04 | 3.034E-11 | $2.584 \mathrm{E}-04$ | 3.114E+03 | 36.4084 | $1.36 E+00$ | 12.003 | 9.055E-04 |
| Mw [g] | 0.9063 | $6.310 \mathrm{E}+05$ | $3.730 \mathrm{E}-11$ | 2.337E-04 | 3.710E-11 | 2.337E-04 | 3.449E-11 | $2.335 \mathrm{E}-04$ | $3.695 \mathrm{E}+03$ | 30.3489 | $1.71 \mathrm{E}+00$ | 13.647 | 8.182E-04 |
| Wcl (dry) | 0.0618 | $3.981 \mathrm{E}+05$ | $4.120 \mathrm{E}-11$ | $2.157 \mathrm{E}-04$ | 4.100E-11 | $2.157 \mathrm{E}-04$ | 3.838E-11 | $2.156 \mathrm{E}-04$ | $4.237 \mathrm{E}+03$ | 24.0039 | $2.25 E+00$ | 15.186 | 7.553E-04 |
| Porosity (dry) | 0.3568 | $2.512 \mathrm{E}+05$ | $4.460 \mathrm{E}-11$ | $2.042 \mathrm{E}-04$ | $4.440 \mathrm{E}-11$ | 2.042E-04 | 4.177E-11 | $2.041 \mathrm{E}-04$ | $4.662 \mathrm{E}+03$ | 17.8971 | $3.10 \mathrm{E}+00$ | 16.527 | $7.152 \mathrm{E}-04$ |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | $4.780 \mathrm{E}-11$ | 1.975E-04 | $4.760 \mathrm{E}-11$ | 1.975E-04 | 4.495E-11 | 1.975E-04 | $4.939 \mathrm{E}+03$ | 12.7739 | $4.41 \mathrm{E}+00$ | 17.787 | 6.918E-04 |
| Sw | 0.3760 | $1.000 \mathrm{E}+05$ | $5.120 \mathrm{E}-11$ | 1.937E-04 | 5.100E-11 | 1.937E-04 | 4.834E-11 | $1.937 \mathrm{E}-04$ | 5.101E+03 | 8.9125 | 6.38E+00 | 19.126 | 6.785E-04 |
|  |  | $6.310 \mathrm{E}+04$ | $5.600 \mathrm{E}-11$ | $1.912 \mathrm{E}-04$ | 5.580E-11 | 1.912E-04 | 5.312E-11 | 1.912E-04 | $5.199 \varepsilon+03$ | 6.2859 | $9.08 \mathrm{E}+00$ | 21.019 | $6.698 \mathrm{E}-04$ |
| Geometry: Diameter [cm] Thickness [ cm ] | $\begin{aligned} & 4.207 \\ & 0.487 \end{aligned}$ | $3.981 \varepsilon+04$ | 6.200E-11 | $1.894 \mathrm{E}-04$ | 6.180E-11 | $1.894 \mathrm{E}-04$ | 5.911E-11 | $1.894 \mathrm{E}-04$ | $5.264 E+03$ | 4.4642 | $1.28 \mathrm{E}+01$ | 23.389 | 6.635E-04 |
|  |  | $2.512 \mathrm{E}+04$ | 7.200E-11 | $1.879 \mathrm{E}-04$ | $7.181 \mathrm{E}-11$ | $1.879 \mathrm{E}-04$ | 6.909E-11 | $1.879 \mathrm{E}-04$ | $5.313 \mathrm{E}+03$ | 3.3216 | $1.72 \mathrm{E}+01$ | 27.339 | 6.583E-04 |
|  |  | $1.585 \mathrm{E}+04$ | $8.800 \mathrm{E}-11$ | $1.866 \mathrm{E}-04$ | $8.781 \mathrm{E}-11$ | $1.866 \mathrm{E}-04$ | 8.508E-11 | 1.866E-04 | 5.354E+03 | 2.5997 | $2.20 \mathrm{E}+01$ | 33.664 | 6.537E-04 |
|  |  | $1.000 \mathrm{E}+04$ | 1.110E-10 | 1.854E-04 | 1.108E-10 | 1.854E-04 | 1.081E-10 | 1.854E-04 | 5.390E +03 | 2.0972 | $2.73 \mathrm{E}+01$ | 42.755 | 6.495E-04 |





| Experiment ID: | MDO522 | Frea [ Hz ] | Cp_m [F] | Gp_m [S] | CP_OSC [F] | Gp_Osc [ [ ] | $\mathrm{Cp}_{2} \mathrm{hc}[\mathrm{F}]$ | Gp_hc [S] | \| 21 [ 0 ] | 6 [deg] | Loss Tan | DielConstant | $\begin{aligned} \hline \text { Cond }[\mathrm{S} / \mathrm{m}] \\ 1.063 \mathrm{E}-03 \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | $1.656 \mathrm{E}-11$ | 3.054E-04 | 1.632E-11 | 3.042E-04 | 1.390E-11 | 3.035E-04 | $1.082 \mathrm{E}+03$ | 70.8393 | 3.47E-01 |  |  |
|  |  | $6.310 \mathrm{E}+06$ | $1.766 \mathrm{E}-11$ | 2.793E-04 | 1.744E-11 | 2.788E-04 | 1.494E-11 | $2.779 \mathrm{E}-1$ | $1.529 E+03$ | 64.8584 | 4.69E-01 | 5.911 | 9.737E-04 |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 916E-11 | 509E-04 | 1.895E-11 | .507E-04 | 1.641E-11 | $2.500 \mathrm{E}-04$ | $2.080 E+03$ | 58.6615 | $6.09 \mathrm{E}-01$ | 6.495 | 859E-04 |
| Mineralogy | Qtz-Kaol | 2.512E+06 | 2.139E-11 | $2.211 \mathrm{E}-04$ | 2.119E-11 | $2.210 \mathrm{E}-04$ | 1.862E-11 | 2.205E-04 | $2.722 \mathrm{E}+03$ | 53.1170 | $7.50 \mathrm{E}-01$ | 7.367 | 7.725E-04 |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 2.464E-11 | $1.906 \mathrm{E}-04$ | 2.444E-11 | 1.906E-04 | 2.186E-11 | 1.902E-04 | $3.459 \mathrm{E}+03$ | 48.8469 | 8.74E-01 | 8.648 | $6.664 \mathrm{E}-04$ |
| Mal [g] | 0.7088 | 1.000E+06 | $2.900 \mathrm{E}-11$ | $1.603 \mathrm{E}-04$ | 2.880E-11 | 1.603E-04 | 2.620E-11 | $1.601 \mathrm{E}-04$ | 4.355E+03 | 45.8098 | $9.72 \mathrm{E}-01$ | 10.369 | 5.608E-04 |
| Mw [g] | 0.5186 | $6.310 \mathrm{E}+05$ | 3.420E-11 | $1.332 \mathrm{E}-04$ | 3.400E-11 | $1.332 \mathrm{E}-04$ | 3.139E-11 | $1.330 \mathrm{E}-04$ | 5.490 E+03 | 43.0876 | $1.07 \mathrm{E}+00$ | 12.420 | $4.661 \mathrm{E}-04$ |
| Wcl (ay) | 0.0618 | $3.981 \mathrm{E}+05$ | 3.950E-11 | 1.117E-04 | 3.930E-11 | $1.117 \mathrm{E}-04$ | 3.668E-11 | $1.116 \mathrm{E}-04$ | 6.922E+03 | 39.4271 | $1.22 E+00$ | 14.513 | 3.909E-04 |
| Porosity (dy) | 0.3568 | $2.512 \mathrm{E}+05$ | 4.450E-11 | 9.680E-05 | 4.430E-11 | $9.680 \mathrm{E}-05$ | 4.167E-11 | $9.673 \mathrm{E}-05$ | $8.549 \mathrm{E}+03$ | 34.2093 | $1.47 \mathrm{E}+00$ | 16.487 | 3.389E-04 |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | 4.883E-11 | $8.738 \mathrm{E}-05$ | 4.863E-11 | $8.738 \mathrm{E}-05$ | 4.598E-11 | $8.733 \mathrm{E}-05$ | $1.014 \mathrm{E}+04$ | 27.6684 | $1.91 \mathrm{E}+00$ | 18.194 | 3.060E-04 |
| Sw | 0.2151 | $1.000 \mathrm{E}+05$ | 5.274E-11 | $8.189 \mathrm{E}-05$ | 5.254E-11 | 8.189E-05 | 4.988E-11 | $8.186 \mathrm{E}-05$ | $1.141 \mathrm{E}+04$ | 20.9481 | $2.61 \mathrm{E}+00$ | 19.735 | $2.868 \mathrm{E}-04$ |
|  |  | $6.310 \mathrm{E}+04$ | $5.660 \mathrm{E}-11$ | 7.869E-05 | 5.640E-11 | $7.869 \mathrm{E}-05$ | 5.372E-11 | 7.867E-0S | $1.227 \mathrm{E}+04$ | 15.1473 | $3.69 \mathrm{E}+00$ | 21.256 | 2.756E-04 |
| Geometry: |  | $3.981 £+04$ | 6.100E-11 | $7.676 \mathrm{E}-05$ | $6.080 \mathrm{E}-11$ | $7.676 \mathrm{E}-05$ | 5.811E-11 | 7.675E-05 | $1.280 \mathrm{E}+04$ | 10.7245 | $5.28 \mathrm{E}+00$ | 22.993 | $2.689 \mathrm{E}-04$ |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 6.660E-11 | $7.553 \mathrm{E}-05$ | $6.640 \mathrm{E}-11$ | $7.553 \mathrm{E}-05$ | 6.369E-11 | $7.552 \mathrm{E}-05$ | $1.313 \mathrm{E}+04$ | 7.5816 | $7.51 \mathrm{E}+00$ | 25.201 | $2.646 \mathrm{E}-04$ |
| Trickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 7.420E-11 | 7.462E-05 | 7.400E-11 | 7.462E-05 | 7.127E-11 | 7.461E-05 | $1.334 \mathrm{E}+04$ | 5.4336 | $1.05 \mathrm{E}+01$ | 28.200 | $2.614 \mathrm{E}-04$ |
|  |  | $1.000 \mathrm{E}+04$ | $8.540 \mathrm{E}-11$ | 7.390E-05 | 8.520E-11 | 7.390E-05 | 8.245E-11 | 7.390E-05 | $1.350 \mathrm{E}+04$ | 4.0101 | $1.43 \mathrm{E}+01$ | 32.624 | 2.589 E - |



| Experiment ID: | MD0524 | Freq [ Hz ] | CP_m [F] | Gp_m [S] | CP_Osc [F] | Gp_osc [S] | Cp_hc [F] | Gp_he [S] | \|z1 [ $\Omega$ ] | 6 [deg] | Loss Tan | DielConstant ${ }^{\text {cond }}$ CS/m] |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.546E-11 | $2.548 \mathrm{E}-04$ | 1.522E-11 | $2.539 \mathrm{E}-04$ | 1.280E-11 | 2.531E-04 | 1.186E+03 | 72.5290 | 3.15E-01 |  |  |
|  |  | $6.310 \mathrm{E}+$ | 1.644E-11 | $2.316 \mathrm{E}-04$ | 1.622E-11 | 2.312E-04 | 1.372E-11 | 2.303E-04 | $1.693 \varepsilon+03$ | 67.0470 | $4.24 \mathrm{E}-01$ | 5.428 | - |
| Sample: | nd-Clay | $3.981 \mathrm{E}+0$ | 1.779E-11 | $2.063 \mathrm{E}-04$ | 1.758E-11 | 2.062E-04 | $1.504 \mathrm{E}-11$ | 2.055E-04 | $2.332 \mathrm{E}+03$ | 61.3669 | $5.46 \mathrm{E}-01$ | 5.95 | 7.198E-04 |
| Mineralog | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 1.979E-11 | $1.801 \mathrm{E}-04$ | 1.959E-11 | 1.800E-04 | 1.702E-11 | $1.795 \mathrm{E}-04$ | 3.095E+03 | 56.2442 | 6.68E-01 | 6.734 | $6.289 \mathrm{E}-04$ |
| Ms [g] | 10.7644 | $1.585 \mathrm{E}+06$ | 2.277E-11 | .533E-04 | 2.257E-11 | 1.533E-04 | 1.999E-11 | $1.529 \mathrm{E}-04$ | 3.984E+03 | 52.4617 | 7.68E-01 | 7.908 | $5.358 \mathrm{E}-04$ |
| Mel [g] | 0.7088 | 1.000E+06 | $2.697 \mathrm{E}-11$ | 1.262E-04 | 2.677E-11 | $1.262 \mathrm{E}-04$ | $2.417 \mathrm{E}-1$ | 1.260E-04 | 5.068E+03 | 50.3317 | 8.29E-01 | 9.565 | $4.413 \mathrm{E}-04$ |
| Mw [g] | 0.4496 | $6.310 E+0$ | 3.220E-11 | 008E-04 | 200E-1 | 008E-0 | .939E- | $1.006 \mathrm{E}-0$ | $6.495 \mathrm{E}+$ | 49.1806 | 8.64E-01 | 11.62 | 3.526E-04 |
| Wcl (dry) | 0.0618 | $3.981 \mathrm{E}+05$ | 3.800E-11 | .960E-05 | $3.780 \mathrm{E}-1$ | .960E-05 | .518E-1 | 7.949E-05 | $8.433 \mathrm{E}+$ | 47.9076 | $9.03 \mathrm{E}-01$ | 13.92 | 2.785E-04 |
| Porosity (dy) | 0.3568 | $2.512 \mathrm{E}+0$ | 4.364E-11 | $6.388 \mathrm{E}-05$ | 4.344E-11 | $6.388 \mathrm{E}-05$ | $4.081 \mathrm{E}-1$ | $6.381 \mathrm{E}-05$ | $1.103 \mathrm{E}+$ | 45.2647 | 9.91E-01 | 16.14 | 2.236E-04 |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+0$ | 4.875E-11 | 5.344E-05 | 4.855E-11 | 5.344E-05 | 4.590E-11 | 5.339E-05 | $1.423 E$ | 40.5665 | $1.17 \mathrm{E}+00$ | 18.163 | 1.871E-04 |
| Sw | 0.1865 | 1.000E+0 | $5.303 \mathrm{E}-11$ | 4.712E-05 | 5.283E-11 | 4.712E-05 | 5.017E-11 | $4.709 \mathrm{E}-05$ | $1.765 E$ | 33.7968 | $1.49 \mathrm{E}+00$ | 19.850 | 1.650E-04 |
|  |  | $6.310 \mathrm{E}+04$ | $5.670 \mathrm{E}-11$ | 4.356E-05 | 5.650E-11 | $4.356 \mathrm{E}-05$ | 5.382E-11 | 4.354E-05 | $2.062 \mathrm{E}+$ | 26.1064 | $2.04 \mathrm{E}+00$ | 21.295 | 1.525E-04 |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 6.020E-11 | $4.157 \mathrm{E}-05$ | 6.000E-11 | $4.157 \mathrm{E}-05$ | $5.731 \mathrm{E}-11$ | $4.156 \mathrm{E}-05$ | $2.275 \mathrm{E}+04$ | 19.0324 | $2.90 E+00$ | 22.676 | 1.456E-04 |
| Diameter [cm] | 4.207 | 2.512E+04 | 6.430E-11 | 4.042E-0S | 6.410E-11 | 4.042E-05 | 6.139E-11 | $4.041 \mathrm{E}-05$ | $2.406 \mathrm{E}+04$ | 13.4826 | $4.17 \mathrm{E}+00$ | 24.291 | .416E-0 |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 6.98 | 3.967E-05 | 6.960E-11 | 3.967E-05 | 6.687E-11 | 3.966E-05 | $2.486 \mathrm{E}+04$ | 9.5302 | $5.96 \mathrm{E}+00$ | 26.459 | 1.390E-04 |
|  |  | 1.000E+0 | 7.760E- | 3.912 E | 7.740E- | 3.912E-0 | 7.465E-11 | 3.912E-05 | $2.538 \mathrm{E}+$ | 6.8376 | 8.34 | 29. | 1.370E-04 |




| Experiment ID: | MD0527 | Freq [ Hz ] | $\mathrm{Cp}_{\text {_ }} \mathrm{m}$ [ F$]$ | $\underline{G p}$ _m [S] | CP_osc [F] | Gp_osc [S] | CP_hc [F] | Gp_hc [S] | \| 21 [0] | 6 [deg] | Loss Tan | DielConstant | Cond [ $5 / \mathrm{m}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.289E-11 | $1.651 \mathrm{E}-04$ | 1.265E-11 | 1.646E-04 | 1.024E-11 | 1.639E-04 | $1.507 \mathrm{E}+03$ | 75.7060 | 2.55E-01 | $4.051 \quad 5.741 \mathrm{E}-04$ |  |
|  |  | $6.310 \mathrm{E}+06$ | $1.362 \mathrm{E}-11$ | 1.444E-04 | 1.340E-11 | $1.442 \mathrm{E}-04$ | 1.090E-11 | 1.433E-04 | $2.196 E+03$ | 71.6552 | 3.32E-01 | 4.314 | $5.021 \mathrm{E}-04$ |
| Sample | Sand-Clay | $3.981 \mathrm{E}+06$ | $1.451 \mathrm{E}-11$ | 1.242E-04 | 1.430E-11 | 1.241E-04 | 1.177E-11 | $1.234 \mathrm{E}-04$ | $3.133 \mathrm{E}+03$ | 67.2470 | $4.19 \mathrm{E}-01$ | 4.656 | 4.324E-04 |
| Mineralog | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 1.566E-11 | 1.060E-04 | 1.546E-11 | 1.060E-04 | 1.289E-11 | $1.054 \mathrm{E}-0$ | $4.364 \mathrm{E}+03$ | 62.6008 | 5.18E-01 | 5.100 | 3.694E-04 |
| Ms [g] | 10.7644 | 1.585E+06 | 1.726E-11 | $8.990 \mathrm{E}-05$ | 1.706E-11 | $8.989 \mathrm{E}-05$ | 1.448E-11 | $8.954 \mathrm{E}-0$ | 5.893E+03 | 58.1543 | 6.21E-01 | 5.728 | 3.137E-04 |
| Mcl [g] | 0.7088 | 1.000E+06 | 1.950E-11 | 7.550E-05 | 1.930E-11 | 7.549E-05 | 1.670E-11 | $7.527 \mathrm{E}-0$ | $7.743 \mathrm{E}+03$ | 54.355 | 7.17E-01 | 6.610 | -04 |
| Mw [g] | 0.2278 | $6.310 \mathrm{E}+0$ | 2.259E-11 | 6.249E-05 | 2.239E-11 | 6.249E-05 | $1.978 \mathrm{E}-1$ | $6.233 \mathrm{E}-05$ | $9.983 \mathrm{E}+$ | 51.519 | 7.95E-0 | 7.826 | $2.184 \mathrm{E}-04$ |
| Wda (ary) | 0.0618 | $3.981 \mathrm{E}+0$ | 2.675E-11 | 5.080E-05 | 2.655E-1 | 5.080E-05 | $2.393 \mathrm{E}-1$ | $5.069 \mathrm{E}-05$ | 1.275 E | 49.739 | $8.47 \mathrm{E}-0$ | 9.46 | $1.776 \mathrm{E}-04$ |
| Porosity (dry) | 0.3568 | 2.512E+05 | 3.197E-11 | 4.055E-05 | 3.177E-11 | 4.055E-05 | 2.914E-11 | $4.048 \mathrm{E}-05$ | 1.632 E | 48.642 | 8.80E-0 | 11.529 | $1.418 \mathrm{E}-04$ |
| Perm [cm^2] | 7.5E-09 | $1.585 \mathrm{E}+05$ | 3.796E-11 | $3.211 \mathrm{E}-05$ | 3.776E-11 | 3.211E-05 | $3.511 \mathrm{E}-11$ | $3.206 \mathrm{E}-0$ | 2.108E+04 | 47.4783 | 9.17E-01 | 13.893 | 1.123E-0 |
| Sw | 0.0945 | $1.000 \mathrm{E}+05$ | 4.423E-11 | $2.573 \mathrm{E}-05$ | 4.403E-11 | 2.573E-05 | 4.137E-11 | 2.570E-05 | $2.736 \mathrm{E}+04$ | 45.3225 | 9.89E-01 | 16.368 | 9.004E-05 |
|  |  | $6.310 E+04$ | 5.040E-11 | 2.132E-05 | 5.020E-11 | 2.132E-05 | 4.752E-11 | 2.130E-05 | $3.517 E+04$ | 41.4907 | $1.13 \mathrm{E}+\infty$ | 18.802 | $7.462 \mathrm{E}-0$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 5.640E-11 | 1.846E-05 | 5.620E-11 | 1.846E-05 | 5.351E-11 | 1.845E-05 | $4.388 \mathrm{E}+04$ | 35.9650 | $1.38 \mathrm{E}+00$ | 21.172 | 6.462E-0 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 6.220E-11 | $1.664 \mathrm{E}-05$ | 6.200E-11 | 1.664E-05 | 5.929E-11 | $1.663 \mathrm{E}-05$ | $5.240 \mathrm{E}+04$ | 29.3641 | $1.78 \mathrm{E}+00$ | 23.459 | 5.827E-05 |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 6.830E-11 | $1.550 \mathrm{E}-05$ | 6.810E-11 | 1.550E-05 | 6.537E-11 | 1.549E-05 | $5.950 \mathrm{E}+04$ | 22.7889 | $2.38 \mathrm{E}+00$ | 25.865 | $5.428 \mathrm{E}-05$ |
|  |  | $1.000 \mathrm{E}+04$ | 7.480E-11 | 1.478E-05 | 7.460E-11 | $1.478 \mathrm{E}-05$ | 7.185E-11 | 1.478E-05 | 6.472E+04 | 16.9891 | 3.27E +00 | 28.429 | 5.177E-0 |







| Experiment iD: | MD0542 | Freg [ Hz ] | Cp_m [F] | Gp_m [S] | CP_osc [F] | Gp_osc [S] | Cp_he [F] | Gp_hc [S] | \|21 [ 2 ] | 6 (deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | $5.416 \mathrm{E}-11$ | $1.779 \mathrm{E}-03$ | 5.369E-11 | $1.756 \mathrm{E}-03$ | $5.127 \mathrm{E}-11$ | $1.755 \mathrm{E}-03$ | 2.726E+02 | 61.4194 | 5.45E-01 | 20.288 | $6.149 \mathrm{E}-03$ |
|  |  | $6.310 \varepsilon+06$ | $5.740 \mathrm{E}-11$ | $1.635 \mathrm{E}-03$ | $5.712 \mathrm{E}-11$ | $1.626 \mathrm{E}-03$ | 5.462E-11 | $1.625 \mathrm{E}-03$ | $3.694 \mathrm{E}+02$ | 53.1086 | 7.51E-01 | 21.611 | $5.694 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 6.080E-11 | $1.521 \mathrm{E}-03$ | 6.060E-11 | 1.518E-03 | 5.806E-11 | $1.517 \mathrm{E}-03$ | $4.762 \mathrm{E}+02$ | 43.7552 | $1.04 \mathrm{E}+00$ | 22.973 | $5.314 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | $6.460 \mathrm{E}-11$ | $1.439 \mathrm{E}-03$ | $6.443 \mathrm{E}-11$ | $1.438 \mathrm{E}-03$ | $6.186 \mathrm{E}-11$ | $1.437 \mathrm{E}-03$ | $5.756 \mathrm{E}+02$ | 34.1924 | $1.47 \mathrm{E}+00$ | 24.478 | 5.035E-03 |
| Ms [g] | 7.1770 | $1.585 E+06$ | 6.920E-11 | $1.379 \mathrm{E}-03$ | $6.904 \mathrm{E}-11$ | $1.378 \mathrm{E}-03$ | 6.646E-11 | $1.378 \mathrm{E}-03$ | $6.541 \mathrm{E}+02$ | 25.6525 | $2.08 \mathrm{E}+00$ | 26.297 | $4.828 \mathrm{E}-03$ |
| Mcl [g] | 4.2454 | $1.000 E+06$ | 7.520E-11 | $1.335 \mathrm{E}-03$ | 7.505E-11 | $1.335 \mathrm{E}-03$ | 7.245E-11 | $1.335 \mathrm{E}-03$ | 7.092E+02 | 18.8354 | $2.93 \mathrm{E}+00$ | 28.668 | 4.675E-03 |
| Mw [g] | 2.1342 | $6.310 \mathrm{E}+05$ | $8.400 \mathrm{E}-11$ | $1.299 \mathrm{E}-03$ | $8.385 \mathrm{E}-11$ | $1.299 \mathrm{E}-03$ | $8.124 \mathrm{E}-11$ | $1.299 \mathrm{E}-03$ | $7.473 \mathrm{E}+02$ | 13.9271 | $4.03 \mathrm{E}+00$ | 32.144 | $4.550 \mathrm{E}-03$ |
| Wcl (dry) | 0.3717 | $3.981 E+05$ | $9.600 \mathrm{E}-11$ | $1.269 \mathrm{E}-03$ | $9.585 \mathrm{E}-11$ | $1.269 \mathrm{E}-03$ | $9.323 \mathrm{E}-11$ | $1.269 \mathrm{E}-03$ | $7.751 \mathrm{E}+02$ | 10.4140 | $5.44 \mathrm{E}+00$ | 36.888 | $4.445 \mathrm{E}-03$ |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | $1.140 \mathrm{E}-10$ | $1.242 \mathrm{E}-03$ | $1.138 \mathrm{E}-10$ | $1.242 \mathrm{E}-03$ | $1.112 \mathrm{E}-10$ | $1.242 \mathrm{E}-03$ | 7.973E+02 | 8.0446 | $7.08 \mathrm{E}+00$ | 44.005 | $4.351 \mathrm{E}-03$ |
| Perm [cm^2] | 7.1E-12 | $1.585 E+05$ | 1.420E-10 | $1.217 \mathrm{E}-03$ | $1.419 \mathrm{E}-10$ | $1.217 \mathrm{E}-03$ | 1.392E-10 | $1.217 \mathrm{E}-03$ | $8.164 \mathrm{E}+02$ | 6.4996 | $8.78 \mathrm{E}+00$ | 55.089 | $4.263 \mathrm{E}-03$ |
| Sw | 0.8797 | $1.000 \mathrm{E}+05$ | 1.840E-10 | $1.194 \mathrm{E}-03$ | $1.838 \mathrm{E}-10$ | $1.194 \mathrm{E}-03$ | 1.812E-10 | $1.194 \mathrm{E}-03$ | $8.338 \mathrm{E}+02$ | 5.4464 | $1.05 \mathrm{E}+01$ | 71.689 | 4.183E-03 |
|  |  | $6.310 \mathrm{E}+04$ | $2.500 \mathrm{E}-10$ | $1.172 \mathrm{E}-03$ | $2.498 \mathrm{E}-10$ | $1.172 \mathrm{E}-03$ | 2.472E-10 | $1.172 \mathrm{E}-03$ | $8.503 \mathrm{E}+02$ | 4.7792 | $1.20 \mathrm{E}+01$ | 97.797 | $4.106 \mathrm{E}-03$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 3.400E-10 | $1.151 \mathrm{E}-03$ | $3.399 \mathrm{E}-10$ | $1.151 \mathrm{E}-03$ | 3.372E-10 | $1.151 \mathrm{E}-03$ | $8.665 \mathrm{E}+02$ | 4.1913 | $1.36 \mathrm{E}+01$ | 133.426 | 4.032E-03 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | $4.900 \mathrm{E}-10$ | $1.131 \mathrm{E}-03$ | $4.900 \mathrm{E}-10$ | $1.131 \mathrm{E}-03$ | 4.873E-10 | $1.131 \mathrm{E}-03$ | $8.821 \mathrm{E}+02$ | 3.8900 | $1.47 \mathrm{E}+01$ | 192.810 | $3.962 \mathrm{E}-03$ |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 7.100E-10 | $1.111 \mathrm{E}-03$ | 7.101E-10 | $1.111 \mathrm{E}-03$ | 7.074E-10 | $1.111 \mathrm{E}-03$ | $8.983 \mathrm{E}+02$ | 3.6281 | $1.58 \mathrm{E}+01$ | 279.912 | $3.892 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | 1.032E-09 | $1.092 \mathrm{E}-03$ | 1.032E-09 | 1.092E-03 | 1.029E-09 | 1.092E-03 | 9.139E+02 | 3.3881 | $1.69 \mathrm{E}+01$ | 407.235 | 3.827E-03 |




| Experiment ID: | MD0545 | Freg [ Hz ] | Cp_m[F] | Gp_m [S] | CP_ose [F] | Gp_osc [S] | Cp_hc [F] | Gp_hc [S] | $121[\Omega]$ | 0 [degl | Loss Tan | DleiConstant | Cond |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 2.847E-11 | 6.580E-04 | 2.817E-11 | 6.535E-04 | 2.575E-11 | $6.528 \mathrm{E}-04$ | 5.731E+02 | 68.0304 | 4.03E-01 | 10.190 | 2.287E-03 |
|  |  | $6.310 \mathrm{E}+06$ | 3.020E-11 | $5.990 \mathrm{E}-04$ | $2.996 \mathrm{E}-11$ | 5.973E-04 | $2.746 \mathrm{E}-11$ | $5.964 \mathrm{E}-04$ | $8.057 E+02$ | 61.2835 | 5.48E-01 | 10.865 | $2.089 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 3.187E-11 | $5.485 \mathrm{E}-04$ | $3.166 \mathrm{E}-11$ | $5.478 \mathrm{E}-04$ | $2.912 \mathrm{E}-11$ | $5.471 \mathrm{E}-04$ | $1.098 \mathrm{E}+03$ | 53.0874 | 7.51E-01 | 11.522 | $1.917 \mathrm{E}-03$ |
| Mineralog | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 3.373E-11 | $5.065 \mathrm{E}-04$ | $3.353 \mathrm{E}-11$ | $5.062 \mathrm{E}-04$ | $3.096 \mathrm{E}-11$ | $5.057 \mathrm{E}-04$ | $1.422 \mathrm{E}+03$ | 44.0161 | $1.03 \mathrm{E}+00$ | 12.250 | $1.772 \mathrm{E}-03$ |
| Ms [g] | 7.1770 | $1.585 \mathrm{E}+06$ | 3.570E-11 | $4.762 \mathrm{E}-04$ | 3.550E-11 | $4.761 \mathrm{E}-04$ | 3.292E-11 | $4.758 \mathrm{E}-04$ | $1.731 \mathrm{E}+03$ | 34.5695 | $1.45 \mathrm{E}+00$ | 13.026 | $1.667 \mathrm{E}-03$ |
| Mcl [g] | 4.2454 | $1.000 \mathrm{E}+06$ | 3.788E-11 | 4.553E-04 | 3.768E-11 | 4.553E-04 | 3.509E-11 | $4.550 \mathrm{E}-04$ | 1.978E+03 | 25.8514 | $2.06 \mathrm{E}+00$ | 13.884 | $1.594 \mathrm{E}-03$ |
| Mw [g] | 1.7125 | $6.310 \mathrm{E}+05$ | 4.050E-11 | $4.411 \mathrm{E}-04$ | 4.030E-11 | $4.411 \mathrm{E}-04$ | 3.769E-11 | $4.409 \mathrm{E}-04$ | $2.148 \mathrm{E}+03$ | 18.7222 | $2.95 \mathrm{E}+00$ | 14.915 | $1.545 \mathrm{E}-03$ |
| Wcl (dry) | 0.3717 | $3.981 \mathrm{E}+05$ | 4.410E-11 | $4.306 \mathrm{E}-04$ | 4.390E-11 | $4.306 \mathrm{E}-04$ | $4.128 \mathrm{E}-11$ | $4.305 \mathrm{E}-04$ | $2.259 \mathrm{E}+03$ | 13.4896 | $4.17 \mathrm{E}+00$ | 16.335 | $1.508 \mathrm{E}-03$ |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | 4.930E-11 | $4.222 \mathrm{E}-04$ | $4.910 \mathrm{E}-11$ | $4.222 \mathrm{E}-04$ | 4.647E-11 | $4.221 \mathrm{E}-04$ | $2.334 \mathrm{E}+03$ | 9.8568 | $5.76 \mathrm{E}+00$ | 18.388 | $1.479 \mathrm{E}-03$ |
| Perm [cm^2] | 7.1E-12 | $1.585 E+05$ | 5.720E-11 | $4.149 \mathrm{E}-04$ | $5.701 \mathrm{E}-11$ | 4.149E-04 | 5.436E-11 | $4.149 \mathrm{E}-04$ | $2.390 E+03$ | 7.4344 | $7.66 \mathrm{E}+00$ | 21.509 | $1.453 \mathrm{E}-03$ |
| Sw | 0.7059 | $1.000 \mathrm{E}+05$ | 6.900E-11 | 4.082E-04 | 6.880E-11 | 4.082E-04 | 6.614E-11 | 4.082E-04 | $2.437 \mathrm{E}+03$ | 5.8135 | 9.82E+00 | 26.171 | $1.430 \mathrm{E}-03$ |
|  |  | $6.310 \mathrm{E}+04$ | $8.700 \mathrm{E}-11$ | $4.020 \mathrm{E}-04$ | $8.681 \mathrm{E}-11$ | 4.020E-04 | $8.412 \mathrm{E}-11$ | 4.020E-04 | 2.479E+03 | 4.7427 | $1.21 \mathrm{E}+01$ | 33.286 | $1.408 \mathrm{E}-03$ |
| Geometry: |  | $3.981 E+04$ | $1.150 \mathrm{E}-10$ | $3.960 \mathrm{E}-04$ | $1.148 \mathrm{E}-10$ | $3.960 \mathrm{E}-04$ | $1.121 \mathrm{E}-10$ | $3.960 \mathrm{E}-04$ | $2.519 \mathrm{E}+03$ | 4.0512 | $1.41 \mathrm{E}+01$ | 44.364 | $1.387 \mathrm{E}-03$ |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 1.580E-10 | $3.902 \mathrm{E}-04$ | 1.578E-10 | 3.902E-04 | 1.551E-10 | 3.902E-04 | $2.558 \mathrm{E}+03$ | 3.5901 | $1.59 E+01$ | 61.375 | 1.367E-03 |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 2.220E-10 | $3.846 \mathrm{E}-04$ | 2.218E-10 | 3.846E-04 | $2.191 \mathrm{E}-10$ | 3.846E-04 | $2.596 \mathrm{E}+03$ | 3.2471 | $1.76 \mathrm{E}+01$ | 86.698 | $1.347 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | 3.210E-10 | $3.793 \mathrm{E}-04$ | 3.208E-10 | 3.793E-04 | 3.181E-10 | 3.793E-04 | $2.633 \mathrm{E}+03$ | 3.0161 | $1.90 \mathrm{E}+01$ | 125.853 | 1.329E-03 |


| Experiment ID: | MD0546 | Freq [ Hz ] | Cp-m [F] | Gp_m [S] | CR_Osc [F] | Gp_osc [S] | CP_hc [F] | Gp_hc [ S ] | \|21] [0] | 6 [deg] | Loss Tan | DielConstant | $\frac{\text { Cond }[\mathrm{S} / \mathrm{m}]}{1.849 \mathrm{E}-03}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 2.648E-11 | 5.320E-04 | 2.619E-11 | $5.286 \mathrm{E}-04$ | $2.377 \mathrm{E}-11$ | $5.279 \mathrm{E}-04$ | $6.313 \mathrm{E}+02$ | 70.5352 | 3.53E-01 |  |  |
|  |  | $6.310 \mathrm{E}+06$ | 2.810E-11 | $4.750 \mathrm{E}-04$ | $2.786 \mathrm{E}-11$ | 4.737E-04 | $2.536 \mathrm{E}-11$ | $4.728 \mathrm{E}-04$ | $9.001 \mathrm{E}+02$ | 64.8124 | $4.70 \mathrm{E}-01$ | 10.034 | $1.657 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 2.986E-11 | $4.255 \mathrm{E}-04$ | 2.964E-11 | 4.250E-04 | 2.711E-11 | $4.243 \mathrm{E}-04$ | $1.250 \mathrm{E}+03$ | 57.9630 | $6.26 \mathrm{E}-01$ | 10.726 | $1.487 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | $3.171 \mathrm{E}-11$ | 3.828E-04 | 3.150E-11 | 3.826E-04 | 2.894E-11 | $3.821 \mathrm{E}-04$ | $1.679 E+03$ | 50.0844 | $8.37 \mathrm{E}-01$ | 11.450 | 1.339E-03 |
| Ms [g] | 7.1770 | $1.585 \mathrm{E}+06$ | 3.356E-11 | 3.521E-04 | 3.336E-11 | 3.520E-04 | 3.078E-11 | 3.517E-04 | $2.144 \mathrm{E}+03$ | 41.0719 | $1.15 \mathrm{E}+00$ | 12.178 | $1.232 \mathrm{E}-03$ |
| Mcl [g] | 4.2454 | 1.000E+06 | 3.540E-11 | 3.318E-04 | 3.520E-11 | 3.318E-04 | 3.261E-11 | 3.315E-04 | $2.566 E+03$ | 31.7137 | $1.62 \mathrm{E}+00$ | 12.902 | $1.162 \mathrm{E}-03$ |
| Mw [g] | 1.6336 | $6.310 \mathrm{E}+05$ | 3.740E-11 | 3.189E-04 | 3.720E-11 | $3.189 \mathrm{E}-04$ | 3.459E-11 | $3.187 \mathrm{E}-04$ | 2.882E+0 | 23.2800 | $2.32 \mathrm{E}+00$ | 13.687 | $1.117 \mathrm{E}-03$ |
| Wcl (dry) | 0.3717 | $3.981 \mathrm{E}+05$ | 4.010E-11 | 3.102E-04 | 3.990E-11 | 3.102E-04 | 3.728E-11 | $3.101 \mathrm{E}-04$ | $3.088 \mathrm{E}+03$ | 16.7382 | $3.33 \mathrm{E}+00$ | 14.752 | $1.086 \mathrm{E}-03$ |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | 4.380E-11 | 3.038E-04 | $4.360 \mathrm{E}-11$ | 3.038E-04 | 4.097E-11 | 3.037E-04 | $3.220 \mathrm{E}+03$ | 12.0182 | $4.70 \mathrm{E}+00$ | 16.211 | $1.064 \mathrm{E}-03$ |
| Perm [cm^2] | 7.1E-12 | $1.585 \mathrm{E}+05$ | $4.950 \mathrm{E}-11$ | 2.983E-04 | 4.930E-11 | 2.983E-04 | 4.666E-11 | $2.983 \mathrm{E}-04$ | $3.313 \mathrm{E}+03$ | 8.8542 | 6.42E+00 | 18.461 | $1.045 \mathrm{E}-03$ |
| Sw | 0.6733 | $1.000 \mathrm{E}+05$ | $5.810 \mathrm{E}-11$ | $2.935 \mathrm{E}-04$ | 5.790E-11 | 2.935E-04 | 5.524E-11 | $2.935 \mathrm{E}-04$ | 3.384E+03 | 6.7448 | 8.46E+00 | 21.857 | $1.028 \mathrm{E}-03$ |
|  |  | $6.310 E+04$ | 7.100E-11 | 2.890E-04 | 7.080E-11 | 2.890E-04 | 6.812E-11 | $2.890 \mathrm{E}-04$ | $3.445 \mathrm{E}+03$ | 5.3390 | $1.07 E+01$ | 26.954 | 1.012E-03 |
| Geometry: |  | $3.981 \mathrm{E}+04$ | $9.100 \mathrm{E}-11$ | $2.847 \mathrm{E}-04$ | $9.081 \mathrm{E}-11$ | 2.847E-04 | $8.811 \mathrm{E}-11$ | 2.847E-04 | 3.502E+03 | 4.4271 | $1.29 \mathrm{E}+01$ | 34.865 | 9.974E-04 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | $1.220 \mathrm{E}-10$ | 2.805E-04 | $1.218 \mathrm{E}-10$ | 2.805E-04 | $1.191 \mathrm{E}-10$ | $2.805 \mathrm{E}-04$ | 3.557E+03 | 3.8340 | $1.49 \mathrm{E}+01$ | 47.126 | 9.827E-04 |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 1.690E-10 | 2.765E-04 | 1.688E-10 | 2.765E-04 | 1.661E-10 | $2.765 \mathrm{E}-04$ | $3.610 E+03$ | 3.4233 | $1.67 \mathrm{E}+01$ | 65.719 | 9.687E-04 |
|  |  | $1.000 \mathrm{E}+04$ | $2.410 \mathrm{E}-10$ | 2.726E-0 | 2.408E-10 | 2.726E-04 | 2.381E-10 | 2.726E-04 | 3.663E+03 | 3.1407 | $1.82 \mathrm{E}+0$ | 94.195 | 9.550E- |



| Experiment ID: | MD0548 | Frea [ Hz ] | $\mathrm{CP}_{\text {- }} \mathrm{m}$ [ F$]$ | Gp_m [S] | Cp_ose [F] | Gp_osc [S] | Cp_hc [F] | Gp_hc [S] | IZI [ $\Omega$ ] | 0 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | $1.997 \mathrm{E}-11$ | $2.315 \mathrm{E}-04$ | 1.971E-11 | 2.304E-04 | 1.729E-11 | 2.297E-04 | $9.006 \mathrm{E}+02$ | 78.0631 | 2.11E-01 | 6.841 | $8.046 \mathrm{E}-04$ |
|  |  | $6.310 \mathrm{E}+06$ | $2.134 \mathrm{E}-11$ | 1.837E-04 | $2.111 \mathrm{E}-11$ | $1.833 \mathrm{E}-04$ | $1.861 \mathrm{E}-11$ | $1.824 \mathrm{E}-04$ | $1.316 \mathrm{E}+03$ | 76.1114 | 2.47E-01 | 7.364 | 6.391 E-04 |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 2.290E-11 | $1.394 \mathrm{E}-04$ | 2.269E-11 | $1.393 \mathrm{E}-04$ | 2.015E-11 | $1.386 \mathrm{E}-04$ | $1.913 \mathrm{E}+03$ | 74.6269 | 2.75E-01 | 7.973 | 4.855E-04 |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | $2.461 \mathrm{E}-11$ | $1.014 \mathrm{E}-04$ | $2.440 \mathrm{E}-11$ | 1.014E-04 | 2.184E-11 | $1.008 \mathrm{E}-04$ | $2.785 \mathrm{E}+03$ | 73.6921 | 2.93E-01 | 8.640 | 3.533E-04 |
| Ms [9] | 7.1770 | $1.585 \mathrm{E}+06$ | $2.624 \mathrm{E}-11$ | 7.260E-05 | 2.604E-11 | $7.259 \mathrm{E}-05$ | 2.346E-11 | $7.224 \mathrm{E}-05$ | $4.090 \mathrm{E}+03$ | 72.8142 | $3.09 \mathrm{E}-01$ | 9.281 | $2.531 \mathrm{E}-04$ |
| Mcl [g] | 4.2454 | $1.000 \mathrm{E}+06$ | $2.756 \mathrm{E}-11$ | 5.400E-05 | $2.736 \mathrm{E}-11$ | $5.399 \mathrm{E}-05$ | 2.476E-11 | 5.377E-05 | $6.074 \mathrm{E}+03$ | 70.9375 | 3.46E-01 | 9.799 | 1.884E-04 |
| Mw [g] | 1.3998 | $6.310 \mathrm{E}+05$ | 2.860E-11 | $4.330 \mathrm{E}-05$ | $2.840 \mathrm{E}-11$ | $4.330 \mathrm{E}-\mathrm{OS}$ | 2.579E-11 | $4.314 \mathrm{E}-05$ | $9.012 \mathrm{E}+03$ | 67.1226 | $4.22 \mathrm{E}-01$ | 10.204 | $1.511 \mathrm{E}-04$ |
| Wcl (dry) | 0.3717 | $3.981 \mathrm{E}+05$ | 2.938E-11 | 3.760E-O5 | $2.918 \mathrm{E}-11$ | $3.760 \mathrm{E}-05$ | 2.656E-11 | $3.749 \mathrm{E}-05$ | $1.311 \mathrm{E}+04$ | 60.5632 | 5.64E-01 | 10.509 | $1.313 \mathrm{E}-04$ |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | 3.020E-11 | $3.458 \mathrm{E}-05$ | $3.000 \mathrm{E}-11$ | $3.458 \mathrm{E}-05$ | 2.737E-11 | $3.451 \mathrm{E}-05$ | $1.809 \mathrm{E}+04$ | 51.3740 | 7.99E-01 | 10.829 | $1.209 \mathrm{E}-04$ |
| Perm [cm^2] | $7.1 \mathrm{E}-12$ | $1.585 \mathrm{E}+05$ | $3.120 \mathrm{E}-11$ | $3.284 \mathrm{E}-05$ | $3.100 \mathrm{E}-11$ | 3.284E-05 | 2.835E-11 | $3.279 \mathrm{E}-05$ | $2.311 \mathrm{E}+04$ | 40.7261 | $1.16 \mathrm{E}+00$ | 11.218 | $1.149 \mathrm{E}-04$ |
| Sw | 0.5770 | $1.000 \mathrm{E}+05$ | 3.255E-11 | 3.169E-05 | 3.235E-11 | 3.169E-05 | 2.969E-11 | 3.166E-05 | $2.721 E+04$ | 30.5040 | $1.70 \mathrm{E}+00$ | 11.746 | 1.109E-04 |
|  |  | $6.310 \mathrm{E}+04$ | $3.450 \mathrm{E}-11$ | $3.083 \mathrm{E}-05$ | $3.430 \mathrm{E}-11$ | $3.083 \mathrm{E}-05$ | 3.162E-11 | $3.081 \mathrm{E}-05$ | $3.006 \mathrm{E}+04$ | 22.1389 | $2.46 E+00$ | 12.511 | $1.079 \mathrm{E}-04$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 3.730E-11 | 3.012E-05 | $3.710 \mathrm{E}-11$ | $3.012 \mathrm{E}-05$ | $3.441 \mathrm{E}-11$ | $3.011 \mathrm{E}-05$ | $3.194 \mathrm{E}+04$ | 15.9546 | $3.50 \mathrm{E}+00$ | 13.615 | $1.055 \mathrm{E}-04$ |
| Diameter [ cm ] | 4.207 | $2.512 \mathrm{E}+04$ | $4.150 \mathrm{E}-11$ | $2.949 \mathrm{E}-05$ | $4.130 \mathrm{E}-11$ | 2.949E-05 | 3.859E-11 | $2.948 \mathrm{E}-05$ | $3.322 \mathrm{E}+04$ | 11.6723 | $4.84 \mathrm{E}+00$ | 15.269 | $1.033 \mathrm{E}-04$ |
| Thickness [ cm ] | 0.487 | $1.585 \mathrm{E}+04$ | 4.770E-11 | 2.893E-05 | 4.750E-11 | $2.893 \mathrm{E}-05$ | 4.477E-11 | 2.892E-05 | $3.417 \mathrm{E}+04$ | 8.7623 | $6.49 \mathrm{E}+00$ | 17.714 | $1.013 \mathrm{E}-04$ |
|  |  | $1.000 \mathrm{E}+04$ | 5.720E-11 | $2.840 \mathrm{E}-05$ | $5.700 \mathrm{E}-11$ | $2.840 \mathrm{E}-05$ | $5.425 \mathrm{E}-11$ | 2.840E-05 | $3.497 \mathrm{E}+04$ | 6.8448 | $8.33 \mathrm{E}+00$ | 21.465 | $9.948 \mathrm{E}-05$ |




| Experiment ID: | MD0552 | Freq [Hz] | Cp_m [F] | Gp_m [S] | Cp_osc [F] | Gp_ose [S] | Cp_he [F] | Gp_hc [S] | \| 71 [ $\Omega$ ] | 6 [deg] | Loss Tan | DleiConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 1.664E-11 | $1.814 \mathrm{E}-04$ | 1.639E-11 | $1.807 \mathrm{E}-04$ | 1.398E-11 | 1.800E-04 | $1.115 \mathrm{E}+03$ | 78.4202 | 2.05E-01 | 5.531 | 6.305E-04 |
|  |  | $6.310 E+06$ | $1.781 \mathrm{E}-11$ | $1.388 \mathrm{E}-04$ | $1.759 \mathrm{E}-11$ | $1.386 \mathrm{E}-04$ | $1.509 \mathrm{E}-11$ | $1.377 \mathrm{E}-04$ | $1.629 \mathrm{E}+03$ | 77.0374 | 2.30E-01 | 5.969 | $4.823 \mathrm{E}-04$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | $1.914 \mathrm{E}-11$ | $1.007 \mathrm{E}-04$ | $1.893 \mathrm{E}-11$ | $1.006 \mathrm{E}-04$ | 1.639E-11 | $9.993 \mathrm{E}-05$ | $2.369 \mathrm{E}+03$ | 76.3042 | $2.44 \mathrm{E}-01$ | 6.486 | 3.501E-04 |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | $2.061 \mathrm{E}-11$ | $6.870 \mathrm{E}-05$ | 2.040E-11 | $6.868 \mathrm{E}-05$ | $1.784 \mathrm{E}-11$ | $6.815 \mathrm{E}-05$ | $3.452 \mathrm{E}+03$ | 76.3925 | $2.42 \mathrm{E}-01$ | 7.058 | $2.388 \mathrm{E}-04$ |
| Ms [g] | 7.1770 | $1.585 E+06$ | $2.212 \mathrm{E}-11$ | $4.420 \mathrm{E}-05$ | 2.192E-11 | $4.419 \mathrm{E}-05$ | $1.934 \mathrm{E}-11$ | 4.384E-05 | $5.064 \mathrm{E}+03$ | 77.1722 | 2.28E-01 | 7.651 | $1.536 \mathrm{E}-04$ |
| Mcl [g] | 4.2454 | $1.000 \mathrm{E}+06$ | 2.350E-11 | $2.730 \mathrm{E}-05$ | 2.330E-11 | 2.730E-05 | 2.070E-11 | 2.707E-05 | 7.526E+03 | 78.2458 | 2.08E-01 | 8.192 | 9.483E-05 |
| Mw [g] | 0.9452 | $6.310 \mathrm{E}+05$ | $2.468 \mathrm{E}-11$ | $1.679 \mathrm{E}-05$ | 2.448E-11 | $1.679 \mathrm{E}-05$ | $2.187 \mathrm{E}-11$ | $1.663 \mathrm{E}-05$ | $1.133 \mathrm{E}+04$ | 79.1417 | 1.92E-01 | 8.653 | $5.826 \mathrm{E}-05$ |
| Wcl (dry) | 0.3717 | $3.981 \mathrm{E}+05$ | 2.570E-11 | $1.060 \mathrm{E}-05$ | 2.550E-11 | 1.060E-05 | 2.288E-11 | $1.049 \mathrm{E}-05$ | 1.719E+04 | 79.6130 | $1.83 \mathrm{E}-01$ | 9.053 | $3.675 \mathrm{E}-05$ |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | $2.661 \mathrm{E}-11$ | $7.100 \mathrm{E}-06$ | $2.641 \mathrm{E}-11$ | $7.099 \mathrm{E}-06$ | $2.378 \mathrm{E}-11$ | 7.032E-06 | $2.619 \mathrm{E}+04$ | 79.3865 | 1.87E-01 | 9.408 | $2.464 \mathrm{E}-05$ |
| Perm [cm^2] | $7.1 \mathrm{E}-12$ | $1.585 \mathrm{E}+05$ | 2.745E-11 | $5.120 \mathrm{E}-06$ | 2.725E-11 | $5.119 \mathrm{E}-06$ | 2.460E-11 | $5.074 \mathrm{E}-06$ | 3.997E+04 | 78.2989 | 2.07E-01 | 9.734 | $1.778 \mathrm{E}-05$ |
| Sw | 0.3896 | $1.000 \mathrm{E}+05$ | $2.831 \mathrm{E}-11$ | 3.970E-06 | $2.811 \mathrm{E}-11$ | 3.970E-06 | 2.545E-11 | $3.940 \mathrm{E}-06$ | $6.073 \mathrm{E}+04$ | 76.1562 | $2.46 \mathrm{E}-01$ | 10.068 | 1.380E-05 |
|  |  | $6.310 \mathrm{E}+04$ | 2.930E-11 | $3.290 \mathrm{E}-06$ | 2.910E-11 | $3.290 \mathrm{E}-06$ | 2.642E-11 | $3.270 \mathrm{E}-06$ | $9.114 \mathrm{E}+04$ | 72.6608 | $3.12 \mathrm{E}-01$ | 10.453 | $1.146 \mathrm{E}-05$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 3.068E-11 | $2.832 \mathrm{E}-06$ | 3.048E-11 | 2.832E-06 | 2.779E-11 | $2.818 \mathrm{E}-06$ | $1.333 \mathrm{E}+05$ | 67.9320 | 4.05E-01 | 10.996 | $9.873 \mathrm{E}-06$ |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 3.257E-11 | $2.474 \mathrm{E}-06$ | $3.237 \mathrm{E}-11$ | $2.474 \mathrm{E}-06$ | $2.966 \mathrm{E}-11$ | $2.465 \mathrm{E}-06$ | $1.890 E+05$ | 62.2286 | $5.27 \mathrm{E}-01$ | 11.735 | 8.636E-06 |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 3.501E-11 | $2.168 \mathrm{E}-06$ | $3.481 \mathrm{E}-11$ | $2.168 \mathrm{E}-06$ | $3.208 \mathrm{E}-11$ | $2.162 \mathrm{E}-06$ | $2.592 \mathrm{E}+05$ | 55.9100 | 6.77E-01 | 12.693 | $7.574 \mathrm{E}-06$ |
|  |  | $1.000 \mathrm{E}+04$ | 3.782E-11 | 1.916E-06 | 3.762E-11 | $1.916 \mathrm{E}-06$ | 3.487E-11 | 1.912E-06 | $3.439 \mathrm{E}+05$ | 48.8884 | 8.73E-01 | 13.797 | 6.699E-06 |





| Experiment ID: | MD0556 | Freq [ Hz ] | Cp-m [F] | Gp_m [S] | Cp_osc [F] | Gp_ose [S] | CP_hc [F] | Gp_hc [S] | \|z1 [ 0 ] | 6 [deg] | Loss Tan | DleiConstant | $\begin{aligned} \hline \text { Cond }[\mathrm{S} / \mathrm{m}] \\ \hline 5.826 \mathrm{E}-04 \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.491E-11 | $1.676 \mathrm{E}-04$ | $1.466 \mathrm{E}-11$ | $1.670 \mathrm{E}-04$ | 1.225E-11 | $1.663 \mathrm{E}-04$ | $1.270 \mathrm{E}+03$ | 77.8054 | 2.16E-01 |  |  |
|  |  | $6.310 \mathrm{E}+06$ | $1.596 \mathrm{E}-11$ | $1.271 \mathrm{E}-04$ | 1.574E-11 | 1.269E-04 | 1.324E-11 | $1.260 \mathrm{E}-04$ | $1.853 \mathrm{E}+03$ | 76.4996 | $2.40 \mathrm{E}-01$ | 5.238 | $4.415 E-04$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | $1.713 \mathrm{E}-11$ | $9.260 \mathrm{E}-05$ | 1.692E-11 | $9.254 \mathrm{E}-05$ | 1.438E-11 | $9.184 \mathrm{E}-05$ | $2.693 \mathrm{E}+03$ | 75.6809 | 2.55E-01 | 5.69 | 3.218E-04 |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 1.847E-11 | $6.430 \mathrm{E}-05$ | 1.826E-11 | 6.428E-05 | 1.570E-11 | 6.375E-05 | 3.909E+03 | 75.5704 | $2.57 \mathrm{E}-01$ | 6.212 | 2.234E-04 |
| Ms [g] | 7.1770 | $1.585 \mathrm{E}+06$ | $1.992 \mathrm{E}-11$ | $4.250 \mathrm{E}-05$ | 1.972E-11 | $4.249 \mathrm{E}-05$ | 1.714E-11 | $4.214 \mathrm{E}-05$ | 5.689E+03 | 76.1268 | $2.47 \mathrm{E}-01$ | 6.780 | 1.477E-04 |
| Mcl [g] | 4.245 | 1.000E+06 | $2.137 \mathrm{E}-11$ | $2.660 \mathrm{E}-05$ | 2.117E-11 | $2.660 \mathrm{E}-05$ | 1.857E-11 | $2.637 \mathrm{E}-05$ | 8.358E+03 | 77.2683 | 2.26E-01 | 7.350 | 9.238E-05 |
| Mw [g] | 5635 | $6.310 \mathrm{E}+0$ | 271E-11 | 1.595E-05 | $2.251 \mathrm{E}-11$ | 1.595E-05 | 1.990E-11 | 1.579E-05 | $1.243 \mathrm{E}+04$ | 78.6814 | $2.00 \mathrm{E}-01$ | 7.873 | 5.532E-05 |
| WCl (dry) | 0.3717 | $3.981 \mathrm{E}+05$ | 2.389E-11 | 9.330E-06 | 2.369E-11 | 9.329E-06 | 2.107E-11 | $9.220 \mathrm{E}-06$ | $1.869 \mathrm{E}+$ | 80.0766 | $1.75 \mathrm{E}-01$ | 8.33 | 3.230E-05 |
| Porosity (dry) | 0.3592 | $2.512 \mathrm{E}+05$ | 2.489E-11 | $5.450 \mathrm{E}-06$ | 2.469E-11 | 5.449E-06 | 2.206E-11 | 5.382E-06 | $2.839 \mathrm{E}+$ | 81.2114 | $1.55 \mathrm{E}-01$ | 8.727 | 1.886E-05 |
| Perm [cm^2] | 7.1E-12 | $1.585 \mathrm{E}+05$ | 2.575E-11 | $3.260 \mathrm{E}-06$ | 2.555E-11 | $3.259 \mathrm{E}-06$ | 2.290E-11 | 3.214E-06 | 4.342E+04 | 81.9783 | $1.41 \mathrm{E}-01$ | 9.06 | $1.126 \mathrm{E}-05$ |
| Sw | 0.2323 | $1.000 \mathrm{E}+05$ | 2.651E-11 | 2.020E-06 | 2.631E-11 | $2.020 \mathrm{E}-06$ | 2.365E-11 | $1.990 \mathrm{E}-06$ | 6.671E+04 | 82.3711 | $1.34 \mathrm{E}-01$ | 9.356 | $6.972 \mathrm{E}-06$ |
|  |  | $6.310 \mathrm{E}+04$ | 2.723E-11 | 1.322E-06 | 2.703E-11 | $1.322 \mathrm{E}-06$ | 2.435E-11 | $1.302 \mathrm{E}-06$ | 1.027E+05 | 82.3182 | 1.35E-01 | 9.63 | $4.561 \mathrm{E}-06$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | $2.791 \mathrm{E}-11$ | $9.210 \mathrm{E}-07$ | $2.771 \mathrm{E}-11$ | 9.210E-07 | 2.502E-11 | 9.070E-07 | $1.581 \mathrm{E}+05$ | 81.7535 | $1.45 \mathrm{E}-01$ | 9.899 | 3.178E-06 |
| Diameter [cm] | 4.207 | $2.512 \mathrm{E}+04$ | 2.858E-11 | 6.830E-07 | 2.838E-11 | $6.830 \mathrm{E}-07$ | 2.567E-11 | 6.740E-07 | $2.435 E+05$ | 80.5542 | $1.66 \mathrm{E}-01$ | 10.157 | $2.361 \mathrm{E}-06$ |
| Thickness [cm] | 0.487 | $1.585 \mathrm{E}+04$ | 2.926E-11 | $5.430 \mathrm{E}-07$ | 2.906E-11 | $5.430 \mathrm{E}-07$ | 2.633E-11 | 5.370E-07 | 3.737E+05 | 78.4250 | $2.05 \mathrm{E}-01$ | 10.418 | 1.881E-06 |
|  |  | $1.000 \mathrm{E}+04$ | 2.998E-11 | 4.570E-07 | 2.978E-11 | 4.570E-07 | 2.703E-11 | 4.530E-07 | 5.689E+05 | 75.0645 | 2.67E-01 | 10.695 | $1.587 \mathrm{E}-06$ |






| Experiment ID: | MD0815 | Freq [ Hz ] | CP_m [F] | Gp_m [S] | CP_Osc [ 5 ] | Gp_osc [S] | Cp_hc [F] | Gp_hc [S] | $121[0]$ | [ [deg] | Loss Tan | $\begin{array}{\|r\|} \hline \text { DielConstant } \\ \hline 27.304 \\ \hline \end{array}$ | $\frac{\text { cond }[\mathrm{S} / \mathrm{m}]}{9.202 \mathrm{E}]}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | $8.076 \mathrm{E}-11$ | $3.020 \mathrm{E}-03$ | 8.004E-11 | $2.961 \mathrm{E}-03$ | 7.779E-11 | $2.961 \mathrm{E}-03$ | 1.750E+02 | 58.7923 | 6.06E-01 |  |  |
|  |  | $6.310 \mathrm{E}+06$ | 9.480E-11 | $2.237 E-03$ | 9.432E-11 | $2.217 \mathrm{E}-03$ | 9.197E-11 | $2.216 \mathrm{E}-03$ | $2.344 \mathrm{E}+02$ | 58.7114 | $6.08 \mathrm{E}-01$ | 32.284 | 9.2887E-03 |
| Sample: | Clay | $3.981 \mathrm{E}+06$ | 1.099E-10 | 1.668E-03 | 1.096E-10 | $1.661 \mathrm{E}-03$ | 1.072E-10 | 1.660E-03 | 3.171E+02 | 58.2291 | $6.19 \mathrm{E}-01$ | 37.620 | $5.160 \mathrm{E}-03$ |
| Mineralogy | Mont | $2.512 \mathrm{E}+06$ | 1.267E-10 | 1.264E-03 | 1.264E-10 | 1.262E-03 | $1.240 \mathrm{E}-10$ | 1.261 E-03 | 4.295E+02 | 57.2070 | $6.44 \mathrm{E}-01$ | 43.531 | 3.919E-03 |
| Ms [g] | 0.0000 | $1.585 \mathrm{E}+06$ | $1.457 \mathrm{E}-10$ | 9.770E-04 | 1.455E-10 | 9.762E-04 | 1.430E-10 | $9.758 \mathrm{E}-04$ | 5.792E+02 | 55.5868 | 6.85E-01 | 50.208 | .033E-03 |
| Mal [g] | 7.9170 | 1.000E+06 | 1.680E-10 | $7.730 \mathrm{E}-04$ | 1.678E-10 | $7.727 \mathrm{E}-04$ | $1.653 \mathrm{E}-10$ | 7.724E-04 | 7.725E+02 | 53.3678 | $7.44 \mathrm{E}-01$ | 58.037 | $2.401 \mathrm{E}-03$ |
| Mw [9] | 0.0000 | $6.310 \mathrm{E}+05$ | 1.944E-10 | 6.247E-04 | 1.942E-10 | $6.246 \mathrm{E}-04$ | 1.917E-10 | 6.244E-04 | $1.017 \mathrm{E}+03$ | 50.5985 | $8.21 \mathrm{E}-01$ | 67.303 | 1.941 E-03 |
| Wd (dry) | 1.0000 | $3.981 \mathrm{E}+0 \mathrm{~S}$ | $2.274 \mathrm{E}-10$ | 5.146E-04 | 2.272E-10 | 5.146E-04 | 2.247E-10 | $5.144 \mathrm{E}-04$ | $1.312 \mathrm{E}+03$ | 47.5373 | $9.15 E-01$ | 78.885 | $1.599 \mathrm{E}-03$ |
| Porosity (dry) | 0.4444 | $2.512 \mathrm{E}+0 \mathrm{~S}$ | $2.693 \mathrm{E}-10$ | $4.310 \mathrm{E}-04$ | 2.691E-10 | $4.310 \mathrm{E}-04$ | 2.666E-10 | $4.309 \mathrm{E}-04$ | $1.660 \mathrm{E}+03$ | 4.3193 | $1.02 \mathrm{E}+00$ | 93.586 | .339E-03 |
| Perm [cm^2] |  | $1.585 \mathrm{E}+05$ | 3.243E-10 | 3.655E-04 | 3.241E-10 | $3.655 E-04$ | 3.216E-10 | 3.654E-04 | $2.058 \mathrm{E}+03$ | 41.2300 | $1.14 \mathrm{E}+00$ | 112 | 3 |
| Sw | . 0000 | $1.000 \mathrm{E}+05$ | 3.979E-10 | 3.127E-04 | 3.977E-10 | 3.127E-04 | 3.952E-10 | 3.127E-04 | $2.505 E+03$ | 38.4547 | $1.26 \mathrm{E}+00$ | 138.716 | 9.717E-04 |
|  |  | $6.310 \mathrm{E}+04$ | 4.980E-10 | 2.692E-04 | $4.978 \mathrm{E}-10$ | 2.692E-04 | 4.953E-10 | $2.692 \mathrm{E}-04$ | 3.001E+03 | 36.1079 | $1.37 E+00$ | 173.846 | $8.366 \mathrm{E}-04$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 6.380E-10 | $2.325 \mathrm{E}-04$ | 6.378E-10 | $2.325 \mathrm{E}-04$ | 6.353E-10 | $2.325 \mathrm{E}-04$ | $3.551 \mathrm{E}+03$ | 34.3525 | $1.46 \mathrm{E}+\infty 0$ | 222.986 | 7.226 E-04 |
| Diameter [cm] | 4.202 | $2.512 \mathrm{E}+04$ | 8.360E-10 | $2.008 \mathrm{E}-04$ | 8.358E-10 | 2.008E-04 | 8.332E-10 | $2.008 \mathrm{E}-04$ | $4.166 E+03$ | 33.2230 | $1.53 \mathrm{E}+00$ | 292.481 | .240E-04 |
| Thickness [cm] | 0.431 | $1.585 E+04$ | $1.123 \mathrm{E}-09$ | $1.730 \mathrm{E}-04$ | 1.123E-09 | 1.730E-04 | 1.120E-09 | 1.730E-04 | $4.858 \mathrm{E}+03$ | 32.8160 | $1.55 \mathrm{E}+00$ | 393.218 |  |
|  |  | $1.000 \mathrm{E}+04$ | 1.540E-09 | 1.479E-04 | 1.540E-09 | 1.479E-04 | 1.537E-09 | 1.479E-04 | 5.661E+03 | 33.1479 | $1.53 \mathrm{E}+00$ | 393.218 539.580 | 5.377E-04 |







| Experiment ID: | MD0826 | Freg [ Hz ] | CP_m [F] | Gp_m [S] | Cp_ose [F] | Gp_osc [S] | C $\mathrm{P}_{\text {n }} \mathrm{hc}$ [F] | Gp,he [S] | 121 [0] | 6 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $1.000 \mathrm{E}+07$ | 4.339E-11 | 1.303E-03 | $4.300 \mathrm{E}-11$ | 1.289E-03 | $4.074 \mathrm{E}-11$ | 1.289E-03 | 3.489E+02 | 63.2784 | 5.03E-01 | 14.301 | 4.005E-03 |
|  |  | $6.310 \mathrm{E}+06$ | 4.640E-11 | $1.210 \mathrm{E}-03$ | 4.614E-11 | $1.205 E-03$ | $4.379 \mathrm{E}-11$ | $1.204 \mathrm{E}-03$ | $4.734 \mathrm{E}+02$ | 55.2616 | $6.93 \mathrm{E}-01$ | 15.371 | $3.741 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 E+06$ | 4.960E-11 | $1.123 \mathrm{E}-03$ | 4.939E-11 | $1.121 \mathrm{E}-03$ | 4.701E-11 | - 1.120E-03 | 6.158E+02 | 46.3901 | 9.53E-O1 | 16.500 | $3.481 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 5.350E-11 | $1.051 \mathrm{E}-03$ | $5.331 \mathrm{E}-11$ | $1.050 \mathrm{E}-03$ | 5.090E-11 | 1.050E-03 | $7.566 \mathrm{E}+02$ | 37.4276 | $1.31 \mathrm{E}+00$ | 17.866 | $3.262 \mathrm{E}-03$ |
| Ms [g] | 9.5002 | $1.585 E+06$ | 5.802E-11 | $9.935 \mathrm{E}-04$ | 5.784E-11 | 9.932E-04 | 5.541E-11 | 9.928E-04 | 8.804E+02 | 29.0644 | $1.80 \mathrm{E}+00$ | 19.450 | $3.086 \mathrm{E}-03$ |
| Mcl [g] | 2.5043 | $1.000 \mathrm{E}+06$ | 6.384E-11 | 9.480E-04 | 6.366E-11 | 9.479E-04 | 6.122E-11 | $9.476 \mathrm{E}-04$ | $9.778 \mathrm{E}+02$ | 22.0930 | $2.46 \mathrm{E}+00$ | 21.489 | $2.945 \mathrm{E}-03$ |
| Mw [9] | 1.2100 | $6.310 \mathrm{E}+05$ | 7.130E-11 | $9.124 \mathrm{E}-04$ | 7.112E-11 | $9.123 E-04$ | 6.867E-11 | $9.122 \mathrm{E}-04$ | $1.051 \mathrm{E}+03$ | 16.6171 | $3.35 \mathrm{E}+00$ | 24.103 | $2.835 E-03$ |
| Wcl (dry) | 0.2086 | $3.981 \mathrm{E}+05$ | $8.150 \mathrm{E}-11$ | 8.841 E-04 | 8.132E-11 | $8.841 \mathrm{E}-04$ | $7.886 \mathrm{E}-11$ | 8.840E-04 | $1.104 \mathrm{E}+03$ | 12.5793 | $4.48 \mathrm{E}+00$ | 27.680 | $2.747 \mathrm{E}-03$ |
| Porosity (dry) | 0.2377 | $2.512 \mathrm{E}+$ OS | 9.580E-11 | $8.609 \mathrm{E}-04$ | 9.562E-11 | 8.609E-04 | $9.314 \mathrm{E}-11$ | $8.608 \mathrm{E}-04$ | $1.145 E+03$ | 9.6904 | $5.86 \mathrm{E}+00$ | 32.692 | $2.675 \mathrm{E}-03$ |
| Perm [cm^2] | 5.38E-12 | $1.585 \mathrm{E}+05$ | $1.169 \mathrm{E}-10$ | $8.408 \mathrm{E}-04$ | 1.167E-10 | 8.408E-04 | $1.142 \mathrm{E}-10$ | 8.407E-04 | $1.179 E+03$ | 7.7055 | 7.39E+00 | 40.098 | $2.613 \mathrm{E}-03$ |
| Sw | 0.8534 | $1.000 E+05$ | 1.487E-10 | 8.226E-04 | 1.485E-10 | 8.226E-04 | $1.460 \mathrm{E}-10$ | 8.226E-04 | $1.208 E+03$ | 6.3636 | 8.97E+00 | 51.249 | 2.556E-03 |
|  |  | $6.310 \mathrm{E}+04$ | 1.970E-10 | 8.057E-04 | 1.968E-10 | 8.057E-04 | $1.943 \mathrm{E}-10$ | 8.057E-04 | $1.236 E+03$ | 5.4609 | $1.05 \mathrm{E}+01$ | 68.197 | $2.504 \mathrm{E}-03$ |
| Geometry: Diameter [cm] Thickness [cm] | $\begin{aligned} & 4.202 \\ & 0.431 \end{aligned}$ | $3.981 \mathrm{E}+04$ | $2.690 \mathrm{E}-10$ | $7.897 \mathrm{E}-04$ | 2.688E-10 | 7.897E-04 | 2.663E-10 | 7.897E-04 | $1.262 \mathrm{E}+03$ | 4.8216 | $1.19 \mathrm{E}+01$ | 93.475 | $2.454 \mathrm{E}-03$ |
|  |  | $2.512 \mathrm{E}+04$ | $3.780 \mathrm{E}-10$ | $7.743 \mathrm{E}-04$ | 3.779E-10 | 7.743E-04 | 3.753E-10 | $7.743 \mathrm{E}-04$ | $1.288 \mathrm{E}+03$ | 4.3748 | $1.31 \mathrm{E}+01$ | 131.746 | $2.406 \mathrm{E}-03$ |
|  |  | $1.585 \mathrm{E}+04$ | $5.440 \mathrm{E}-10$ | 7.598E-04 | 5.440E-10 | $7.598 \mathrm{E}-04$ | $5.414 \mathrm{E}-10$ | $7.598 \mathrm{E}-04$ | $1.313 \mathrm{E}+03$ | 4.0586 | $1.41 \mathrm{E}+01$ | 190.033 | $2.361 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | 7.930E-10 | 7.460E-04 | 7.929E-10 | $7.460 \mathrm{E}-04$ | 7.903E-10 | 7.480E-04 | $1.338 E+03$ | 3.8080 | $1.50 \mathrm{E}+01$ | 277.395 | $2.319 \mathrm{E}-03$ |




| Experiment ID: | MD0833 | Freg [ Hz ] | CP_m [F] | Gp_m [S] | CP_osc [F] | Gp_ose [S] | Cp_he [F] | Gp_hc [S] | [21 [0] | 0 [deg] | Loss Tan | DletConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.278E-11 | 7.470E-05 | 1.255E-11 | 7.448E-05 | $1.029 \mathrm{E}-11$ | $7.386 \mathrm{E}-05$ | $1.537 E+03$ | 83.4827 | 1.14E-01 | 3.612 | 2.296E-04 |
|  |  | $6.310 \mathrm{E}+06$ | 1.333E-11 | $4.770 \mathrm{E}-05$ | $1.311 \mathrm{E}-11$ | $4.764 \mathrm{E}-05$ | 1.077E-11 | $4.674 \mathrm{E}-05$ | 2.329E+03 | 83.7513 | $1.09 \mathrm{E}-01$ | 3.612 3.779 | $1.453 \mathrm{E}-04$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | $1.377 \mathrm{E}-11$ | 2.970E-05 | 1.356E-11 | $2.968 \mathrm{E}-05$ | 1.118E-11 | 2.888E-05 | $3.557 E+03$ | 84.1036 | $1.03 \mathrm{E}-01$ | 3.925 | $8.977 \mathrm{E}-05$ |
| Mineralogy | Qtz-Kaol | $2.512 \mathrm{E}+06$ | 1.414E-11 | $1.820 \mathrm{E}-05$ | $1.394 \mathrm{E}-11$ | 1.820E-05 | $1.152 \mathrm{E}-11$ | $1.764 \mathrm{E}-05$ | $5.473 \mathrm{E}+03$ | 84.4610 | 9.70E-O2 | 4.045 | $5.481 \mathrm{E}-\mathrm{OS}$ |
| Ms [g] | 3.1669 | $1.585 \mathrm{E}+06$ | $1.448 \mathrm{E}-11$ | $1.120 \mathrm{E}-05$ | $1.428 \mathrm{E}-11$ | $1.120 \mathrm{E}-05$ | 1.185E-11 | $1.083 \mathrm{E}-05$ | 8.440E+03 | 84.7561 | 9.18E-02 | 4.159 | 3.366E-OS |
| Mcl [g] | 5.0067 | $1.000 E+06$ | 1.480E-11 | 6.940E-06 | $1.460 \mathrm{E}-11$ | $6.938 \mathrm{E}-06$ | 1.216E-11 | 6.690E-06 | $1.304 \mathrm{E}+04$ | 84.9947 | 8.76E-02 | 4.267 | 2.079E-05 |
| Mw [g] | 0.0000 | $6.310 \mathrm{E}+05$ | $1.512 \mathrm{E}-11$ | $4.320 \mathrm{E}-06$ | $1.492 \mathrm{E}-11$ | $4.318 \mathrm{E}-06$ | 1.246E-11 | $4.150 \mathrm{E}-06$ | 2.017E+04 | 85.1992 | 8.40E-02 | 4.375 | 1.290E-05 |
| Wcl (dry) | 0.6125 | $3.981 \mathrm{E}+05$ | $1.543 \mathrm{E}-11$ | 2.720E-06 | $1.523 \mathrm{E}-11$ | $2.719 \mathrm{E}-06$ | 1.276E-11 | $2.600 \mathrm{E}-06$ | 3.122E+04 | 85.3445 | $8.14 \mathrm{E}-02$ | 4.480 | $8.081 \mathrm{E}-06$ |
| Porosity (dry) | 0.4795 | $2.512 \mathrm{E}+05$ | $1.573 \mathrm{E}-11$ | $1.730 \mathrm{E}-06$ | $1.553 \mathrm{E}-11$ | $1.729 \mathrm{E}-06$ | 1.304E-11 | $1.655 \mathrm{E}-06$ | 4.842E+04 | 85.4038 | $8.04 \mathrm{E}-02$ | 4.579 | $5.144 \mathrm{E}-06$ |
| Perm [cm^2] | 7.64E-12 | $1.585 \mathrm{E}+05$ | $1.603 \mathrm{E}-11$ | 1.110E-06 | $1.583 \mathrm{E}-11$ | $1.109 \mathrm{E}-06$ | 1.333E-11 | $1.060 \mathrm{E}-06$ | 7.511E+04 | 85.4337 | 7.99E-02 | 4.678 | $3.294 \mathrm{E}-06$ |
| Sw | 0.0000 | $1.000 E+05$ | 1.635E-91 | 7.270E-07 | 1.614E-11 | 7.270E-07 | $1.363 \mathrm{E}-11$ | 6.940E-07 | $1.164 E+05$ | 85.3660 | 8.11E-02 | 4.783 | 2.157E-06 |
|  |  | $6.310 E+04$ | $1.667 \mathrm{E}-11$ | $4.850 \mathrm{E}-07$ | 1.647E-11 | $4.850 \mathrm{E}-07$ | $1.393 \mathrm{E}-11$ | $4.630 \mathrm{E}-07$ | $1.804 \mathrm{E}+05$ | 85.2089 | $8.38 \mathrm{E}-02$ | 4.891 | $1.439 \mathrm{E}-06$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 1.700E-11 | $3.310 \mathrm{E}-07$ | $1.680 \mathrm{E}-11$ | $3.310 \mathrm{E}-07$ | $1.425 \mathrm{E}-11$ | $3.160 \mathrm{E}-07$ | $2.794 E+05$ | 84.9352 | $8.86 \mathrm{E}-02$ | 5.003 | $9.821 \mathrm{E}-07$ |
| Diameter [cm] | 4.202 | $2.512 \mathrm{E}+04$ | $1.736 \mathrm{E}-11$ | $2.290 \mathrm{E}-07$ | $1.716 \mathrm{E}-11$ | 2.290E-07 | 1.459E-11 | $2.190 \mathrm{E}-07$ | $4.322 \mathrm{E}+05$ | 84.5686 | 9.51E-02 | 5.123 | $6.806 \mathrm{E}-07$ |
| Thickness [cm] | 0.431 | $1.585 \mathrm{E}+04$ | 1.776E-11 | 1.620E-07 | $1.756 \mathrm{E}-11$ | 1.620E-07 | $1.497 \mathrm{E}-11$ | 1.550E-07 | $6.670 \varepsilon+05$ | 84.0656 | $1.04 \mathrm{E}-01$ | 5.256 | $4.817 \mathrm{E}-07$ |
|  |  | $1.000 \mathrm{E}+04$ | $1.821 \mathrm{E}-11$ | 1.170E-07 | 1.801E-11 | 1.170E-07 | 1.540E-11 | $1.120 \mathrm{E}-07$ | $1.026 \mathrm{E}+06$ | 83.3991 | $1.16 \mathrm{E}-01$ | 5.407 | 3.481E-07 |


| Experiment ID: | MD0835 | Freq [ Hz$]$ | Cp_m [F] | Gp_m [S] | CP_Osc [F] | Gp_osc [S] | Cp_he [F] | Gp_hc [S] | \|Z1 [ 0 ] | 0 [deg] | Loss Tan | DielConstant | Cond [ $\mathrm{S} / \mathrm{m}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 8.699E-11 | 2.745E-03 | 8.610E-11 | $2.688 \mathrm{E}-03$ | 8.384E-11 | $2.687 \mathrm{E}-03$ | $1.6918+02$ | 62.9756 | 5.10E-01 | 29.430 | $8.351 \mathrm{E}-03$ |
|  |  | $6.310 \mathrm{E}+06$ | $9.360 E-11$ | $2.471 \mathrm{E}-03$ | $9.316 \mathrm{E}-11$ | $2.449 \mathrm{E}-03$ | 9.082E-11 | $2.448 \mathrm{E}-03$ | $2.297 E+02$ | 55.7857 | $6.80 \mathrm{E}-01$ | 31.879 | $7.609 \mathrm{E}-03$ |
| Sample: | Sand-Clay | $3.981 \mathrm{E}+06$ | 1.008E-10 | $2.245 \mathrm{E}-03$ | $1.006 \mathrm{E}-10$ | $2.237 \mathrm{E}-03$ | $9.818 \mathrm{E}-11$ | $2.236 \mathrm{E}-03$ | 3.011E+02 | 47.6859 | 9.10E-01 | 34.462 | $6.948 \mathrm{E}-03$ |
| Mineralogy | Qtz-Kaol | $2.512 E+06$ | 1.089E-10 | 2.071 E-03 | 1.087E-10 | $2.068 \mathrm{E}-03$ | 1.063E-10 | $2.067 \mathrm{E}-03$ | $3.756 \mathrm{E}+02$ | 39.0708 | $1.23 \mathrm{E}+00$ | 37.322 | $6.424 E-03$ |
| Ms [9] | 3.1669 | $1.585 \mathrm{E}+06$ | 1.183E-10 | $1.942 \mathrm{E}-03$ | 1.182E-10 | $1.941 \mathrm{E}-03$ | $1.157 \mathrm{E}-10$ | $1.940 \mathrm{E}-03$ | $4.431 \mathrm{E}+02$ | 30.7115 | $1.68 \mathrm{E}+00$ | 40.628 | $6.030 \mathrm{E}-03$ |
| Mcl [g] | 5.0067 | $1.000 \mathrm{E}+06$ | 1.299E-10 | 1.848E-03 | 1.298E-10 | 1.847E-03 | 1.273E-10 | $1.847 \mathrm{E}-03$ | $4.968 \mathrm{E}+02$ | 23.4197 | $2.31 \mathrm{E}+00$ | 44.699 | $5.741 \mathrm{E}-03$ |
| Mw [g] | 2.4400 | $6.310 €+05$ | 1.450E-10 | $1.777 \mathrm{E}-03$ | $1.449 \mathrm{E}-10$ | $1.777 \mathrm{E}-03$ | $1.424 \mathrm{E}-10$ | $1.777 \mathrm{E}-03$ | $5.364 \mathrm{E}+02$ | 17.6319 | $3.15 \mathrm{E}+00$ | 49.996 | $5.522 \mathrm{E}-03$ |
| Wci (dry) | 0.6125 | $3.981 \mathrm{E}+05$ | 1.670E-10 | $1.720 \mathrm{E}-03$ | 1.669E-10 | $1.720 \mathrm{E}-03$ | $1.644 \mathrm{E}-10$ | $1.720 \mathrm{E}-03$ | 5.65SE+02 | 13.4495 | $4.18 E+00$ | 57.714 | $5.345 \mathrm{E}-03$ |
| Porosity (dry) | 0.4795 | $2.512 \mathrm{E}+05$ | 2.000E-10 | $1.671 \mathrm{E}-03$ | 1.999E-10 | $1.671 \mathrm{E}-03$ | 1.974E-10 | $1.671 \mathrm{E}-03$ | $5.883 \mathrm{E}+02$ | 10.5619 | $5.36 E+00$ | 69.290 | 5.193E-03 |
| Perm [cm^2] | 7.64E-12 | $1.585 E+05$ | 2.490E-10 | 1.627E-03 | 2.489E-10 | $1.627 \mathrm{E}-03$ | $2.464 \mathrm{E}-10$ | $1.627 \mathrm{E}-03$ | $6.078 \mathrm{E}+02$ | 8.5777 | $6.63 \mathrm{E}+00$ | 86.501 | $5.056 \mathrm{E}-03$ |
| Sw | 0.8533 | $1.000 E+05$ | 3.220E-10 | $1.585 \mathrm{E}-03$ | 3.219E-10 | $1.585 \mathrm{E}-03$ | 3.194E-10 | 1.585E-03 | $6.259 E+02$ | 7.2154 | $7.90 \mathrm{E}+00$ | 112.100 | $4.926 \mathrm{E}-03$ |
|  |  | $6.310 \varepsilon+04$ | $4.300 \mathrm{E}-10$ | $1.547 \mathrm{E}-03$ | 4.299E-10 | $1.547 \mathrm{E}-03$ | 4.273E-10 | $1.547 \mathrm{E}-03$ | $6.426 E+02$ | 6.2498 | $9.13 \mathrm{E}+00$ | 150.003 | 4.808E-03 |
| Geometry: |  | $3.981 E+04$ | $6.000 \mathrm{E}-10$ | $1.509 \mathrm{E}-03$ | 6.000E-10 | $1.509 \mathrm{E}-03$ | 5.974E-10 | $1.509 \mathrm{E}-03$ | $6.595 E+02$ | 5.6557 | $1.018+01$ | 209.704 | $4.690 \mathrm{E}-03$ |
| Diameter [ cm ] | 4.202 | $2.512 E+04$ | 8.600E-10 | $1.474 \mathrm{E}-03$ | $8.601 \mathrm{E}-10$ | $1.474 \mathrm{E}-03$ | 8.576E-10 | $1.474 \mathrm{E}-03$ | $6.756 \mathrm{E}+02$ | 5.2464 | $1.09 \mathrm{E}+01$ | 301.024 | $4.581 \mathrm{E}-03$ |
| Thickness [cm] | 0.431 | $1.585 \mathrm{E}+04$ | $1.240 \mathrm{E}-09$ | $1.441 \mathrm{E}-03$ | 1.240E-09 | $1.441 \mathrm{E}-03$ | 1.238E-09 | $1.441 \mathrm{E}-03$ | $6.914 \mathrm{E}+02$ | 4.8891 | $1.17 \mathrm{E}+01$ | 434.495 | $4.479 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | $1.820 \mathrm{E}-09$ | $1.409 \mathrm{E}-03$ | 1.820E-09 | $1.409 \mathrm{E}-03$ | 1.817E-09 | $1.409 \mathrm{E}-03$ | $7.074 \mathrm{E}+02$ | 4.6335 | $1.23 \mathrm{E}+01$ | 637.951 | $\begin{array}{r}4.379 \mathrm{E}-03 \\ \hline\end{array}$ |



| Experiment ID: MDO839(\&253ave_c810_432) |  | Frea [ Hz ] | Cp_m[F] | Gp m [S] | CP_ose [F] | Gp_osc [S] | Cp_he [F] | Gp_he [S] | \|zi [ก] | 6 [deg] | Loss Tan | DielConstant | Cond [S/m] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.000E+07 | 1.148E-10 | 3.316E-03 | 1.133E-10 | $3.224 \mathrm{E}-03$ | $1.111 \mathrm{E}-10$ | 3.224E-03 | 1.301E+02 | 65.2022 | $4.62 \mathrm{E}-01$ | 38.981 1.002E-02 |  |
|  |  | $6.310 \mathrm{E}+06$ | $1.231 \mathrm{E}-10$ | 2.932E-03 | $1.224 \mathrm{E}-10$ | $2.897 \mathrm{E}-03$ | 1.201E-10 | $2.896 \mathrm{E}-03$ | $1.794 \mathrm{E}+02$ | 58.6854 | 6.08E-01 | 42.154 | $9.002 \mathrm{E}-03$ |
| Sample: | Clay | $3.981 \mathrm{E}+06$ | $1.326 \mathrm{E}-10$ | $2.623 \mathrm{E}-03$ | $1.322 \mathrm{E}-10$ | $2.609 \mathrm{E}-03$ | $1.298 \mathrm{E}-10$ | $2.609 \mathrm{E}-03$ | $2.400 E+02$ | 51.2294 | $8.03 \mathrm{E}-01$ | 45.578 | 8.108E-03 |
| Mineralogy | Kaol | $2.512 \mathrm{E}+06$ | $1.431 \mathrm{E}-10$ | $2.386 \mathrm{E}-03$ | $1.429 \mathrm{E}-10$ | $2.380 \mathrm{E}-03$ | 1.405E-10 | 2.380E-03 | $3.075 \mathrm{E}+02$ | 42.9681 | $1.07 \mathrm{E}+00$ | 49.302 | $7.396 \mathrm{E}-03$ |
| Ms [g] | 0.0000 | $1.585 \mathrm{E}+06$ | $1.551 \mathrm{E}-10$ | $2.213 \mathrm{E}-03$ | 1.549E-10 | $2.211 \mathrm{E}-03$ | 1.525E-10 | 2.210E-03 | $3.729 \mathrm{E}+02$ | 34.4935 | $1.46 \mathrm{E}+00$ | 53.530 | 6.869E-03 |
| McI [g] | 6.2590 | $1.000 \mathrm{E}+06$ | 1.693E-10 | 2.090E-03 | $1.691 \mathrm{E}-10$ | 2.089E-03 | 1.667E-10 | 2.088E-03 | 4.280E+02 | 26.6360 | $1.99 \mathrm{E}+00$ | 58.516 | $6.491 \mathrm{E}-03$ |
| Mw [g] | 3.1600 | $6.310 \varepsilon+05$ | 1.875E-10 | $1.999 \mathrm{E}-03$ | 1.874E-10 | 1.999E-03 | 1.850E-10 | $1.998 \mathrm{E}-03$ | $4.698 E+02$ | 20.1475 | $2.73 \mathrm{E}+00$ | 64.920 | $6.211 \mathrm{E}-03$ |
| Wcl (dry) | 1.0000 | $3.981 \mathrm{E}+05$ | $2.130 \mathrm{E}-10$ | $1.930 \mathrm{E}-03$ | $2.129 \mathrm{E}-10$ | $1.930 \mathrm{E}-03$ | 2.104E-10 | 1.930E-03 | $4.999 E+02$ | 15.2580 | $3.67 \mathrm{E}+00$ | 73.868 | $5.998 \mathrm{E}-03$ |
| Porosity (dry) | 0.5993 | $2.512 \mathrm{E}+05$ | 2.496E-10 | $1.872 \mathrm{E}-03$ | 2.495E-10 | $1.872 \mathrm{E}-03$ | 2.470E-10 | $1.872 \mathrm{E}-03$ | $5.231 \mathrm{E}+02$ | 11.7640 | $4.80 \mathrm{E}+00$ | 86.690 | 5.817E-03 |
| Perm [cm^2] | $1.51 \mathrm{E}-11$ | $1.585 \varepsilon+05$ | 3.049E-10 | $1.820 \mathrm{E}-03$ | 3.049E-10 | 1.820E-03 | 3.024E-10 | 1.820E-03 | $5.421 \mathrm{E}+02$ | 9.3948 | $6.04 \mathrm{E}+00$ | 106.135 | 5.656E-03 |
| Sw | 0.8841 | $1.000 \mathrm{E}+05$ | 3.877E-10 | $1.773 \mathrm{E}-03$ | $3.875 \mathrm{E}-10$ | $1.773 \mathrm{E}-03$ | 3.850E-10 | $1.773 \mathrm{E}-03$ | 5.589E+02 | 7.7714 | $7.33 \mathrm{E}+00$ | 135.151 | $5.509 \mathrm{E}-03$ |
|  |  | $6.310 \varepsilon+04$ | 5.125E-10 | 1.728E-03 | 5.124E-10 | $1.728 \mathrm{E}-03$ | 5.099E-10 | $1.728 \mathrm{E}-03$ | $5.747 \mathrm{E}+02$ | 6.6707 | $8.55 E+00$ | 178.968 | $5.371 \mathrm{E}-03$ |
| Geometry: |  | $3.981 \mathrm{E}+04$ | 7.070E-10 | $1.686 \mathrm{E}-03$ | 7.070E-10 | $1.686 \mathrm{E}-03$ | 7.045E-10 | $1.686 \mathrm{E}-03$ | 5.899E+02 | 5.9670 | $9.57 \mathrm{E}+00$ | 247.278 | $5.240 \mathrm{E}-03$ |
| Diameter [ cm ] | 4.202 | $2.512 \mathrm{E}+04$ | 9.885E-10 | $1.645 \mathrm{E}-03$ | 9.887E-10 | $1.645 \mathrm{E}-03$ | 9.862E-10 | $1.645 \mathrm{E}-03$ | $6.051 \mathrm{E}+02$ | 5.4040 | $1.06 E+01$ | 346.159 | $5.114 \mathrm{E}-03$ |
| Thickness [ cm ] | 0.431 | $1.585 \mathrm{E}+04$ | 1.421 E-09 | $1.607 \mathrm{E}-03$ | $1.421 \mathrm{E}-09$ | $1.607 \mathrm{E}-03$ | 1.418E-09 | $1.607 \mathrm{E-03}$ | $6.197 E+02$ | 5.0220 | $1.14 \mathrm{E}+01$ | 497.906 | $4.996 \mathrm{E}-03$ |
|  |  | $1.000 \mathrm{E}+04$ | 2.068E-09 | 1.571E-03 | 2.068E-09 | 1.571E-03 | 2.065E-09 | 1.571E-03 | $6.344 \mathrm{E}+02$ | 4.7213 | $1.21 E+01$ | 724.849 | 4.883E-03 |




[^0]:    ${ }^{1}$ Users of this table are cautioned that some of the values listed are strongly dependent on frequency, pore fluid salinity, temperature and other parameters.

[^1]:    ${ }^{1}$ In this chapter, the term "permeability" means hydraulic permeability, not magnetic permeability as discussed in earlier chapters. Furthermore, in adherence with hydrogeological conventions (e.g., Freeze and Cherry, 1979), the symbol $\mu$ is used for dynamic viscosity, not magnetic permeability, in this chapter. Magnetic permeability values are assumed to be constant and equal to the value for free space, as discussed in Section 2.3.

