

LABORATORY ANALYSIS OF ELECTRICAL ROCK PROPERTIES AND CAPILLARY PRESSURE IN TIGHT GAS SANDS WITH LOW WATER SATURATIONS

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Abstract

Laboratory electrical properties and capillary pressure analysis of core samples are useful tools in understanding and calculating oil and gas reserves. Tight gas sands with low water saturations present challenges that standard laboratory methodologies can only partially address. This paper presents recent laboratory advances that have been developed to measure capillary pressure and electrical resistivities (a, m and n) under low water saturation conditions.

We first will discuss the methodologies of resistivity measurements to determine the Archie properties of m and n followed by capillary pressure tests using a 1000 psi porous plate. We will then discuss extending the electrical properties and capillary pressure tests using a vapor desorption method wherein brine salinity increases as water saturations decrease. Saturation exponent (n) variability as a function of capillary pressure dynamics is presented.

Resistivity and capillary pressure laboratory data are presented for core samples with porosities and permeabilities ranging from 4.0% to 10.8% and 0.0057 md to 0.017 md, respectively.

Introduction

Tight gas sands offer both significant gas reserves and significant challenges to the oil and gas industry. Within the laboratory, methods are continuing to be developed that help characterize and understand these systems. There are two classes of tight gas sands: those exhibiting conventional capillary pressure-based water saturation distributions; and those that exhibit sub-capillary equilibrium water saturation distributions. The latter result in ultra-low or sub-saturated wetting phase distributions as described by Newsham (1). This paper will address the measurement of electrical properties at ultra-low water saturations through the use of vapor desorption capillary pressure. The first section will provide an overview of electrical property and plate capillary pressure laboratory methods that apply to conventional reservoirs characterized by low permeability and low porosity. The second section will introduce specific vapor desorption techniques that were developed to investigate the ultra-low water saturation conditions. The third, and final section, will review two data sets that illustrate and present the results of this study.

Basic Laboratory Methods

Sample Selection.

Sample selection is a defining process for special core analysis test results. Ideally a specific uniform rock type (pore geometry) should be represented in each sample and unconformities should be avoided. Any bedding if present must be oriented along the long axis of a plug sample.

Basic physical requirements should also be met. These include: parallel and even end-faces, uniform cross sectional area and preserved rock fabric. In addition, for analysis involving the

subject of this paper, electrical properties with vapor desorption capillary pressure, samples need to have dry weights of at least 50 grams and pore volumes of at least 1 cc. Smaller samples will not yield sufficient data quality.

Sample Preparation.

Most special core analysis is conducted on clean, dry and stable samples of known physical properties. The physical properties (aside from grain volumes) need to be determined at the same net confining stress as the analysis. With cleaning and drying it is particularly important not to damage or alter the rock fabric. Cool solvent cleaning is highly recommended so that any rock fabric damage is minimized. In addition, dry weights are absolutely crucial and must be well defined, stable and controlled throughout handling ... before, during and after analysis.

Electrical Properties / Plate Capillary Pressure Overview.

A basic discussion of laboratory methods used in the conventional determination of electrical properties and porous plate capillary pressure is in order prior to addressing non-conventional vapor desorption analysis. These methods include: the analysis being conducted at a net confining stress matched to reservoir conditions, a single compression cycle for the advanced testing, desaturation conducted as a drainage cycle using humidified gas to displace the brine and the use of ambient temperature.

Electrical properties as defined in the pioneering work done by Archie (2) include the formation factor (F), the cementation exponent (m) and the saturation exponent (n). Basic formulas are:

$$\begin{aligned} F &= R_o / R_w & 1) \\ m &= \log F / \log \phi & 2) \\ n &= \log (R_t / R_o) / \log S_w & 3) \end{aligned}$$

The effect of in-situ clay conductivity upon electrical properties was defined by Waxman-Smits (3) in their classic study. Here, the plotting of rock conductivity vs. brine conductivity yields an intercept, BQv that defines clay conductivity for that sample. The basic formulas are:

$$\begin{aligned} F^* &= (\phi)^{-m^*} & 4) \\ F^* &= R_o/R_w (1+R_w BQv) & 5) \\ I &= R_t/R_o = S_w^{-n^*} ((1 + R_w BQv)/(1+R_w BQv/S_w)) & 6) \end{aligned}$$

Porous plate capillary pressure analysis can be determined separately or in conjunction with the saturation exponent analysis. The plate provides the means whereby a sample can be uniformly desaturated along the entire sample length in a step-wise set of discrete increasing pressures up to a maximum of 1000 psi in an air / brine system. Plate capillary pressure, although time consuming, is recognized as the method best suited in modeling the dynamics of capillary pressure within a reservoir.

Centrifuge desaturation is not a recommended practice in electrical properties determinations mainly due to significant evaporation that occurs. With tight gas sands this evaporation error can exceed 20%. A secondary issue involves the potential uneven brine distribution within a sample due to residual effects of the gravitational field developed during centrifugation.

Formation Factor.

The initial step in most electrical properties testing involves the determination of the formation factor, F. This analysis is straightforward but basic protocols must be followed to avoid error and data artifacts. Each sample must be flushed with a sufficient volume of synthetic formation brine to establish rock / brine equilibrium and each sample must be 100% saturated with brine. Samples that are non-uniform and are of low porosity will exacerbate the problems associated with equilibrium and entrained gas. In particular, the samples must be flushed with brine against back pressure, soak cycles employed and resistances monitored on a daily basis with the time base set against the permeability range of each sample. For example, high permeability high porosity sandstones may well equilibrate electrically within 4 to 6 days. With a tight gas sands, stability might not actually be reached until 4 to 6 weeks have elapsed. Independent assessment for any remaining gas must also be done to assure that all gas is removed.

CoCw Clay Conductivity.

Clay conductivity determinations are useful in conventional reservoirs where the formation brine is relatively fresh (less than 50 g/L salt) and clay content is variable and generally above 5% of the grain structure by weight. CoCw analysis can also be of use where the formation brine is either variable or is not well defined.

Samples are flushed with a sequence of a minimum of three saline brines ending with the final formation brine. The rock conductivity is monitored to stability for each brine using the techniques outlined in the preceding formation factor section.

Resistivity Index and Capillary Pressure.

Typically, the saturation exponent is determined on initially clean and dry samples proceeding from 100% brine saturation to a final irreducible brine saturation, Swi. (Issues of fresh/preserved state analysis, wettability and elevated temperature are outside of the scope of this study.)

The determination of the saturation exponent n (or of incremental n values) is dependant upon two main precepts: the control of an even desaturation process through use of a porous plate and the material balance confirmed and defined value of the final brine saturation percent, Swi. During the desaturation process, the rock fabric controls the desaturation pressures needed and minimum time required. Many rock types are susceptible to desaturation that is too rapid, leading to non-uniform saturation profiles and anomalous resistivity response. Therefore, incremental pressure steps should be employed to control the desaturation process. The determination of volumetric equilibrium at each pressure step is best approached with a conservative definition of stability. In practice, three days of no volumetric change is reasonable standard of equilibrium for most rock types.

The second critical element in determining laboratory based saturation exponents, is the ability to verify Swi values. Low porosity rotary and conventional plug samples are particularly susceptible to errors in Swi due to the relatively small pore volumes involved. Specifically, production-based Swi values

should be confirmed by the differences between pre and post-test dry weights and the Swi weight as well as final Dean-Stark extraction. Dean-Stark extraction must be carefully assessed with regard to the potential damage to rock structure as well as considerations to free and bound water issues. With 1 inch diameter samples uncertainties greater than 0.01 cc can introduce un-acceptable error. These errors are cumulative and are resultant from volumetric desaturation uncertainties, pore volume variability and most importantly dry weight variability.

1000 psi Plate / Membrane System.

The 1000 psi plate/membrane system was designed primarily to improve saturation exponent accuracy by lowering the final Swi saturation obtained in low porosity materials (3 to 8 % porosity). Few conventional reservoirs would require analysis with this high of a capillary pressure in order to model reservoir conditions.

Uncertainty in saturation exponent values is usually unacceptable if conventional low porosity samples are desaturated to only 70 or 80 percent using an industry standard 15 bar plate with a maximum 200 psi air/brine desaturation pressure. Note again that cumulative errors greater than 0.01 cc often produce unacceptable results.

However, where pore structures exhibit varied micro and macro pore throat components, the higher desaturation pressure allows for a more inclusive investigation of the resultant variable saturation exponent n. If the resultant n values are basically linear over the full desaturation range, the gained confidence of response is none-the-less an added benefit.

Vapor Desorption.

Capillary Pressure and vapor pressure relationships have been investigated and presented in the literature by Calhoun (4), Collins (5) and Melrose (6). More recently, Newsham (7, 8), has expanded these earlier studies to define vapor desorption as a possible mechanism to describe the capillary pressure/rock fabric/brine salinity relationships within specific basin-centered tight gas sand reservoirs. Vapor desorption methodologies were developed within the laboratory to model these systems and achieved air / brine capillary pressures in excess of 12000 psi. The basic equation is:

$$P_c = - \ln (RH / 100) RT / V_m \quad 7)$$

The laboratory basics start with an initial desaturation of the samples to Swi using a maximum capillary pressure of 1000 psi. Both plate and centrifugation were used in the studies by Newsham (7, 8) to achieve the 1000 psi Swi step, but this investigation is limited to the use of plate capillary pressure as the appropriate methodology due to the salinity / saturation errors inherent with centrifugation.

The 1000 psi step is followed by using an electronically controlled humidity chamber to sequentially lower the vapor pressure surrounding the samples and monitoring the resultant drop in Swi at each pressure step for each sample. Typically this involves four relative humidities (RH): 90, 80, 70 and 60 percent. Weight at each step is monitored daily and on average requires approximately 20 days to reach stability for any given sample at the first 90% RH step. Subsequent RH steps required

from 8 to 10 days to reach stability. Vapor desorption is used to develop high capillary pressures within each sample based on the relative humidity surrounding the samples and the brine salinity of the wetting phase within each sample. The Swi values obtained for each sample are based on these capillary forces and the pore geometry of each sample. It is a true capillary pressure relationship that is definable, specific and reversible.

Newsham (7, 8) presented vapor desorption capillary pressure as an extension of the capillary pressure curves developed using standard laboratory methods.

Case Study: Electrical Properties and Vapor Desorption Capillary Pressure

Introduction.

A total of 16 samples from 3 fields were included in an original study combining electrical properties analysis and vapor desorption analysis. Data from two representative samples will be presented in detail ... providing both an outline of the methodology and a platform for a discussion of the results.

The samples were of two sizes: 1" diameter by 2" in length and 1 1/2" in diameter by 2 1/2" in length. The samples were initially cool solvent extracted and dried to stable weights using conditions that minimized any rock fabric alteration or damage. Physical properties were determined at the net confining stress that matched the specific reservoir conditions for each sample.

All samples were screened for physical condition and physical properties prior to inclusion in the testing program. Specifically the representative samples needed to possess excellent physical properties mentioned before: parallel end faces, uniform cross sectional area and stable rock fabric. Dry weights, pore volumes and grain volumes were repeatedly checked both before testing as well as after testing. (Note that weights were recorded to 0.001 g and volumetrics were calculated from these weights throughout the analysis program.)

Procedures: 1000 psi Conventional Electrical Properties and Capillary Pressure Analysis.

The selected samples were evacuated and pressure saturated with a 50 g/L brine solution made up of representative salts. This brine salinity was selected so that during the course of evaporation and brine concentration within the vapor desorption process, the final brine salinity would not produce a salt saturated solution at room temperature. This selection is based both the estimation of the 50 g/L brine saturation at the 1000 psi capillary pressure point as well as the estimation of the final brine saturation at the 10000 psi capillary pressure point. Too low of an initial salinity will subject the analysis to excess clay conductivity effects and possible alteration of the clay fabric.

The samples were then mounted into electrical properties test cells with a 1000 psi plate/membrane in capillary contact with the lower face of each sample. The appropriate net confining stress was applied to each sample. This stress was maintained throughout the resistivity index / plate capillary pressure tests to the 1000 psi stability desaturation pressure point. The samples were backpressure flushed with the 50 g/L brine and 2E electrical resistances and phase angles monitored on a daily basis using a test frequency of 1 kHz. Note: Phase angles remained at or below 1 degree throughout testing. Typical

electrical stability time was 2 1/2 weeks, but the key is multiple days of no resistivity change after sufficient brine volume throughput. In most cases 20 to 50 pore volumes of throughput were needed before stability was reached.

The samples were then checked to be sure no gas was remaining within any of the sample pore structures before continuing to the desaturation phase.

The samples were then desaturated in place using humidified nitrogen as the displacing phase in discrete pressure steps. The initial starting pressure was 20 psi and the entire pressure sequence was: 20, 40, 60, 100, 140, 200, 400, 700 and 1000 psi. Production was monitored to insure that samples did not desaturate too quickly...usually not a problem with tight gas sands. Even so, the use of interim pressures and close monitoring of sample response is required. Stability at each pressure step was defined as no net volumetric change over three to five consecutive days. With tight gas sands, incremental daily volumetric changes can be rather small so extra care is needed to discern capillary pressure stability.

Following stability at 1000 psi air / brine, the samples were carefully removed from the test cells and immediately weighed. Extra care was taken to be sure that no sample was contaminated with the overburden fluid as all saturations are based on weight.

Procedures: Electrical Properties and Vapor Desorption Capillary Pressure.

Samples were next placed in an electronically controlled humidity chamber at 90 percent relative humidity / 30 degrees C. (90 percent relative humidity roughly translates to 2000 psi.) Sample weights were monitored daily. As each sample equilibrates to the relative humidity of the chamber, the brine lining the pores loses water through evaporation and the brine concentrates as a result of the evaporation. The evaporation will continue for each sample until capillary pressure equilibrium is reached within the pores of each sample. As mentioned before, this is truly a capillary pressure based system within which each sample establishes a given brine saturation at a given capillary pressure based on the pore geometries of that sample.

Weights were recorded to 0.001 g and stability was defined as a minimum of three consecutive days with weights bracketing a given number plus or minus 0.005 grams on average without any remaining upward or downward trends. As weights tend to change slowly, weights can change less than 0.005 grams from one day to the next, yet after 7 days, the weights might still be dropping. Therefore, it is the weight trend that must stabilize. Figure 1 summarizes gravimetric saturation changes on 2 generic (but actual) samples during vapor desorption capillary pressure tests.

At stability, the samples were weighed and immediately loaded into 2E electrical test cells and net confining stress was applied. Resistances were then monitored on a daily basis until stable for each sample. On average, electrical stability was reached within 3 to 6 days. Each sample was removed from the test cell and weighed immediately.

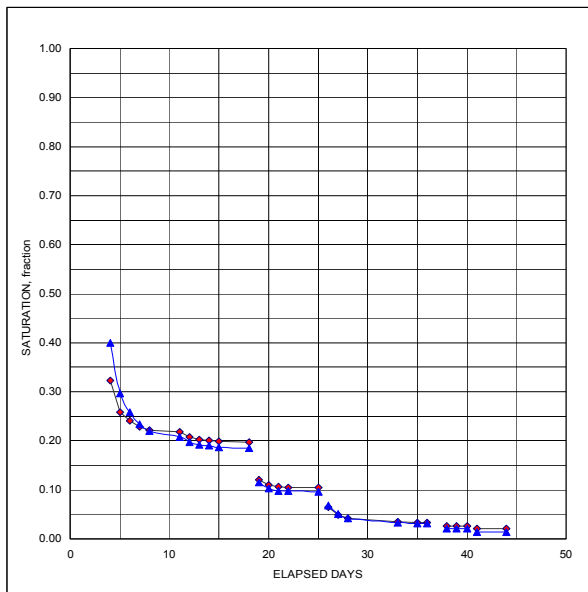


Figure 1. Vapor desorption capillary pressure stability plot: fractional saturation vs. elapsed time.

Samples were placed back into the electronically controlled humidity chamber at 80 percent relative humidity / 30 degrees C and the process was then repeated as for the 90 percent RH step. This was again repeated at a 70 percent RH step and finally a 60 percent RH step. The criterion for stability remained the same for each stage of the process.

Upon final resistivity stability at the final RH step, the samples were removed from the test cells and reweighed. The samples were then Dean-Stark extracted with toluene for final water saturation verification. Note: Samples with clay or other structures that might be damaged by this extraction process should not be subjected to this extraction step and proceed directly to final drying using the pre-test drying methodology. Salts then will need to be backed out of the final weights through either cool solvent extraction or by calculation.

The samples were redried following extraction using the original methodology and stability criterion of pre-test drying. This step is extremely important, as the post-test dry weights are often the most accurate benchmark for calculating the brine saturations for a given sample.

CoCw.

Depending upon the clay content and structure of the samples being analyzed, CoCw analysis could be an important test to include in the analysis program. The electrical properties investigations to 1000 psi are conducted with a brine concentration of 50 g/L. As vapor desorption proceeds, the brine is concentrated to nearly 250 g/L and should there be significant clays present, electrical response will reflect the contribution of the clay conductivities, especially with respect to the changing brine salinities.

Calculations: Conventional 1000 psi Electrical Properties / Plate Capillary Pressure.

Formation factor calculations were based on the pre-test physical properties and the initial brine resistivity at 50 g/L. Resistivity index resistivity calculations are also based on the initial formation factor with the 50 g/L brine salinity.

Resistivity index and plate capillary pressure saturation calculations were tied to the final saturation at the 1000 psi capillary pressure point. This Swi calculation is not necessarily a straightforward and easy process, especially with tight gas sands.

Experience has shown that the weight differences most accurately define final brine saturations: Swi weight minus the dry weight. In addition, as dry weights often change between the pre-test and post-test steps, the question is posed as to which dry weight should be used in the calculations. Again, experience has shown that in most cases the post-test dry weights provide the most accurate calculation of Swi following the 1000 psi step. This is decidedly not the case with some clay sensitive materials following Dean-Stark toluene extraction and therefore each set of rock lithologies must be considered separately. Should significant weight changes occur between pre and post test steps, consideration should be given to the measurement of post-test properties...especially the pore and grain volumes.

Calculations: Electrical Properties / Vapor Desorption Capillary Pressure.

Resistivity, brine saturation and salinity calculations are treated the same for each sample at each vapor desorption / resistivity index point.

Resistivity calculations at each vapor desorption step were based on two readings for each sample: the resistance after 24 hours and the final resistance at stability. Although resistance changes were relatively small for each sample at each step, both readings were included in the calculations of an average n value for each sample. It was assumed that much of the resistance change is due to continued evaporation from handling therefore each reading should be considered valid. At the very least a resistance range is given at each vapor desorption point.

Within each sample, as the brine concentrates through the process of vapor desorption, R_w , no longer is a constant. Therefore the next calculation at each vapor desorption pressure / resistivity index step is to calculate the associated R_w based on the weight before and the weight after the resistivity measurements. At the 1000 psi point for each sample, a given Swi is calculated and the salinity is assumed to be 50 g/L. All desaturation up to and including the 1000 psi point were conducted using humidified gas to minimize salinity change. Therefore for each sample there is a given weight of salt within the volume of brine. As the brine within each sample loses volume a new R_w can be calculated based on the g salt/unit of new brine volume. If clay conductivity is deemed to be insignificant then a new R_o for each sample, before and after each vapor desorption / resistivity index point, is calculated from a rearrangement of Archie's formation factor equation:

$$R_o = F * R_w \quad 8)$$

If clay conductivity is significant then the formation factor at each vapor desorption step is not a constant and therefore must be calculated using Waxman-Smiths based CoCw methodology. Here, by substituting in the new R_w with a known BQv, a corresponding formation factor can be calculated. From the calculated formation factor, a corresponding R_o is calculated using before and after weights at each vapor desorption /

resistivity index point using the above formula. Based on the new Ro, the resistivity index point is calculated using Archie's resistivity index, equation:

$$I = (R_t / R_o) \tag{9}$$

Saturations at each vapor desorption / resistivity index point for each sample are calculated using the before and after weights at each point and the final dry weight. Sample handling therefore becomes very important as to not introduce error by de-coupling the resistances from the saturations since both are dependent upon "known" salinities. In part this is normalized by using pre-point weights with the 24 hour resistance reading and post-point weights with the final resistance reading at a given point.

Weight differences, although rather small at higher vapor desorption pressures, produce correspondingly large changes in Rw and brine saturation calculations. Therefore, all handling and weight stability steps must be taken with great care. In addition, should contamination occur at any step, then the test must be halted, the sample re-cleaned and the test restarted.

Data Sets. Two data sets are presented to illustrate the vapor desorption / electrical resistivity analysis hi-lighted by ultra-low water saturations.

The first sample, 16, has a porosity of 4.0 % and an air permeability of 0.0057 md. The equivalent CEC is relatively low at 0.0063 meq/g. In Figure 2, the combined plate and vapor desorption based capillary pressure curve and resistivity index response seem to be rather typical for this rock type.

FORMATION FACTOR AND RESISTIVITY INDEX

2-Terminal Method, 1 kHz
Net Confining Stress: 2300 psi

Sample Number: 16
Permeability to Air, md: 0.0057
Porosity, fraction: 0.040
Saturant: Synthetic Formation Brine
Rw, ohm-m @25°C: 0.1100

Formation Factor FF (Ro/Rw)	Water Saturation, fraction pv	A/B Capillary Pressure, psi	Resistivity Index RI (Rt/Ro)	Incremental Saturation Exponent, n
387.8	1.000	42.66	1.000	
0.961		43.50	1.020	
0.958		43.64	1.023	
42.66	0.958	43.82	1.027	
0.956		43.88	1.028	
0.947		44.82	1.051	
0.943		45.53	1.067	
0.939		45.73	1.072	
0.938		45.78	1.073	
0.938	200	45.96	1.077	
-1.85	0.809	58.39	1.369	-1.48
0.724		70.68	1.657	-1.57
0.699		75.07	1.760	-1.58
0.671		80.43	1.885	-1.59
0.635		87.56	2.052	-1.58
0.628		89.33	2.094	-1.59
0.628	400	89.59	2.100	-1.59
0.624		90.26	2.116	-1.59
0.557		115.9	2.717	-1.71
0.539		122.9	2.880	-1.71
0.528		127.7	2.994	-1.72
0.514		132.2	3.098	-1.70
0.500		136.2	3.192	-1.68
0.487		141.5	3.316	-1.67
0.461	700	150.4	3.526	-1.63
0.445		157.2	3.685	-1.61
0.438		162.0	3.797	-1.62
0.429		164.7	3.861	-1.60
0.421		170.8	4.003	-1.60
0.395		189.3	4.437	-1.60
0.391		195.3	4.577	-1.62
0.384		201.6	4.726	-1.62
0.384	1000	201.9	4.732	-1.62
0.206		424.6	14.01	-1.67
0.201	2338	417.8	14.30	-1.66
0.105		832.6	41.05	-1.65
0.102	4472	857.5	43.55	-1.65
0.057		1963	115.4	-1.65
0.056	7094	1913	112.5	-1.64
0.039		3550	219.1	-1.67
0.039	10154	3689	227.7	-1.68

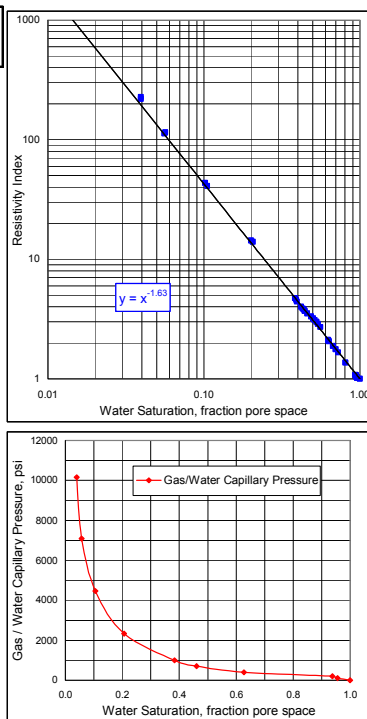


Figure 2. Resistivity Index and Capillary Pressure Data Sample 16.

In Figure 3, sample 32, has a porosity of 10.8 % and an air permeability of 0.017 md. The equivalent CEC is 0.0454 meq/g, which is moderate to moderately high. Somewhat atypically, this sample exhibited less of a transition in the capillary pressure data.

FORMATION FACTOR AND RESISTIVITY INDEX

2-Terminal Method, 1 kHz
Net Confining Stress: 2300 psi

Sample Number: 32
Permeability to Air, md: 0.017
Porosity, fraction: 0.108
Saturant: Synthetic Formation Brine
Rw, ohm-m @25°C: 0.1100

Formation Factor FF (Ro/Rw)	Water Saturation, fraction pv	A/B Capillary Pressure, psi	Resistivity Index RI (Rt/Ro)	Incremental Saturation Exponent, n
113.1	1.000	12.44	1.000	
0.956		12.99	1.044	
0.948		13.07	1.051	
0.905		14.50	1.165	
0.881		15.16	1.219	
0.865		15.59	1.253	-1.55
0.853		15.97	1.284	-1.57
0.844		16.28	1.309	-1.58
0.834		16.50	1.326	-1.56
0.830	200	16.65	1.338	-1.57
-2.12	0.756	19.00	1.527	-1.51
0.693		21.28	1.711	-1.46
0.642		23.09	1.856	-1.40
0.583		25.99	2.089	-1.37
0.552		27.99	2.250	-1.37
0.537		28.42	2.285	-1.33
-1.31	0.506	30.81	2.477	-1.33
0.496		31.30	2.516	-1.32
0.481		32.43	2.607	-1.31
0.474		32.54	2.616	-1.29
0.470	400	33.13	2.663	-1.30
0.430		36.36	2.923	-1.27
0.397		39.77	3.197	-1.26
0.379		42.58	3.423	-1.27
0.371		43.37	3.487	-1.26
0.343		46.66	3.751	-1.23
0.311		51.00	4.100	-1.21
0.294		54.59	4.388	-1.21
0.271		59.70	4.799	-1.20
0.260		62.81	5.049	-1.20
0.257	700	63.86	5.134	-1.20
0.244		66.07	5.311	-1.18
0.235		68.68	5.521	-1.18
0.228		70.66	5.680	-1.17
0.224	1000	73.99	5.948	-1.19
0.170		118.8	10.23	-1.31
0.167	2131	115.3	10.03	-1.29
0.094		186.7	24.20	-1.35
0.092	4540	186.0	24.32	-1.34
0.047		384.7	72.26	-1.40
0.046	7199	377.6	71.23	-1.38
0.033		623.0	121.1	-1.41
0.032	10314	613.1	118.7	-1.39

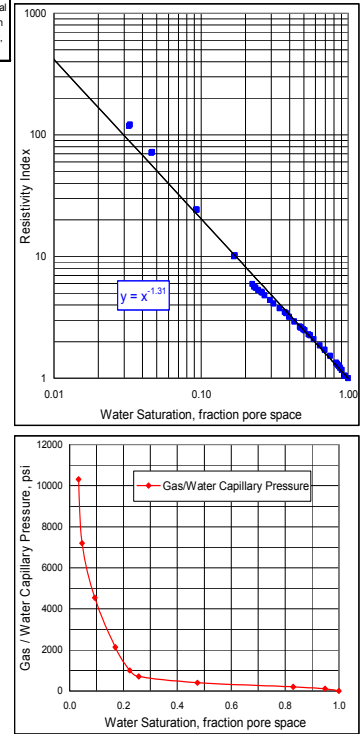


Figure 3. Resistivity Index and Capillary Pressure Data Sample 32.

- For both samples, several points of common process are:
1. Individual incremental saturation exponent values were calculated to show the variation (or lack of variation) in "n" over the entire testing range.
 2. Rt and Ro values were normalized to 77 degrees F.
 3. Capillary pressure curves are shown as a continuum between the 1000 psi porous plate and vapor desorption data sets.
 4. Vapor desorption capillary pressures are calculated from the relative humidity, temperature and saturating brine salinity. These are specific for each sample and should be noted in the data sets.
 5. The resistivity index data are also reported as a continuum for each sample. Linearity is exhibited over a significant extended range of brine saturations.
 6. Stability time for the vapor desorption capillary pressure steps ranged from the maximum at the initial RH point (20-25 days) to a minimum at the final two RH points (5-7 days).
 7. Resistivity stability for the vapor desorption steps ranged from 3 to 6 days.
 8. Linearity of the resistivity index response within the vapor desorption test range suggests that the wetting phase (brine) remains continuous and intact over the rock surfaces.

In general, the 16 samples studied exhibited similar results as the two data sets summarized in this paper. Data continuity was exhibited both in the electrical response as well as the capillary pressure response. All samples showed very low final water saturations that were controlled by the capillary forces within each sample. In addition, these low brine saturations tended to model the reservoir brine saturations.

It should be noted that the vapor desorption process was shown to be reversible within samples studied to-date. Moving a sample back to a higher relative humidity setting results in a re-absorption of water into the wetting phase brine...back to the original weight/saturation observed at that setting.

Clay Effects and Salinity Normalization.

Clay conductivity combined with changes in brine salinity will alter sample resistivity response. In an effort to illustrate these effects, three data sets are graphically presented in Figures 4 and 5.

The first set of data represents the original measured data and is presented in both Figures 4 and 5 as the red symbols. These data represent the lowest resistivity index values shown.

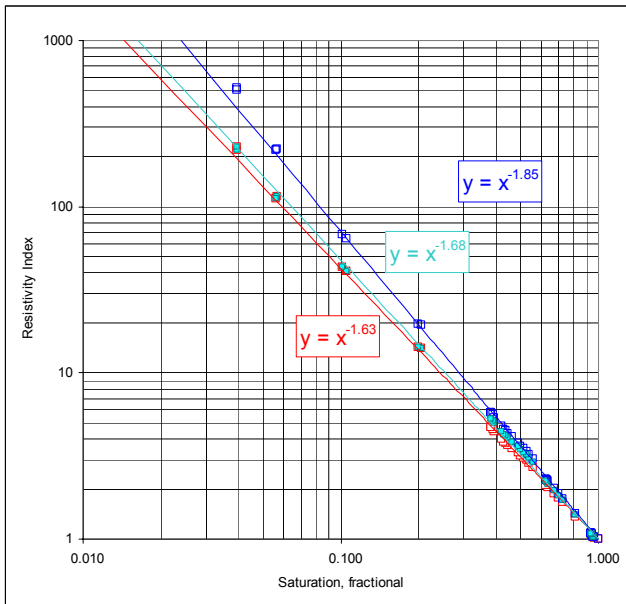


Figure 4. Sample 16 Resistivity Index Response vs. Clay

The second data set shows the results of the salinity normalization involving a re-calculation of the resistivity response for the 50 g/L salinity data and the vapor desorption data as if the brine salinity was 250 g/L.... similar to the final brine salinity at the end of the vapor desorption testing. In essence the data is presented as if the whole of testing was conducted with a brine salinity of 250 g/L. These calculations are done using the Waxman-Smits resistivity equation, the BQv intercept (or the estimated equivalent from CEC), and the ratio of the two Rw values (the actual g/L and 250 g/L). Initially, the effects of clay are backed out of the resistivity index data using Waxman-Smits resistivity equation 6:

$$I = Rt/Ro = Sw^{-n} * ((1 + RwbQv)/(1+RwbQv/Sw)).$$

Then, the clay conductivity contribution is recalculated based on the new higher brine salinity (250 g/L), yielding a new resistivity response. These data sets are shown in figures 4 and 5 as the intermediate (light blue symbols) resistivity index points. In particular, this method calculates higher incremental resistivity index data, n, over the initial 1000 psi capillary pressure portion of the data sets. Negligible resistivity change occurs for the resistivity index data within the vapor desorption data range as little salinity adjustment was involved. This data set presents a reasonable resistivity normalization where clay conductivities are present and the formation brine salinity is high. Normalizations to other salinities can be performed as required.

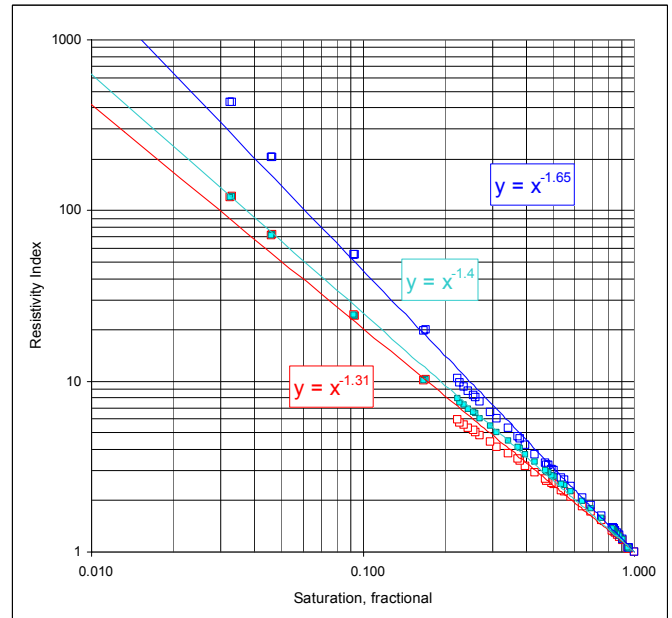


Figure 5. Sample 32 Resistivity Index Response vs. Clay

The third data set is simply the Waxman-Smits shaly saturation exponents: resistivity index data calculated as if no clay conductivity existed. These data are shown in Figures 4 and 5 (dark blue symbols) as the highest resistivity index values.

Conclusions

Vapor desorption has been shown to be a method that both models capillary pressure (Newsham 7, 8) and extends electrical response into the lowest of saturation ranges observed in tight gas sands with ultra-low water saturation.

The linearity and continuity of the resistivity index data reinforces the linkage observed between vapor desorption data and traditional capillary pressure data. The electrical response indicates that the vapor desorption desaturation process is uniform, continuous and rock dependant without hysteresis effects.

Recalculation of the 1000 psi and vapor desorption resistivity index response based on a selected brine salinity (eg 250 g/L) provides a normalization of parallel clay conductivity effects.

The vapor desorption and “best practice” electrical properties methodologies could be employed to extend electrical resistivity response investigations into those materials characterized by moderate as well as lower rock qualities.

Nomenclature

F	= formation factor
Ro	= resistivity of 100% saturated rock, ohm m
Rw	= resistivity of test brine, ohm m
m	= cementation exponent
ϕ	= porosity, fractional
n	= saturation exponent
Rt	= resistivity of partially saturated rock, ohm m
Sw	= brine saturation, fractional
F*	= shaly formation factor
m*	= shaly cementation exponent
B	= equivalent conductance of clay exchange cations, liter equiv ⁻¹ ohm ⁻¹ m ⁻¹
Qv	= effective concentration of clay exchange cations, meq ml ⁻¹ at Sw = 1
I	= resistivity index
n*	= shaly saturation exponent
Pc	= capillary pressure, psig
Co	= conductivity of 100 % saturated rock, mho cm ⁻¹
Cw	= conductivity of test brine, mho cm ⁻¹
RH	= relative humidity, percent
R	= universal gas constant, 8.314 J/Mol K
T	= absolute temperature, degrees Kelvin
Vm	= molar volume of water
CEC	= cation exchange capacity, meq/g

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