QUARTERLY TECHNICAL PROGRESS REPORT
FOR THE PERIOD ENDING DECEMBER 31, 2006

TITLE: ANALYSIS OF CRITICAL PERMEABLITY, CAPILLARY PRESSURE AND ELECTRICAL PROPERTIES FOR MESAVERDE TIGHT GAS SANDSTONES FROM WESTERN U.S. BASINS

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ABSTRACT:

Final samples have been received from participating companies. Analysis of the nearly all of the total of approximately 1300 unique sample depths and 700 duplicate core plugs has been completed. Based on analysis of paired samples within 2-6 cm on the same bedding plane, approximately 90% of all samples exhibit porosity within 10%-20%. Permeability values exhibit up to 40% variance from a mean value for 80% of samples. Analysis of drainage capillary pressure curves indicates that threshold entry pressures (P_{te}) for all lithofacies are well correlated with in situ Klinkenberg permeability (k_{ik}) and can be characterized by the relationship: $P_{te} = 30.27k_{ik}^{-0.44}$. The coefficient and exponent is likely to change slightly as the final data are added. Hysteresis capillary pressure analysis indicates that residual nonwetting phase saturation (Srnw) increases with increasing initial nonwetting phase saturation (Snwi) and is generally consistent with the Land (1971) relation: 1/Snwr-1/Snwi = C with C = 0.8±0.2. This relationship is still being investigated. Electrical resistivity measurements show that the Archie cementation exponent (*m*) decreases with decreasing porosity (ϕ) below approximately 6% and can be generally described by the empirical relationship: $m = 0.95 - 0.092\,\phi + 0.635\,\phi^{0.5}$. Analysis is proceeding on routine and *in situ* capillary pressure, and formation resistivity factor and wireline log interpretation.

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Acronyms

C = Land equation constant
DOE = Department of Energy
Hg = mercury
k_{ik} = *in situ* Klinkenberg permeability, millidarcies
m = Archie cementation exponent, (ohm-m/ohm-m)
md = millidarcy, 1 md = 9.87×10^{-4} μm^2
n = number
psi = pound per square inch, 1 psi = 6.89 kPa
P_{te} = Capillary pressure threshold entry pressure, psi
Snwi = initial nonwetting phase saturation
Srnw = residual nonwetting phase saturation
ϕ = porosity, percent or fraction depending on context

INTRODUCTION

Objectives - Industry assessment of the regional gas resource, projection of future gas supply, and exploration programs require an understanding of the reservoir properties and accurate tools for formation evaluation of drilled wells. The goal of this project is to provide petrophysical formation evaluation tools related to relative permeability, capillary pressure, electrical properties and algorithm tools for wireline log analysis. Major aspects of the proposed study involve a series of tasks to measure drainage critical gas saturation, capillary pressure, electrical properties and how these change with basic properties such as porosity, permeability, and lithofacies for tight gas sandstones of the Mesaverde Group from six major Tight Gas Sandstone basins (Washakie, Uinta, Piceance, Upper Greater Green River, Sand Wash and Wind River). Critical gas saturation (Sgc) and ambient and *in situ* capillary pressure (Pc) will be performed on 150 rocks selected to represent the range of lithofacies, porosity and permeability in the Mesaverde.

Project Task Overview -

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- Subtask 3.1. Compile published advanced properties data
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- Subtask 3.3. Acquire logs from sample wells and digitize

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EXECUTIVE SUMMARY:

Final samples have been received from participating companies. Analysis of the nearly all of the total of approximately 1300 unique sample depths and 700 duplicate core plugs has been completed. Based on analysis of paired samples within 2-6 cm on the same bedding plane, approximately 90% of all samples exhibit porosity within 10%-20%. Permeability values exhibit up to 40% variance from a mean value for 80% of samples. Analysis of drainage capillary pressure curves indicates that threshold entry pressures (P_{te}) for all lithofacies are well correlated with in situ Klinkenberg permeability (k_{ik}) and can be characterized by the relationship: $P_{te} = 30.27k_{ik}^{-0.44}$. The coefficient and exponent is likely to change slightly as the final data are added. Hysteresis capillary pressure analysis indicates that residual nonwetting phase saturation (Srnw) increases with increasing initial nonwetting phase saturation (Snwi) and is generally consistent with the Land (1971) relation: 1/Snwr-1/Snwi = C with C = 0.8$\pm$0.2. This relationship is still being investigated. Electrical resistivity measurements show that the Archie cementation exponent (*m*) decreases with decreasing porosity (ϕ) below approximately 6% and can be generally described by the empirical relationship: $m = 0.95-0.092\,\phi + 0.635\,\phi^{0.5}$. Analysis is proceeding on routine and *in situ* capillary pressure, and formation resistivity factor and wireline log interpretation.

RESULTS AND DISCUSSION:

TASK 3. ACQUIRE DATA AND MATERIALS

Subtask 3.2. Compile representative lithofacies core and logs from major basins

Core plugs have been received from ExxonMobil and Shell. These represent the last samples that will be **accepted from participating companies.**

Subtask 3.3. Acquire logs from sample wells and digitize

Logs have been obtained for most of the wells for which core plugs have been obtained. Remaining logs primarily comprise logs for recently obtained core plugs.

TASK 4. MEASURE ROCK PROPERTIES

Subtask 4.1. Measure basic properties (k, ϕ, grain density) and select advanced population

Basic properties have been measured on 2040 samples. Remaining cores needing basic properties include new cores received from industry partners and various very low permeability cores. Over 80% of the advanced properties samples have selected to represent the range in porosity, permeability, lithofacies, depth, and basin exhibited by the sample population. For over 800 samples core plugs greater than 3 –inches in length were cut in half to provide two paired core plugs for advanced properties measurements. Figure 1 illustrates the ratio of helium porosities of samples to the mean porosity of the sample pair. Over 75% of all samples exhibit porosity within 10% of the mean porosity of the porosity pair, and 88% exhibit porosities within 20%. Figure 2 illustrates the ratio of *in situ* Klinkenberg permeabilities of samples to the geometric mean permeability of the sample pair. Approximately 35% of all samples exhibit a permeabilities within 10% of the mean, 55% within 20%, 70% within 30%, and 80% within 40%.

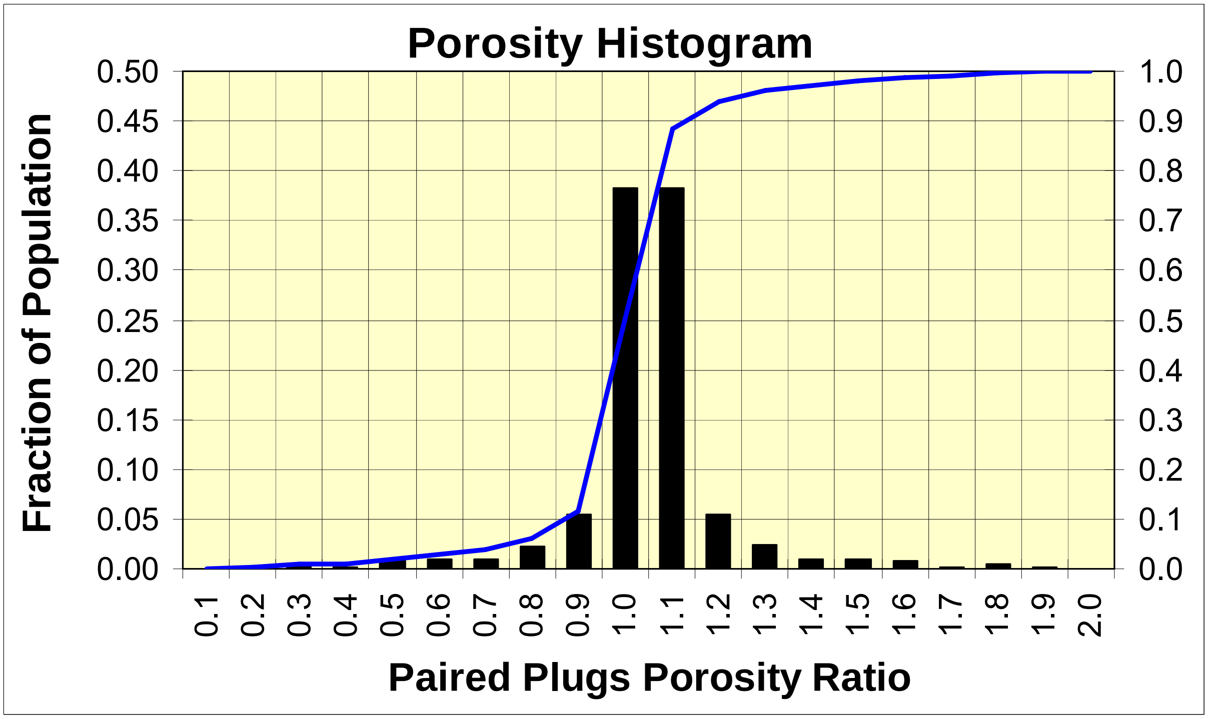

Figure 1. Histogram of ratio of paired plug porosities to mean porosity of plug pair. n = 652 x 2= 1304.

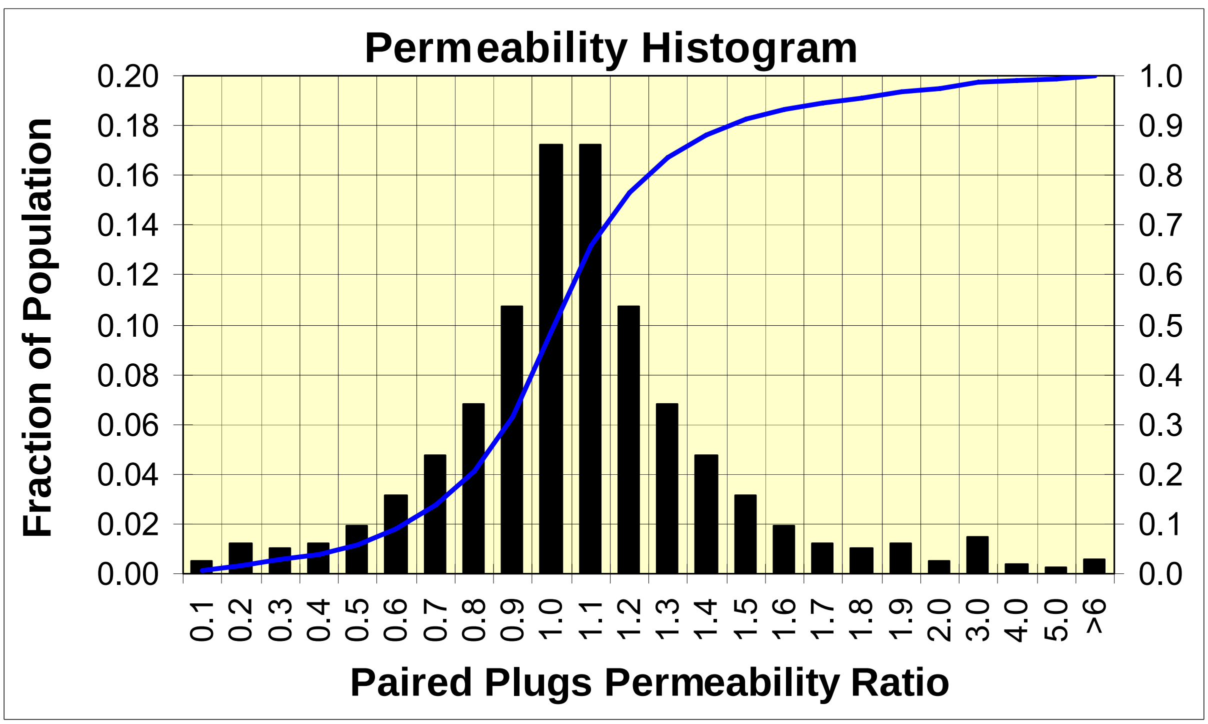

Figure 2. Histogram of ratio of paired plug *in situ* Klinkenberg permeabilities to mean permeability of plug pair. n = 634 x2 = 1268.

Subtask 4.3. Measure *in situ* and routine capillary pressure

Mercury intrusion analysis from 2 to 10,000 psi injection pressure provides drainage capillary pressure curves for 87 advanced properties samples. These curves exhibit the trend that threshold entry pressure (P_{te}, the minimum pressure at which the non-wetting phase can invade the sample pore space excluding minor surface pores) measured by extrapolation of the Pc curve in the transition zone to Sw = 100% (avoiding surface pore influence on the Pc curve), increases with decreasing permeability (Figure 3). This trend is the direct result of the association between decreasing pore throat size and permeability.

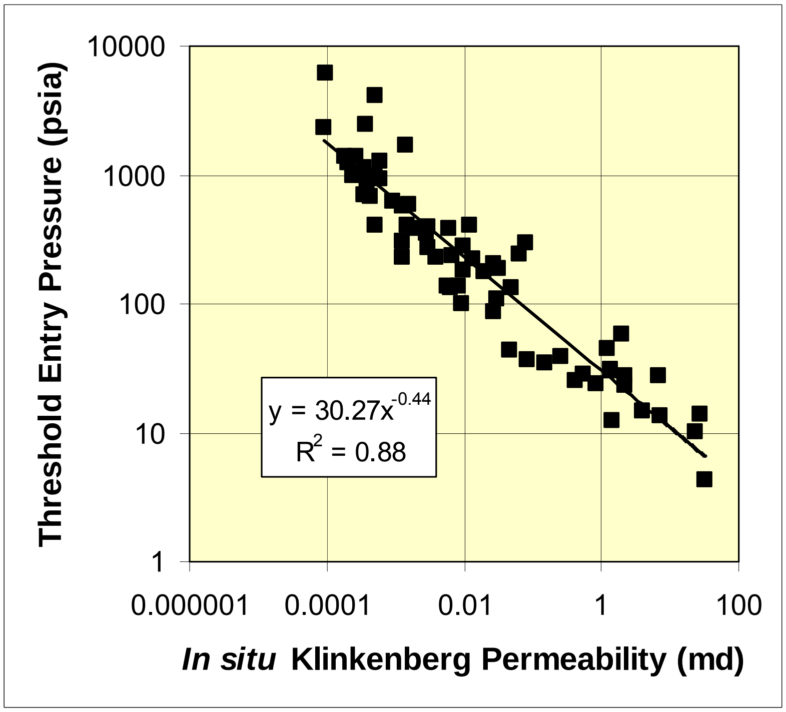

Figure 3. Crossplot of air-mercury (Hg) threshold entry pressure (P_{te}) versus *in situ* Klinkenberg permeability (k_{ik}) illustrating log-log linear trend of increasing Pte with decreasing permeability. The relationship can be characterized by the power-law equation shown.

Capillary pressure hysteresis curves were measured for a select group of samples of varied porosity, permeability, and lithofacies and are continuing. Figure 4 illustrates hysteresis curves for a Washakie Basin medium-grained, planar-bedded sandstone. As with other samples analyzed, a significant fraction of the trapped non-wetting phase saturation (Snw) results from the early intrusion at low Snw values. In the example shown a residual nonwetting phase saturation (Srnw) of 32% results after primary drainage intrusion of 42%. Subsequent drainage-imbibition cycles results in progressively less increase in Srnw with increasing maximum or initial nonwetting phase saturation (Snwi). This is consistent with the Land (1971) relation for strongly wet samples:

$$1/Srnw - 1/Snwi = C$$

Where for the samples analyzed to date C = 0.8 ± 0.2. It is important to note these results are for the air-mercury system and have not been tested for an air-brine system yet.

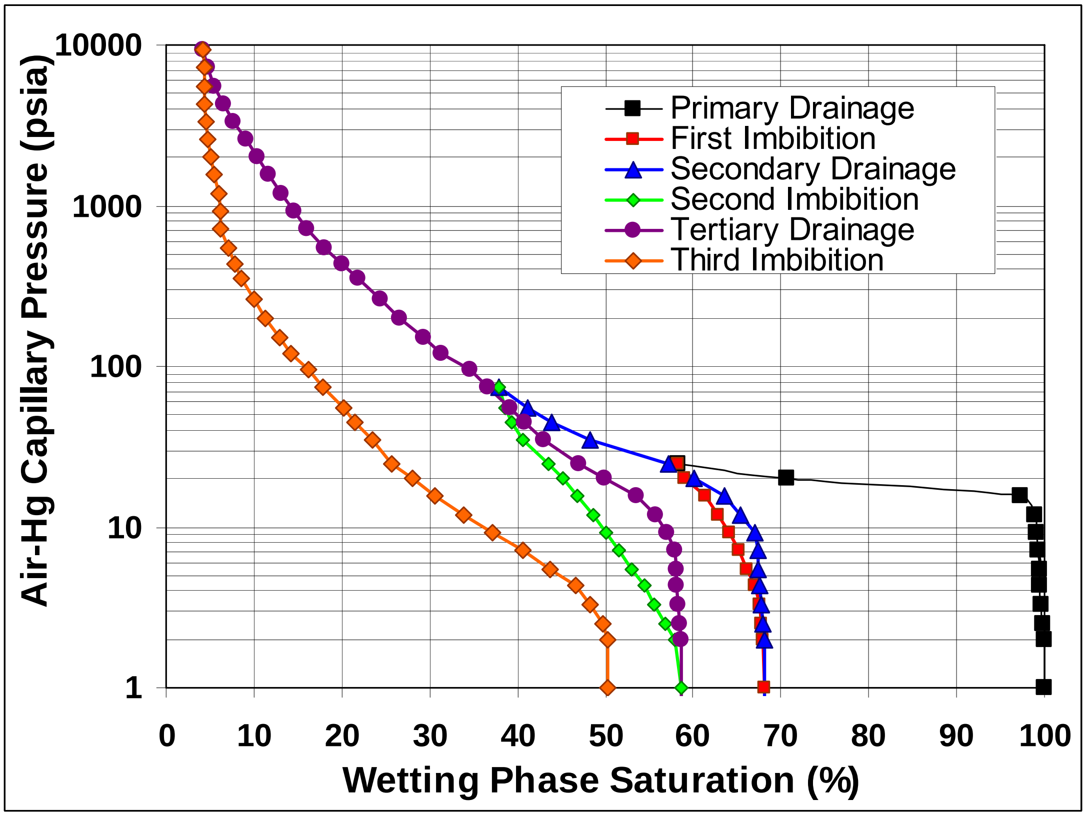

Figure 4. Air-mercury successive drainage and imbibition capillary pressure curves exhibiting hysteresis with successively increasing residual nonwetting phase saturation (Srnw) with increasing initial nonwetting phase saturation (Snwi).

Subtask 4.4. Measure electrical properties

Electrical resistivity analysis for 200,000 ppm NaCl brine, performed on 287 samples of varied lithology and porosity, indicates that the Archie cementation exponent, *m*, decreases with decreasing porosity (Figure 5). Multisalinity measurements to obtain salinity independent electrical properties are being conducted. The data shown represent final high salinity analyses and samples not already flushed with lower salinity brine are being flushed to provide resistivity measurements at lower salinity for Waxman-Smits analysis. Further analysis is also being performed on the data obtained. Lower salinity measurements indicates Archie cementation exponent decreases with decreasing salinity indicating some conductive solids effects are present. Equilibrium data must be collected to quantitatively evaluate the effect.

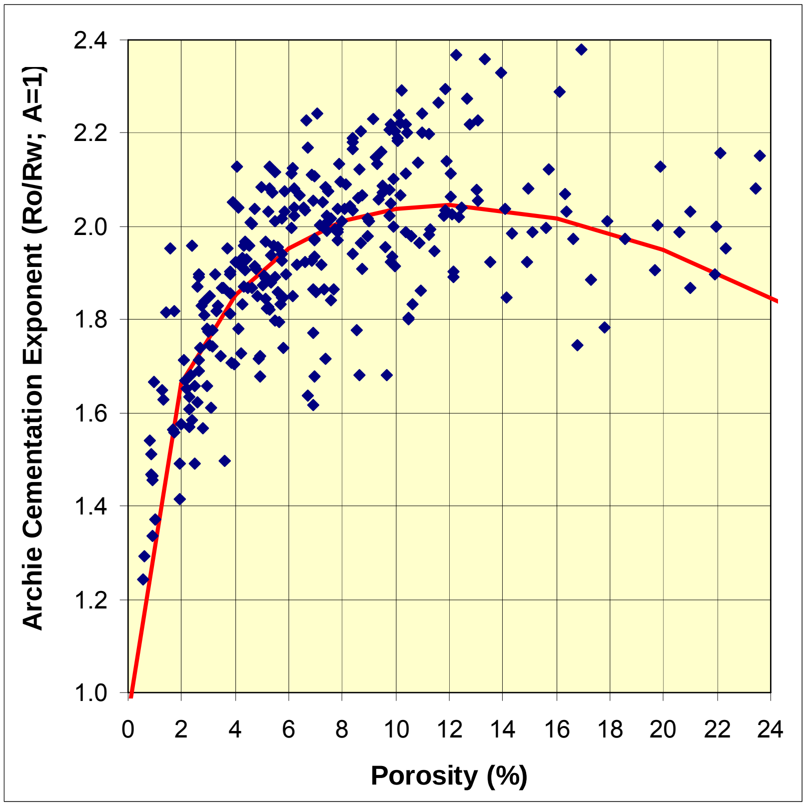

Figure 5. Crossplot of Archie cementation exponent, measured using 200,000 ppm NaCl versus routine porosity (%) showing a decrease in m with decreasing porosity. This trend may reflect a shift towards more thin, sheet-like tabular pores with decreasing porosity. The curve represents: $m = 0.95-0.092\ \phi + 0.635\ \phi^{0.5}$, where ϕ = porosity (%). n = 287.

TASK 8. TECHNOLOGY TRANSFER, REPORTING, PROJECT MANAGEMENT

Subtask 8.1 Technology Transfer

A paper was prepared as part of the proceedings of the American Association of Petroleum Geologists Vail Hedberg Conference. The paper explores models for critical gas saturation. An abstract of the paper follows:

ISSUES WITH GAS AND WATER RELATIVE PERMEABILITY IN LOW-PERMEABILITY SANDSTONES

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ABSTRACT
Gas and water relative permeability can be effectively modeled in low-permeability gas sandstones using the modified Corey (1954) equations: $k_{rg} = (1 - (S_w\text{-}S_{wc,g})/(1\text{-}S_{gc}\text{-}S_{wc,g}))^{p}\ (1\text{-}((S_w\text{-}S_{wc,g})/(1\text{-}S_{wc,g}))^{q})$ and $k_{rw} = ((S_w\text{-}S_{wc})/(1\text{-}S_{wc}))^{r}(k_w/k_{ik})$, where S_w = water saturation, S_{gc} = critical gas saturation (expressed as fraction gas saturation), $S_{wc,g}$ = critical water saturation for gas equation (expressed as fraction water saturation), S_{wc} = critical water saturation, and p, q, and r are exponents reflecting pore size distribution and architecture. Gas relative permeability can be modeled at low S_w using: $S_{wc,g} \approx 0.16 + 0.053*\log k_{ik}$ ($S_{wc,g} = 0 \mid k_{ik} < 0.001$ md). At high S_w, few data exist but projection of k_{rg} curves support two models: 1) constant k_{rg} exponents ($p = 1.7$, $q = 2$) with varied $S_{gc}(k)$, $S_{gc} \approx 0.15 - 0.05*\log k_{ik}$, and 2) near constant S_{gc} (0%<Sgc<10%) with varied k_{rg} exponent $p(k)$ ($2<p<2.8$). Threshold mercury injection capillary pressure measurements, coupled with electrical resistivity measurements on selected Mesaverde sandstones can be explained using four pore network architecture models: 1) percolation (N_p), 2) parallel (N_{II}), 3) series (N_{s1}), and 4) discontinuous series (N_{s2}). Data and analysis suggest that critical gas saturation is likely to be very low (e.g., S_{gc} < 3%) in thinly laminated sandstones where properties among beds vary, low (e.g., S_{gc} < 10%) in homogeneous sandstones of any permeability, and may be low to high (e.g., 10% < S_{gc} < 50%) in heterogeneous lithologies. As with any percolating network, S_{gc} decreases with increasing lattice dimension. Results indicate that in heterogeneous lithologies the (p=C; $S_{gc}(k)$) equations may be more appropriate while in homogeneous lithologies the ($p(k)$; $S_{gc}\approx$C) may apply. These also suggest that k_{rg} data scatter is the result of unspecified lithologic variability. Measurements of S_{wc} indicate that the k_{rw} exponent $r \approx 6$ if S_{wc} is assigned to equal $S_{wi}(k)$ (capillary pressure "irreducible" water saturation).

Abstracts are being prepared for the AAPG Western Regional meeting in October, Snowbird, UT,

CONCLUSIONS

Final cores have been received from industry. Advanced properties measurements are preceding smoothly and only slightly behind the timetable presented in the Management Plan. Analysis is being performed within the approved budget. The capillary hysteresis data indicate that the Land (1971) relation may approximately apply to low-permeability sandstones. Low Archie cementation exponents at porosities less than 6% help to explain standard wireline log calculation indicating saturations in excess of Sw=100% using an Archie cementation exponent m = 2.

REFERENCES

Land, C.S., 1971, "Comparison of calculated with experimental imbibition relative permeability," Soc. Petroleum Engineering Journal (Dec. 1971) p. 419-425.