QUARTERLY TECHNICAL PROGRESS REPORT
FOR THE PERIOD ENDING JUNE 30 2006

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

DOE Contract No. DE-FC26-05NT42660

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DISCLAIMER:

ABSTRACT:

Analysis of the remaining core plugs of the total of 1753 core plugs has been proceeding. The Mesaverde Project website has been set up (http://www.kgs.ku.edu/mesaverde). Published and newly measured data and core images are being added to the site. Capillary pressure (Pc) measurements for cores exhibiting *in situ* Klinkenberg permeability (k_{ik}, md) ranging from $0.00025 < k_{ik} < 2.5$ md exhibit the trend that threshold entry pressure (P_{te}) and wetting phase saturation at any given Pc increases with decreasing permeability. For the samples measured to date a P_{te} versus k_{ik} trend can be characterized using the relation: $P_{te} = 53.3\ k_{ik}^{-0.375}$. The relationship between wetting phase saturation at any given Pc (for 350< Pc < 3350 psia air-Hg) and k_{ik} can be characterized using: $S_w = A\ k_{ik}^{-0.138}$ where $A = -13.1*\ln(Pc_{air\text{-}Hg})+117$. Application of the Leverett J function for modeling capillary pressure is not accurate for the rocks measured. For 77 samples measured to date Archie cementation exponent, ***m***, decreases with decreasing porosity. Java code, utilized in the US DOE-sponsored GEMINI Project (Contract No. DE-FC26-00BC15310), has been modified to create a stand-alone graphical user interface (GUI) for accessing, querying, displaying, and downloading published and measured petrophysical and geologic data. This web tool, termed Rock Catalog, is designed to help the user locate core data and core image files and help the user to select search constraints to filter, display, and download data relative to their specific query and application. This tool will be incorporated into the Data Page in the next quarter.

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Acronyms

DOE = Department of Energy
GUI = graphical user interface
k_{ik} = *in situ* Klinkenberg permeability, millidarcies
m = Archie cementation exponent
md = millidarcy, 1 md = 9.87×10^{-4} μm^2
n = number
Pc = capillary pressure, psia
psi = pound per square inch, 1 psi = 6.89 kPa
P_{te} = threshold entry pressure, psi
S_w = wetting phase saturation, %
σ = interfacial tension, dyne/cm
θ = contact angle, degrees
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 five major Tight Gas Sandstone basins (Washakie, Uinta, Piceance, Greater Green River, 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.

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EXECUTIVE SUMMARY:

Analysis of the remaining core plugs of the total of 1753 core plugs has been proceeding. The Mesaverde Project website has been set up (http://www.kgs.ku.edu/mesaverde). Published and newly measured data and core images are being added to the site. Capillary pressure (Pc) measurements for cores exhibiting *in situ* Klinkenberg permeability (k_{ik}) ranging from $0.00025 < k_{ik} < 2.5$ md exhibit the trend that threshold entry pressure (P_{te}) and wetting phase saturation at any given Pc increases with decreasing permeability. A P_{te} versus k_{ik} trend can be characterized using the relation: $P_{te} = 53.3\ k_{ik}^{-0.375}$. The relationship between wetting phase saturation at any given Pc (for 350< Pc < 3350 psia air-Hg) and k_{ik} can be characterized using: $S_w = A\ k_{ik}^{-0.138}$ where $A = -13.1*\ln(Pc_{air\text{-}Hg})+117$. Application of the Leverett J function for modeling capillary pressure is not accurate for the rocks measured. For 77 samples measured to date Archie cementation exponent, ***m***, decreases with decreasing porosity.. Java code, utilized in the US DOE-sponsored GEMINI Project (Contract No. DE-FC26-00BC15310), has been modified to create a stand-alone graphical user interface (GUI) for accessing, querying, displaying, and downloading published and measured petrophysical and geologic data. This web tool, termed Rock Catalog, is designed to help the user locate core data and core image files and help the user to select search constraints to filter, display, and download data relative to their specific query and application. This tool will be incorporated into the Data Page in the next quarter.

RESULTS AND DISCUSSION:

TASK 3. ACQUIRE DATA AND MATERIALS

Subtask 3.1. Compile published advanced properties data

The compiled reference list, to date, has been posted on the Mesaverde website (http://www.kgs.ku.edu/mesaverde/index.html). Data for relative permeability have been compiled from all identified references found concerning low-permeability sandstone gas relative permeability. These data have been input into a database and are available on the Mesaverde website in spreadsheet format. These data will be accessible through the Web GUI when this tool is installed next quarter.

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

The Core Plug Inventory (http://www.kgs.ku.edu/mesaverde/datalist.html) lists the total of 1753 core plugs, including matched pairs at 827 unique depths, which have been obtained from 38 wells (http://www.kgs.ku.edu/mesaverde/wellinv.html). The number of samples obtained significantly exceeds the proposed sample set (n= 300) but more thoroughly samples Mesaverde lithofacies. The wells sampled to date are widely geographically distributed across the five principal basins of the study area (http://www.kgs.ku.edu/mesaverde/map.html). Core plugs from recently drilled wells are continuing to be contributed by industry partners. Because of drilling schedules, fresh core will continue to be submitted through the next quarter. Analysis is proceeding on received cores and cores arriving later will placed in the analysis workflow. Due to work load, it is anticipated that no additional cores will be accepted after September 30th unless they represent an under sampled lithofacies/porosity/permeability permutation that significantly enhances the sample population.

Subtask 3.3. Acquire logs from sample wells and digitize

Logs have been obtained for many of the wells for which core plugs were obtained. The remaining logs are being obtained.

TASK 4. MEASURE ROCK PROPERTIES

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

As noted, the present core sample set (n=827/1753) is significantly greater than the proposed sample set (n=300). This has required greater time than planned for sample collection and sample preparation. Measurement of basic properties has continued on core plugs obtained. A portion of the plug population that will have advanced properties measurement has been selected and some advanced properties are shown below. Completion of the selection of advanced samples will be performed after basic analysis is finished on all 827 "A" core plugs.

Subtask 4.3. Measure in situ and routine capillary pressure

Capillary pressure analysis was performed on a select group of core plugs that are presently estimated to be appropriate for the advanced properties group. Mercury intrusion analysis from 2 to 10,000 psi injection pressure provided the drainage capillary pressure curves shown in Figure 1.

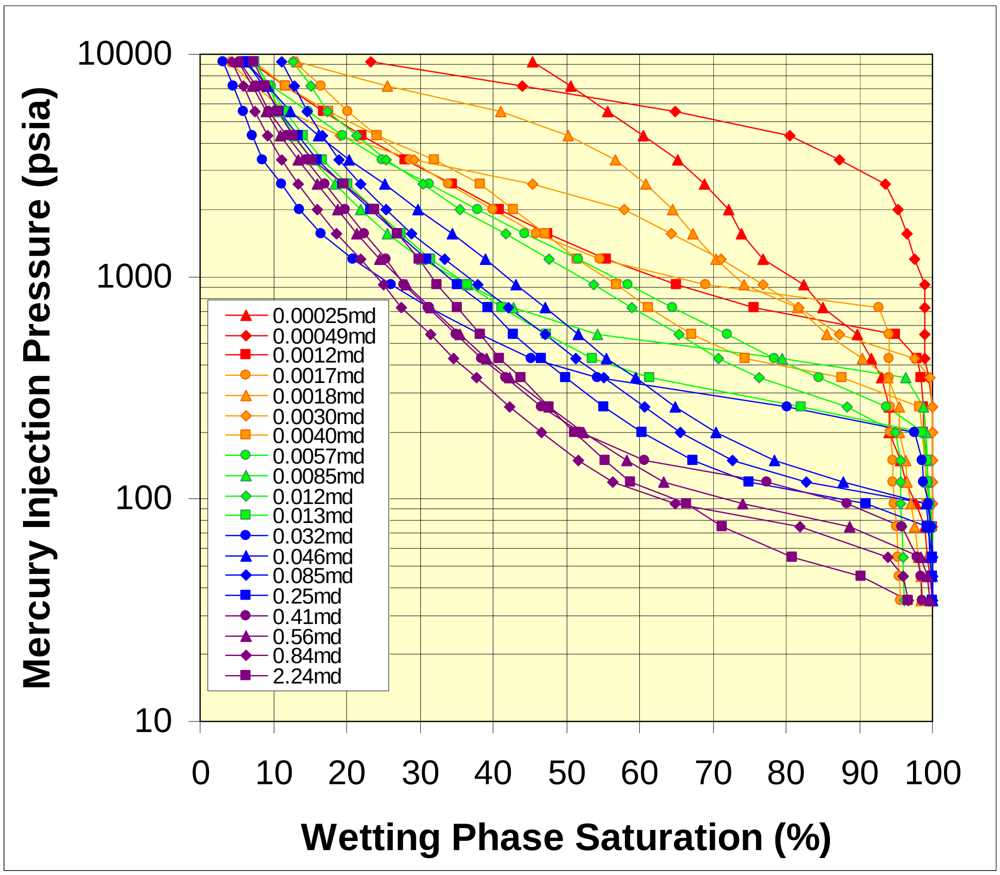

Figure 1. Air-mercury capillary pressure curves for selected samples ranging in *in situ* Klinkenberg permeability from 0.00025 md to 2.25 md. These curves exhibit increasing threshold entry pressure and increasing "irreducible" water saturation with decreasing permeability.

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 2). This trend is the direct result of the association between decreasing pore throat size and permeability.

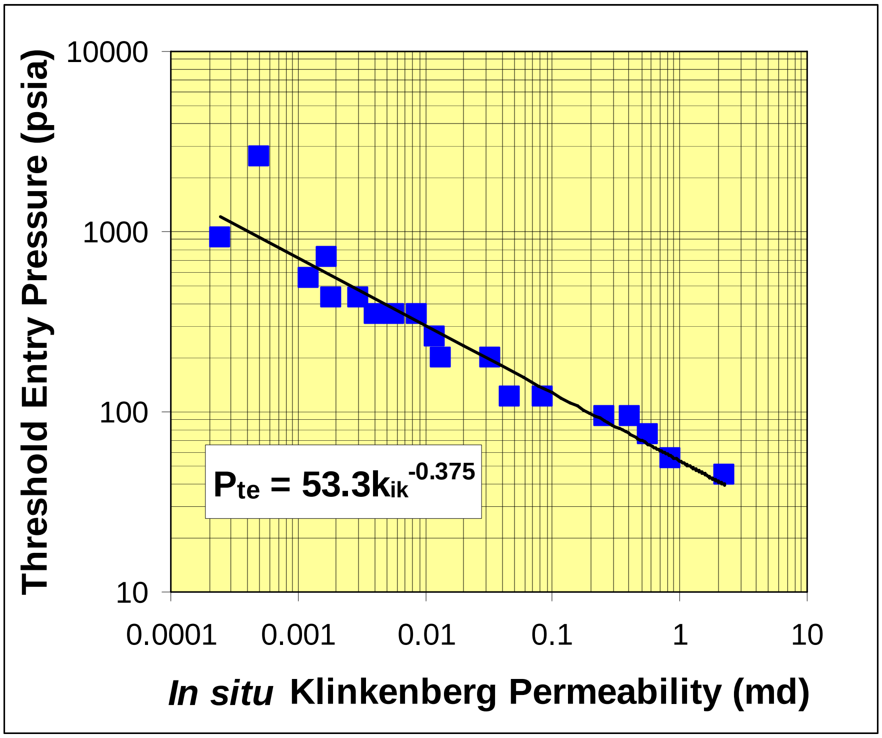

Figure 2. Crossplot of air-mercury threshold entry pressure (P_{te}) versus *in situ* Klinkenberg permeability (k_{ik}) illustrating log-log linear trend of increasing P_{te} with decreasing permeability. The relationship can be characterized by the power-law equation shown.

In low-permeability sandstones the conventional use of the criteria for defining "irreducible" saturation, the saturation at which the non-wetting phase saturation changes negligibly with significant increase in capillary pressure, are not clear and it can be argued that this metric is not applicable. The crossplot of wetting phase saturation (S_w) versus *in situ* Klinkenberg permeability (k_{ik}) shows increasing S_w with decreasing permeability for a range of pressures (Figure 3). This relationship can be characterized using a power-law function where $S_w = A\, k_{ik}^{-0.138}$ and $A = -13.1{*}\ln(Pc_{air\text{-}Hg})+117$ (shown by lines for each Pc). Figure 4 illustrates the relationship between the Leverett J Function (where $J(S_w) = Pc/\sigma\cos\theta\,(k_{ik}/\phi)^{0.5}$ and σ = interfacial tension in dyne/cm, θ = contact angle and ϕ = fractional porosity) and wetting phase saturation. For higher permeability rocks the Leverett J function can exhibit a similar J-S_w trend for a wide range of rock permeability. However, in low-permeability rocks the scatter in this relationship can make the use of the J Function impractical. The J function scatter can be attributed to change and variance in the relationship between threshold entry and capillary pressure slope and the Leverett J assumed relationship that this correlates with $(k_{ik}/\phi)^{0.5}$.

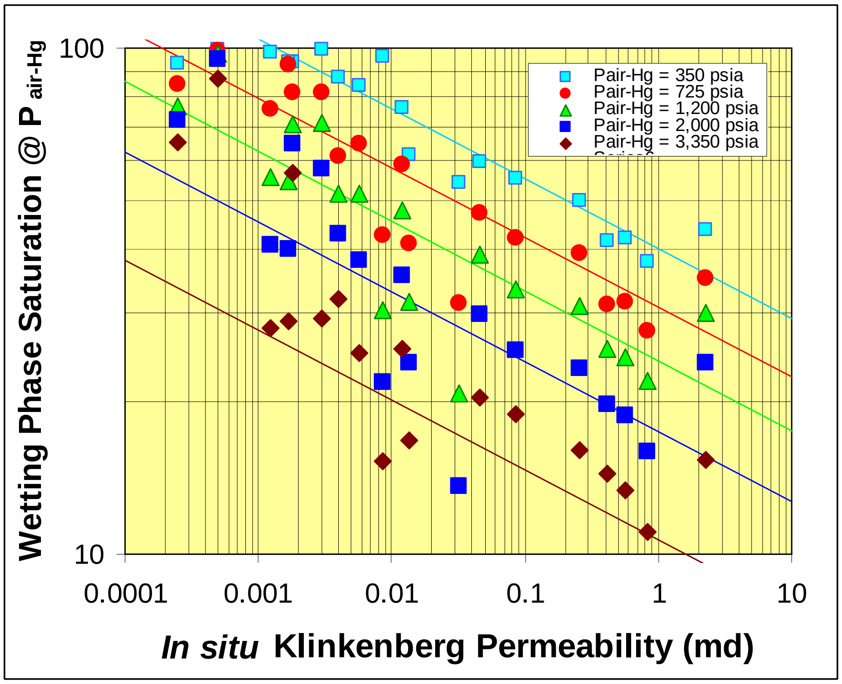

Figure 3. Crossplot of wetting phase saturation (Sw) versus *in situ* Klinkenberg permeability (k_{ik}) showing increasing Sw with decreasing permeability for a range of pressures. This relationship can be characterized using a power-law function where $S_w = A\ k_{ik}^{-0.138}$ and $A = -13.1*\ln(Pc_{air\text{-}Hg})+117$ (shown by lines for each Pc).

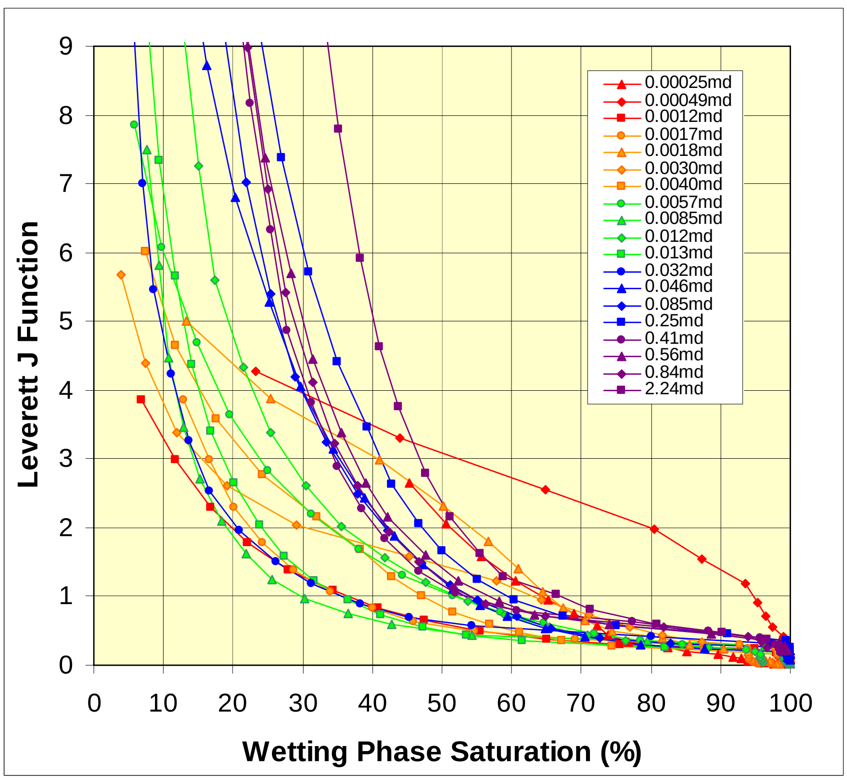

Figure 4. Crossplot of Leverett J Function versus wetting phase saturation showing wide scatter in relationship.

Subtask 4.4. Measure electrical properties

Electrical resistivity analysis for 200,000 ppm NaCl brine, performed on 77 samples of varied lithology and porosity, indicates that the Archie cementation exponent, ***m***, decreases with decreasing porosity (Figure 5). Low-permeability sandstones are characterized by thin, sheet-like tabular pore throats often connecting larger, isolated, frequently secondary porosity pore bodies. With progressive occlusion of secondary porosity, the pore system can be interpreted to evolve towards a simpler network of just thin tabular pores. This pore architecture is similar to a simple fracture that exhibits cementation exponents near ***m*** =1. From this analysis the trend in Figure 2 can be interpreted to reflect the progressive occlusion of the pore system to a simple fracture/sheet pore network with low cementation exponent with decreasing porosity. More high and low porosity data will allow better definition of the apparent trend. Multisalinity measurements to obtain salinity independent electrical properties are being conducted.

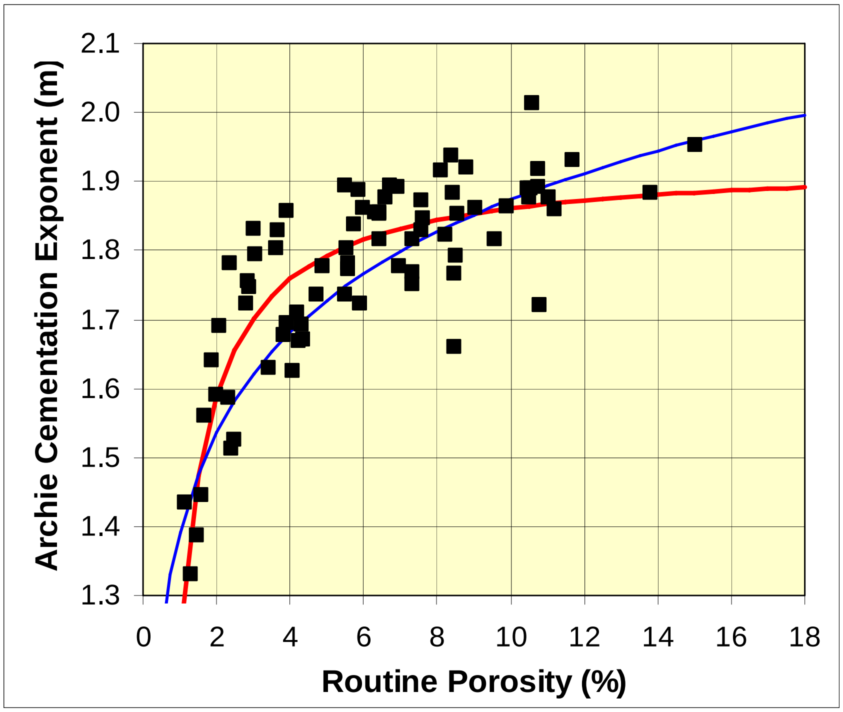

Figure 5. Crossplot of Archie cementation exponent, measured using 200,000 ppm NaCl versus routine porosity (%) showing a decrease in m with decreasing porosity. This trend may reflect a shift towards more thin, sheet-like tabular pores with decreasing porosity. Present data trends can be empirically modeled using various relations including: ***m*** = 1.93-0.68/ϕ (red) and ***m*** = 1.39 + 0.21 ln(ϕ) (blue) where ϕ = porosity (%). The first relationship is only valid for ϕ > 0.75%.

TASK 5. BUILD DATABASE AND WEB-BASED ROCK CATALOG

Subtask 5.1. Compile published and measured data into Oracle database

Published relative permeability data have been collected from the literature and input in an Oracle database. These data are presently available on the Mesaverde website in spreadsheet format. The web tools for accessing and displaying all data are nearly complete and access, plotting and data presentation tools for querying the Oracle database will be implemented in the next quarter. Rock core images for cores in the study are available on the website and will also be accessible by the web tools.

Subtask 5.2. Modify existing web-based software to provide GUI data access

Java code utilized in the US DOE-sponsored GEMINI Project (Contract No. DE-FC26-00BC15310) has been modified to create a stand-alone graphical user interface (GUI) for accessing, querying, displaying, and downloading published and measured petrophysical and geologic data. This web tool, termed Rock Catalog, is designed to help the user locate core data and core image files that meet the user search criteria and help the user to select search constraints to filter the data relative to their application. The user can construct measured core data crossplots, e.g. Routine Porosity versus Routine Air Permeability data plots, and display core images and wireline log profiles from LAS files based on search constraints. The tools allow the user to save the images and plots to their personal computer by constructing a rock catalog web page, printout, or direct download of comma-delimited data files for the data selected. Several example (Figures 6-10) screen captures are presented that show some of the interfaces. These interfaces are nearly complete but are being modified with testing to make them user-friendly and efficient. Basic search criteria are presented as text descriptors that are created by GUI selection.

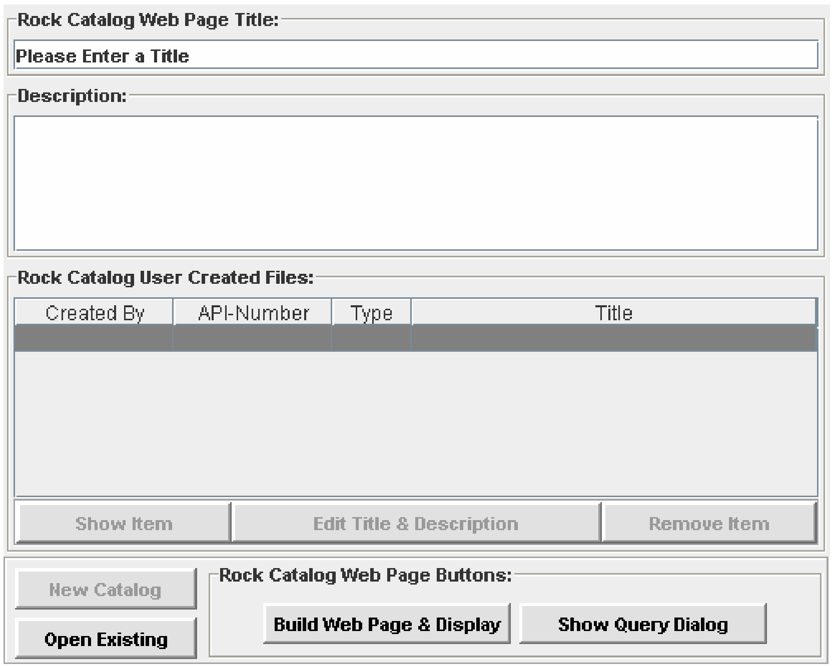

Figure 6. Entry GUI window providing title and project description input and allowing user to open an existing Rock Catalog project for modification.

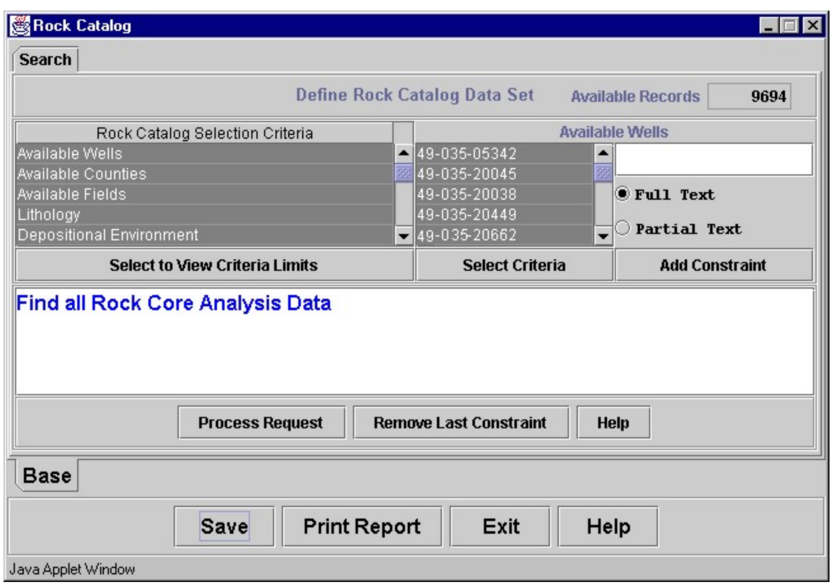

Figure 7. Search GUI window with criteria input window allowing definition of basic search criteria including by: well, county, field, lithology, depositional environment. Multiple search criteria can be specified.

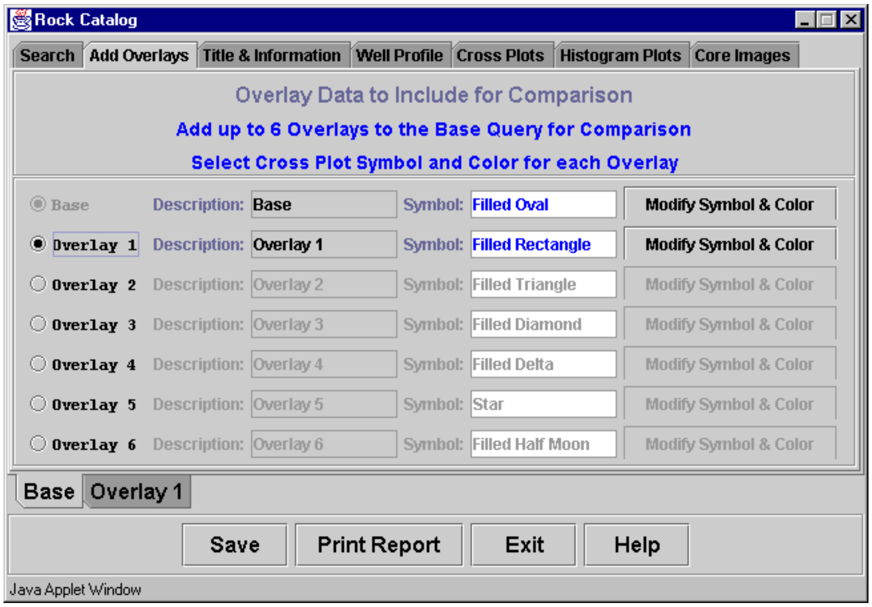

Figure 8. Add Overlays GUI construction window. User may select up to 6 different symbols to distinguish between different data sets on a crossplot. wells or rock types can be shown with different symbols.

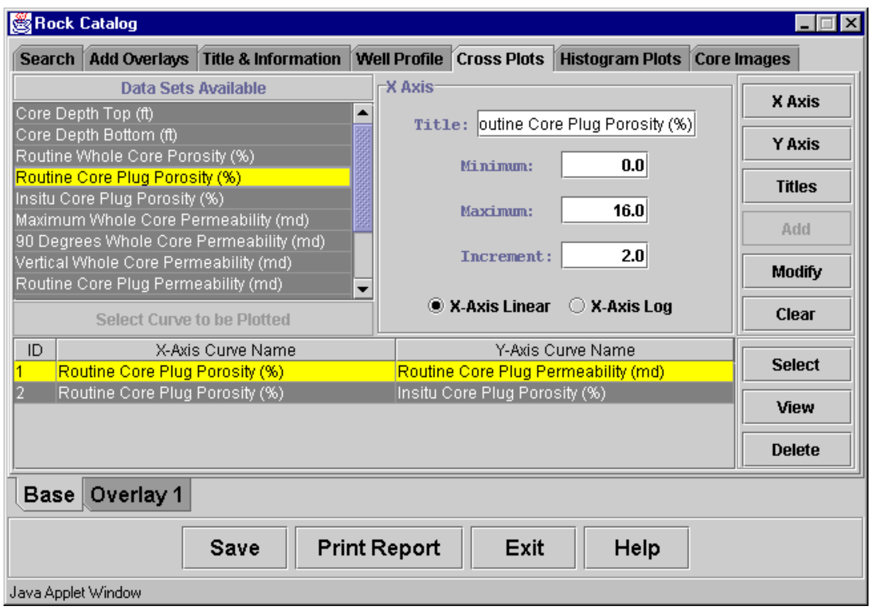

Figure 9. **Crossplots** GUI construction window. User selects from available data fields the variables that are to be cross-plotted and the range for each variable. Multiple crossplots can be constructed. On each crossplot data from different sets of samples can presented using the symbols defined in the **Add Overlays** window (e.g. data from 2-6 different wells or rock types can be shown with different symbols.

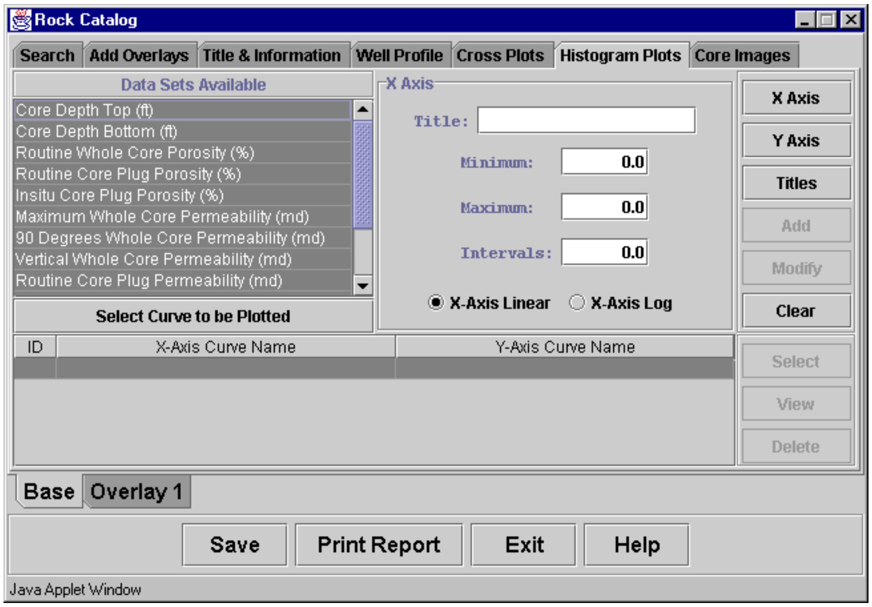

Figure 10. Histogram GUI window. User can specify a variable and the range for which distribution frequency analysis is performed and shown graphically in histogram form. **Histogram** is performed for the population selected that meets **Search** criteria.

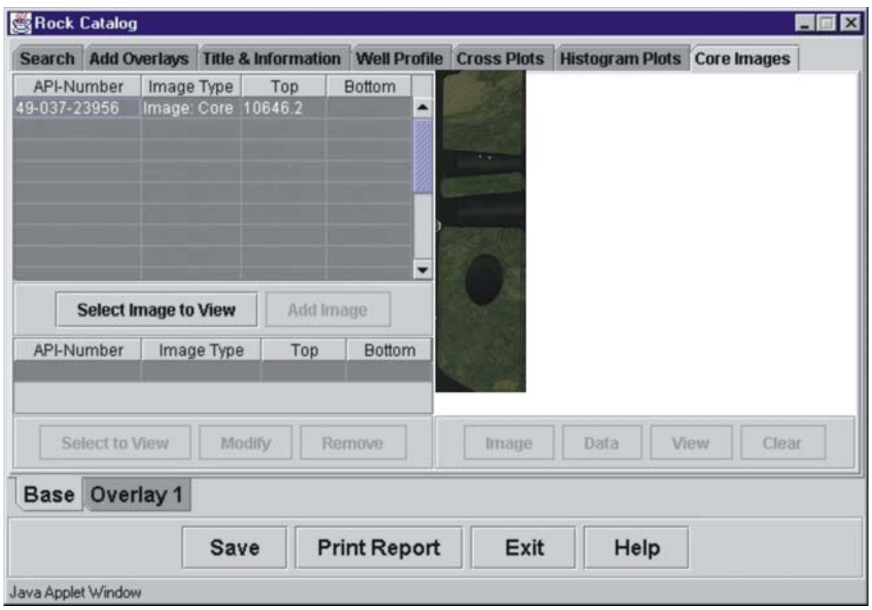

Figure 11. Core Images GUI window showing selection of core images to be included in Rock Catalog Page being constructed. Multiple core images can be selected for inclusion.

TASK 8. TECHNOLOGY TRANSFER, REPORTING, PROJECT MANAGEMENT

Subtask 8.1 Technology Transfer

The Mesaverde website has been developed (http://www.kgs.ku.edu/mesaverde) presenting some of the project findings to date. Additional data will be uploaded as they are measured and quality checked. The web database tools for database access and analysis will be installed in the next quarter.

CONCLUSIONS

Cores continue to be contributed by Industry participants though this will begin to be curtailed in the next quarter due to sample number and scheduling constraints. Basic and advanced properties measurements are proceeding smoothly and only slightly behind the timetable presented in the Management Plan. The minor delay is the result of analysis of nearly three times the number of samples originally proposed. These additional samples represent important sampling of various parameter permutations and analysis is being performed within the approved budget. Results are being uploaded to the Mesaverde website and installation of the developed Rock Catalog GUI in the next quarter will facilitate accessing, querying, displaying, and downloading published and measured petrophysical and geologic data. This web tool is designed to help the user locate core data and core image files that meet the user search criteria and help the user to select search constraints to filter the data relative to their application.