QUARTERLY TECHNICAL PROGRESS REPORT
FOR THE PERIOD ENDING DECEMBER 30, 2005

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

Contractor:	University of Kansas Center for Research, Inc. 2385 Irving Hill Road Lawrence, KS 66044

DOE Program:	Natural Gas Technologies (Advanced Diagnostics & Imaging)
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Program Period:	October 1, 2005 – September 30, 2007
Reporting Period:	October 1, 2005 – December 30, 2005
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ABSTRACT:

Progress is reported for the period from October 1, 2005 to December 30, 2005. Currently work has been performed on Tasks 1, 2, 3, 4, 5 and 8. Compilation of over 230 technical publications with petrophysical data relevant to the Mesaverde has provided a sound basis for the petrophysical database being compiled. Digitization of this data is progressing and will continue through the next quarters. In the first quarter of the project, industry has shown great interest in the project and willingness to participate through contribution of core. Sampling design integrates both sampling of Mesaverde core at the U.S. Geological Survey Core Research Center and obtaining core from industry participants. Because several industry participants wish to contribute core that will be taken in Spring 2006, the sampling plan has extended the period over which core material will be obtained. Obtaining both library and newly-acquired core will increase in the next two quarters. Core analysis has just begun in this quarter. Initial measurements for Greater Green River Basin Five Mile Gulch Unit #3 samples indicate that porosity and permeability trends are consistent with other previously reported Mesaverde/Frontier trends. Comparison of confined and unconfined drainage capillary pressure curves for a first sample indicates that confining stress results in reduction of pore throat size by approximately a factor 2 for the largest pores and that the smallest pores, probably within clays or between clay particles lining pore walls, are not significantly affected by confining stress. Core collection, and basic analysis will proceed through the next quarter and electrical measurement s will commence.

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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, Upper 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.

Project Task Overview -

Task 1. Research Management Plan
Task 2. Technology Status Assessment
Task 3. Acquire Data and Materials
- Subtask 3.1. Compile published advanced properties data
- Subtask 3.2. Compile representative lithofacies core and logs from major basins
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Task 4. Measure Rock Properties
- Subtask 4.1. Measure basic properties (k, ϕ, grain density) and select advanced population
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- Subtask 4.4. Measure electrical properties
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Task 5. Build Database and Web-based Rock Catalog
- Subtask 5.1. Compile published and measured data into Oracle database
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Task 7. Simulate Scale-dependence of Relative Permeability
- Subtask 7.1. Construct basic bedform architecture simulation models
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Task 8. Technology Transfer, Reporting, and Project Management
- Subtask 8.1 Technology Transfer
- Subtask 8.2. Reporting Requirements
- Subtask 8.3. Project Management

EXECUTIVE SUMMARY:

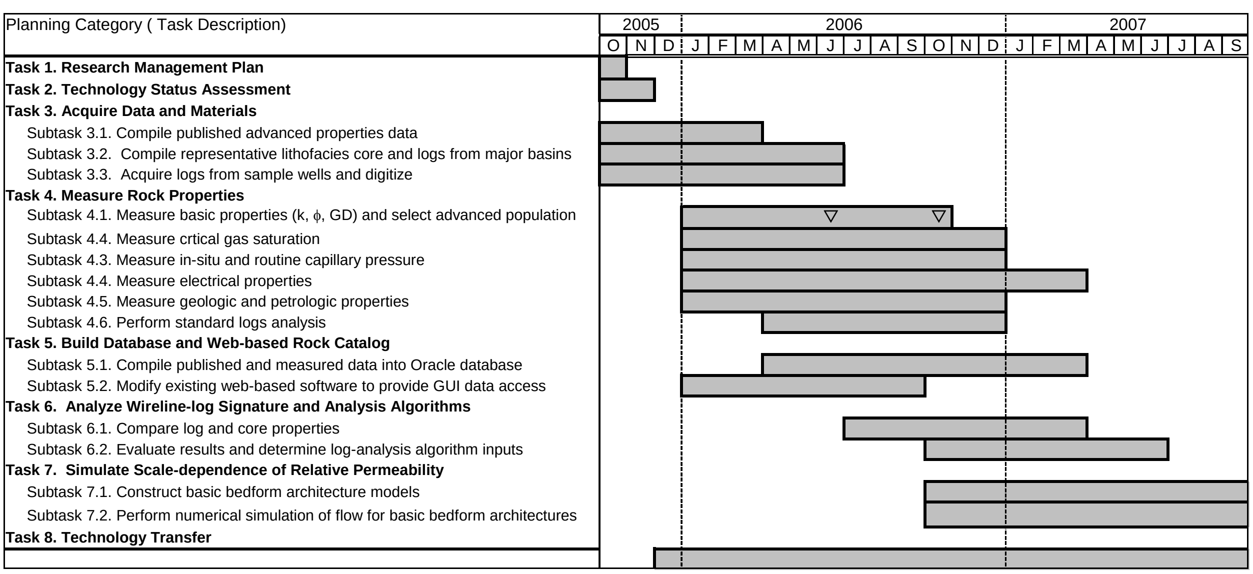
Compilation of over 230 technical publications with petrophysical data relevant to the Mesaverde has provided a sound basis for the petrophysical database. Digitization of this data is progressing and will continue through the next quarters. In the first quarter of the project, industry has shown great interest in the project and willingness to participate through contribution of core. Sampling design integrates both sampling of Mesaverde core at the U.S. Geological Survey Core Research Center and obtaining core from industry participants. Because several industry participants wish to contribute core that will be taken in Spring 2006, the sampling plan has extended the period over which core material will be obtained. Obtaining both library and newly-acquired core will increase in the next two quarters. Core analysis has just begun in this quarter. Initial measurements for Greater Green River Basin Five Mile Gulch Unit #3 samples indicate that the properties are consistent with previously reported Mesaverde/ Frontier values. Comparison of confined and unconfined drainage capillary pressure curves for a first sample indicates that confining stress results in reduction of pore throat size by approximately a factor 2 for the largest pores and that the smallest pores, probably within clays or between clay particles lining pore walls, are not significantly affected by confining stress.

RESULTS AND DISCUSSION:

TASK 1. RESEARCH MANAGEMENT PLAN

A revised research management plan including Work Breakdown Structure was drafted, submitted and approved. The approved management plan mirrored the proposal with minor modification. Based on initial contacts with gas companies that want to contribute core to the study but will not be drilling and coring wells until Spring 2006, the schedule for acquiring core material was modified from the proposal to allow time in Spring 2006 for sample acquisition. The final Project Schedule is shown in Figure 1.

Figure1. Project Schedule



TASK 2. TECHNOLOGY STATUS ASSESSMENT

The Technology Status Assessment has been drafted and is being finalized.

TASK 3. ACQUIRE DATA AND MATERIALS

Subtask 3.1. Compile published advanced properties data

Reference searches were performed in the following databases: Georef, NTIS, DAI, GPO, Compendex, USBM, WorldCat, FSProc, SPE. Of the over nearly 2,000 references that are relevant to low-permeability sandstones and Mesaverde, over 230 technical publications have been identified, to date, that are directly relevant to Mesaverde petrophysical properties or to petrophysical properties of non-Mesaverde low-permeability sandstones but are petrophysically relevant. Physical or electronic copies were obtained for the publications identified. Data in these publications is being entered into a database either from tables in the publication or is being interpreted from figures. Obtaining data from figures is significantly slower than from tables but is proceeding smoothly. Technical articles are continuing to be obtained to evaluate their relevance to the project database.

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

A database of full-diameter and slab Mesaverde and Cretaceous cores at the U.S. Geological Survey (USGS) Core Facility was compiled. This is being reviewed and integrated with fresh cores being obtained from industry partners to optimize selection of cores for each basin. Ninety three sets of core plugs were obtained from two wells in the Greater Green River Basin (American Hunter Old Road #1, Amoco Five Mile Gulch Unit #3). The Enserch Expl. 2-7 Flat Mesa-Federal was sampled but will be more extensively plugged next quarter. The Inexco Oil Co. A-1 Wasp was sampled but will be more extensively plugged next quarter. Core plugs, obtained from a newly cut core, were contributed by Bill Barrett Corp. from the Bill Barrett Corp. Last Dance 43-C-3-792, Mamm Creek Field, Piceance Basin. Four cores have been taken within the interval 3300-6400 ft, representing fluvial and marine environments. Intervals sampled in wells represent the range of lithofacies and porosity exhibited by the Mesaverde in these wells. Arrangements are being made to sample the contributed BP Champlin 261 8-13. In addition arrangements are being made to obtain samples from Exxon-Mobil and Shell wells.

Subtask 3.3. Acquire logs from sample wells and digitize

Logs were obtained for the wells from which cores were plugged and for prospective wells. Logs will be digitized for wells that are sampled.

TASK 4. MEASURE ROCK PROPERTIES

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

Experimental Methods-

Sample Preparation: Core plugs measuring approximately 1-inch (2.54 cm) in diameter and 1.5-2.3 inches (3.8-5.8 cm) long were cut from full-diameter or slabbed core using a diamond core drill bit with tap water as a coolant at the USGS Core Facility. Core plug ends were trimmed to make right cylinders using tap water as coolant at the Kansas Geological Survey. The samples were vacuum/pressure saturated with a toluene/methyl alcohol azeotrope and then soxhlet extracted with toluene/methyl alcohol to remove any remnant oil and salts. They were dried in an oven at 80 ^{o}C to a constant weight within $\pm$ 0.003 g.

Routine Helium Porosity and Grain Density: Routine helium porosities were determined using a Boyle's Law technique. Dry sample weights will measured to ±0.001 g and bulk volume was determined by Archimede's Law method by immersion in mercury and by caliper to an accuracy of ±0.02 cc. Ambient Helium porosity was measured to an accuracy and precision of better than ± 0.1 porosity percent.

Routine Air and In situ Klinkenberg Permeability: To measure routine air and *insitu* Klinkenberg gas permeabilities, each core was placed in a biaxial Hassler-type core holder and subjected to a hydrostatic confining stress of 600 psi (4,140 kPa) and a confining pressure approximating net effective *in situ* stress. It is well recognized that it is necessary to restore low-permeability core samples to *in situ* stress conditions to obtain permeability values that are representative of the reservoir (Vairogs et al., 1971; Thomas and Ward, 1972; Byrnes et al., 1979; Jones and Owens, 1980; Walls et al., 1982; Sampath and Keighin, 1981; Ostensen, 1983; Wei et al., 1986; Luffel et al., 1991; Byrnes, 1997; Byrnes and Castle, 2000; Byrnes, 2005). To achieve approximate *in situ* conditions, core plugs in a biaxial Hassler-type core holder were subjected to a confining stress (in pounds per square inch, psi) equal in value to 0.5 times the sample depth (in feet; e.g., confining pressure for 10,000 ft (3,050 m) is 5,000 psi(34.5 MPa)). For measurements of *in situ* Klinkenberg gas permeability, the Klinkenberg gas slippage effect was measured by extrapolation of permeabilities measured at two different pore pressures.

Results-

Comparison of measured *in situ* Klinkenberg permeabilities with routine air permeabilities for samples exhibiting a range of lithofacies from the Amoco Five Mile Gulch Unit#3 indicates that the Almond Fm exhibits a similar influence of confining stress on permeability to other low-permeability sandstones. Measured core plug values exhibit a similar k_i-k_{air} relationship to other low permeability sandstones as represented by the equation presented by Byrnes (2003, 2005) and shown in Figure 2.

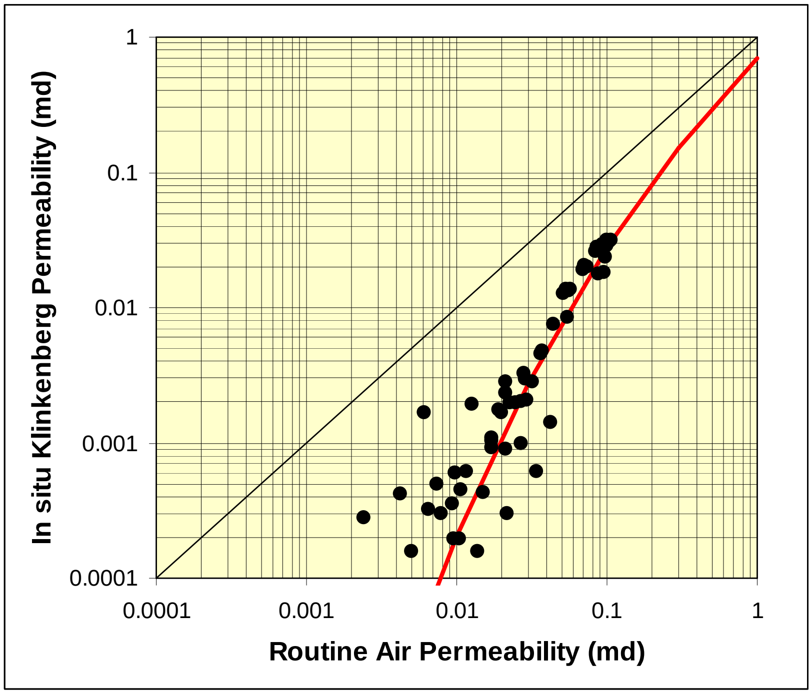


Figure 2. Crossplot of routine air permeability versus *in situ* Klinkenberg permeability for Amoco Five Mile Gulch Unit #3 samples of various lithology (black circles) and compared with predictive equation of Byrnes(2003,2005): $\log k_i = 0.059\log(k_{air})^3 - 0.187\log k_{air}^2 + 1.154\log k_{air} - 0.159$.

The permeability-porosity relationship for samples from the Five Mile Gulch Unit #3 are consistent with other Mesaverde/Frontier sandstones (Fig. 3).

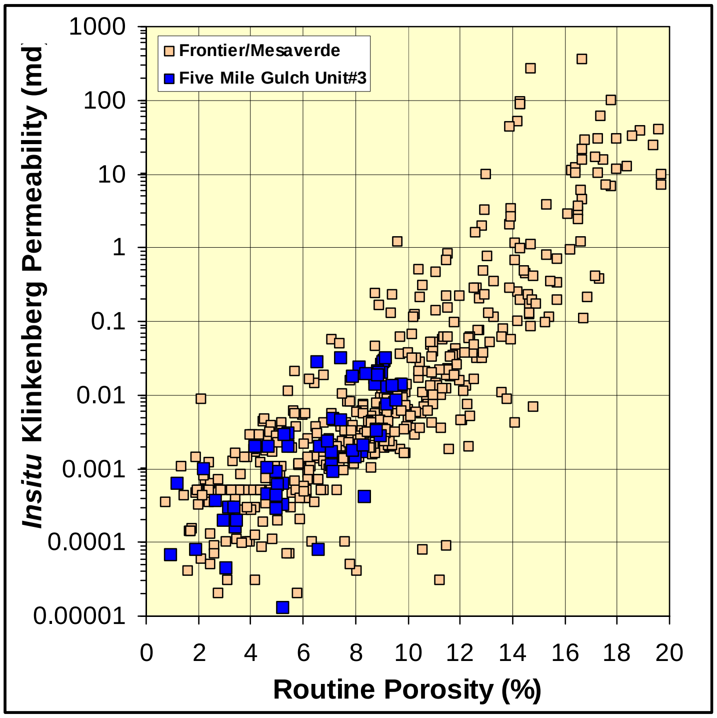


Figure 3. Crossplot of routine unconfined helium porosity versus *in situ* Klinkenberg permeability for Frontier/Mesaverde samples from across the western U.S. (tan square; compiled from Byrnes (1997) and for the Mesaverde samples from the Five Mile Gulch Unit #3 (blue square).

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

During this reporting period the mercury intrusion equipment was modified to accommodate *in situ* measurements and calibration runs were performed. Measurements were conducted on a few select samples to confirm system operability.

Experimental Methods-

Unconfined Capillary Pressure: Subsequent to porosity and permeability analysis select cores were transferred to a vacuum desiccator and maintained at vacuum conditions for a period of not less than 8 hours until ready for analysis. Each sample was transferred to the capillary pressure instrument and evacuated to a pressure of less than 0.01 torr for a period of 15 minutes. The sample was then subjected to increasing mercury injection pressures ranging from 2 to 10,000 psia (14-69,000kPa)). At each pressure, equilibrium was assumed to have been established when the volume of mercury injected was less than 0.1% of the pore volume for a three minute period. Injected mercury volumes were corrected for system and mercury compressibility effects. Accuracy and precision vary with sample pore volume and outer pore sizes and surface roughness. Pump injection volumes are readable to 0.001cc. Based on pore volumes from 1 to 3 cc, estimated precision for the measurement is 0.5% for pore sizes less than 107µm.

Confined Capillary Pressure: For confined samples each matching plug was placed in a Hassler type confining pressure cell and subjected to 4,000 psi (27.6 MPa) confining pressure greater than the injection pressure of the mercury. This provided a constant net effective stress of approximately 4,000 psi. Confining pressures ranged from 4,000 psi (27.6 MPa) up to 14,000 psi (96.5 MPa). Because of the small pressure steps taken during the analysis the application of a new higher confining stress before increasing mercury pressure did not result in a significant additional stress.

Results-
Figure 4 shows both an unconfined and a confined mercury capillary pressure for a 0.001 md ($9.9x10^{-7}$ μm^2), 6.2% very-fine grained massive sandstone. Confining stress results in a significant increase in threshold entry pressure. The parallel curves for the saturation range between approximately 60% and 100% can be interpreted as a decrease in the pore throat diameter of the largest pores by approximately a factor of 2. For pore throats that were initially between approximately 0.1 µm and 0.05 µm the decrease in size is less. Confining stress appears to have no significant influence on pore throats less than 0.05 µm. This is consistent with these pores occurring in clays lining pores.

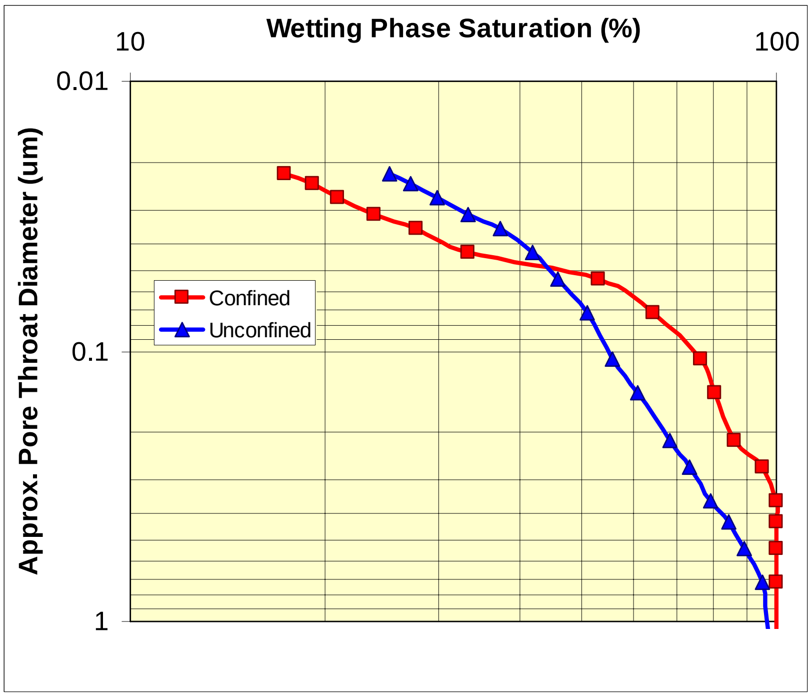


Figure 4. Crossplot of approximate pore throat diameter (microns) versus wetting phase saturation as measured by mercury intrusion capillary pressure analysis for paired core plugs of 0.001 md ($9.9x10^{-7}$ μm^2) and 6.2% porosity under unconfined (blue triangle) and confined (red square) conditions. Pore diameters were calculated using the Washburn relation $P_c = 2\sigma\cos\theta/r$.

Subtask 4.5. Measure geologic and petrologic properties

All cores sampled were described. Core plug ends are being preserved to select material for thin-section microscopy.

TASK 5. BUILD DATABASE AND WEB-BASED ROCK CATALOG

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

Initial design of the Java code for modify existing web-based software to provide GUI data access has been performed.

TASK 8. TECHNOLOGY TRANSFER, REPORTING, PROJECT MANAGEMENT

Subtask 8.1 Technology Transfer

A Powerpoint presentation was created to present to companies to inform them of the project and request participation through contribution of newly-obtained fresh core. Presentations were made to major and independent gas industry companies to solicit participation directly through contribution of core and indirectly through review of activities and methods and results. Presentations were made in both Denver, CO and Houston, TX. Examples of companies for whom presentations were made include: Exxon-Mobil, BP Exploration and Production, Inc., Shell Exploration and Production, Encana, Williams Gas, Bill Barrett Corp. Companies that have indicated they will take core (one company switched from taking sidewall core to taking full-diameter core just to be in the program) and wish to be part of the study include Bill Barrett Corp., BP Exploration and Production, Encana Corp., Endurance Resources, Exxon-Mobil Corp., and Questar Corp. Many other companies have called expressing interest.

Subtask 8.2. Reporting Requirements

A project overview including project objectives and improvements to be achieved, project schedule and budget was presented at a project kickoff meeting at the National Energy Technology Laboratory in Morgantown, PN on December 12, 2005.

Alan Byrnes met with Robert Cluff of Discovery Group in Denver on December 28, 2005 at the USGS Core Research Center.

CONCLUSIONS

Compilation of technical publications has provided a sound basis for the petrophysical database and digitization is progressing slowly but steadily. Industry has shown great interest in the project and willingness to participate through contribution of core. Because several industry participants wish to contribute core that will be taken in Spring 2006, the sampling plan has extended the period over which core material will be obtained. Obtaining both library and newly-acquired core will increase in the next two quarters. Core analysis has just begun in this quarter and initial measurements indicate core obtained exhibit properties consistent with previously reported Mesaverde/Frontier values. Comparison of confined and unconfined drainage capillary pressure curves for a first sample indicates that confining stress results in reduction of pore throat size by approximately a factor 2 for the largest pores and that the smallest pores, probably within clays or between clay particles lining pore walls, are not significantly affected by confining stress.