RPSEA-0013-04 **GRI-04/0199**

IDENTIFICATION OF BEHIND-PIPE PAY ZONES IN LOW PERMEABILITY SAND/SHALE/COAL SEQUENCES

FINAL REPORT

(July 2003 – September 2004)

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Prepared for:

RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
Subcontract No. R-504

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September 2004

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information, Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
September 2004

3. REPORT TYPE AND DATES COVERED
Final Report
July 2003 – September 2004

4. TITLE AND SUBTITLE
Identification of Behind-Pipe Pay Zones in Low Permeability Sand/Shale/Coal Sequences

5. FUNDING NUMBERS
RPSEA Subcontract R-504
GRI Contract 8693

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING ORGANIZATION NAME AND ADDRESS
Research Partnership to Secure Energy for America
1650 Highway 6, Suite 300
Sugar Land, TX 77478

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
RPSEA-0013-04

GRI-04/0199

11. SUPPLEMENTARY NOTES
The work documented in this RPSEA report was funded under GRI Contract 8693 with RPSEA, Technology Development for Unconventional and Ultra Deep Offshore Natural Gas Resources.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
This work begins to address the problem of complex reservoir architecture in the Menefee Formation and to estimate its impact on gas recovery from existing and infill wells. Surface outcrop measurements were used to develop analogs for correlation with subsurface well logs. Unfortunately, difficulties became readily apparent when the observed gamma ray responses at the surface were not unique to a given facies. However, the principles of the reservoir architecture were included in a conceptual reservoir model to assess the impact of the Menefee contribution. Significant remaining gas reserves exist in the Menefee interval, but to acquire these reserves requires strategically locating infill wells to penetrate Menefee channels. For example, in this model the first well completed in a Menefee channel adds over 300 mmscf of incremental gas, a second well adds 180 to 300 mmscf, and a third well only 35 mmscf.

A comparison of original (1950s to 60s) wells completed with and without the Menefee revealed that initially adding the Menefee resulted in approximately 100 mmscf of incremental gas per well. In comparison, when the Menefee was added later as a remedial workover, only 46 mmscf of incremental gas was developed. In all cases effective stimulation plays a key role in the success of the well.

14. SUBJECT TERMS
behind-pipe pay, reservoir architiecture, Mesaverde, Menefee

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

RESEARCH SUMMARY

Title	Identification of Behind-Pipe Pay Zones in Low Permeability Sand/Shale/Coal Sequences
Contractor(s) GRI Contract Number	New Mexico Institute of Mining & Technology
Principal Investigators	Thomas W. Engler, Brian Brister
Report Type Report Period	Final Report July 2003 – September 2004
Objective	Combine geological surface outcrop studies with subsurface geological and engineering work for the purpose of improving reservoir architecture and subsequently better define behind-pipe pay zones in tight-gas sand sequences.
Technical Perspective	Improvement in the recognition of bypassed pay in complex, geologic sequences will benefit industry by optimizing gas recovery from existing wells. The need in "existing wells" is driven by the request of independents, and reflects the preference to perform remedial work on existing wells over capital expenditures for new development. Maximizing recovery requires accounting for the complexity of the reservoirs. Numerous field studies have revealed areas of higher than average production, and yet the mechanisms that are controlling this behavior are poorly understood. Intensity and orientation of natural fractures, superimposed natural fracture sets, architecture of the formations can all play a role in enhancing the reservoir deliverability. This work begins to address the problem of complex reservoir architecture on the Menefee Formation and estimate its impact on gas recovery.
Technical Approach	The identification of "by-passed" pay requires better description of the reservoir architecture. The approach taken was to use surface outcrops as analogs to illustrate the complexity of the Menefee Formation and then compare these analogs to subsurface well log data. Extensive, well-exposed outcrops were selected in the Menefee. Detailed stratigraphic sections were measured on these outcrops to illustrate the lateral and vertical variability in reservoir rock quality, flow barriers and stratigraphic facies. Surface gamma ray measurements were also obtained for the purpose of correlation with subsurface geophysical well logs. Applying this updated architecture to a conceptual reservoir model, the impact of Menefee attributes on recovery of infill wells was

assessed. Parametric analysis was used to evaluate the variation in gas recovery over a range of values.

A final task included a statistical analysis of completion and stimulation practices and comparison of well performance from past wells with or without the Menefee and from Menefee payadd wells only.

Results

Surface measured sections revealed the variability in both the lateral and vertical continuity of channel sands imbedded in the overall Menefee. Gamma ray measurements provided excellent repeatability; however, the range of readings along a transect were highly variable. Unequal leaching of radioactive isotopes in the surface exposures is suspected to be the culprit. Subsequently, overlap was observed in gamma ray responses for different lithologies and resulted in nonunique gamma ray curves to match subsurface well logs.

The reservoir modeling efforts demonstrated significant gas recovery for wells penetrating the Menefee Formation and pressure depletion in the Cliff House and Point Lookout Formations. Substantial remaining gas reserves exist in the Menefee interval, but to acquire these reserves requires strategic location of infill wells to penetrate Menefee channels. For example, in this model the first well completed in a Menefee channel adds over 300 mmscf of incremental gas, a second well adds 180 to 300 mmscf, and a third well only 35 mmscf.

During the review of historical production data, a comparison of original (1950s to 60s) wells completed with and without the Menefee revealed that initially adding the Menefee resulted in approximately 100 mmscf of incremental gas per well. In contrast, when the Menefee was added later as a remedial workover, only 46 mmscf of incremental gas was developed. The best payadd candidate resulted in 285 mmscf of incremental reserves which confirms the need for improved reservoir description to identify the best targets for adding Menefee pay and to avoid those areas that do not exhibit potential.

List of Symbols, Abbreviations, and Acronyms

CBM	- Coalbed Methane
N_2	- Nitrogen
NMT	- New Mexico Tech
NMBGMR	- New Mexico Bureau of Geology and Mineral Resources
Mmscf	- million standard cubic feet
Tcf	- trillion standard cubic feet
RPSEA	- Research Partnership to Secure Energy for America

Acknowledgements

The authors would like to recognize GRI and RPSEA for their support in funding this project. Also, specific individuals who were supported by this project and their contributions are listed below.

Thanks to Jianhui Zhang (M.S. student, Petroleum Engineering) for his work on preparing and running the numerous simulation cases for the parametric study in Chapter 5.

Thanks to Ashlee Ryan and Jeremy Mardembek (B.S. students, Petroleum Engineering) who compiled all of the completion records and production data in Chapter 6 to differentiate the Menefee contribution and to analyze stimulation effectiveness. Sometimes a tedious task but the benefits are worth the effort. Also, thanks to Walter Moreno (M.S. student, Petroleum Engineering) who investigated fracture propagation modeling for the Menefee.

Mike Iacoboni (M.S. student, Geology) deserves most of the credit for accomplishing the surface fieldwork from measuring sections to carrying the spectrometer up the slopes to obtain gamma ray measurements. He also was instrumental in the correlation efforts.

Chapter 1

Introduction

Problem

An important problem in low-permeability gas sands is the identification, stimulation and production of behind-pipe pay zones in existing wells. Industry focus group meetings in gas productive regions across the United States confirmed this problem as a high priority for future R&D (Engler, 2002). An example is the commingling of the Menefee Formation with other formations of the Mesaverde Group in the prolific San Juan Basin, New Mexico. Literally thousands of wellbores are available for recompletion and/or commingling efforts, with the potential to significantly increase gas reserves, while reducing the number of new wellbores and thus surface disturbance. Traditionally the focus of most operators was to concentrate efforts on the clean, relatively thick and laterally extensive lower sand, Point Lookout Sandstone, and upper sand, the Cliff House Sandstone, ignoring the Menefee Formation located between the two. This underdevelopment of the Menefee is due to two factors: (1). the lenticular nature of the reservoirs, and (2). difficulty of evaluating the reservoirs using geophysical logs. Little has been published describing the Menefee and its various sandstone and coal lithologies with most work focused on its potential for being mined for coal in outcrops in the southern San Juan Basin (Fassett, 1988, 1989, Hoffman,1994, 1995). A number of gas well operators in the basin have attempted Menefee studies and completions. Most indicate that they suffer from a lack of understanding of its geology, how to evaluate the reservoirs using well logs, and how to access the reserves efficiently.

Typical gas productive "tight" reservoirs are composed of a sequence of low-permeability sands and shales of varying lateral and vertical extent. The level of complexity is often high due to the existence of natural fractures, and variable reservoir architecture caused by abrupt changes in stratigraphic facies. Geological problems in the Mesaverde Group reservoirs include transitional upper and lower contacts of the included formations, a broad range of depositional environments represented by lithofacies assemblages that vary vertically and laterally in their distribution, geographical variations in formation, and statutory variations that contradict the stratigraphy. In addition, the complexity of the Mesaverde reservoirs is often much greater than generally acknowledged. This study demonstrates that the best way to subdivide the Mesaverde is to use criteria that optimize exploitation of reserves. Using the proper outcrops, field-based observations allow the complexities of the reservoirs to be demonstrated, mapped and quantified. Outcrop analogs allow the reservoir to be understood on the scale of 80-acre infill wells or less and can help operators understand "anomalously good" reservoir units and predict their distribution.

Due to the low-permeability of these types of reservoirs, stimulation (particularly hydraulic fracturing) is required to develop a commercial well. Typically, this stimulation is done during the initial completion of a well. Unfortunately, the addition of "behind-pipe" pay leads to a variety of problems in designing an effective stimulation treatment. Using the Menefee as our example, the lenticular and discontinuous nature of the imbedded sands can lead to complex fracture geometries; exacerbated by the reduced net effective stress due to partially-depleted layers above and below the Menefee. Furthermore, the mechanics of fracturing are subject to maximum allowable pump rate and pressure for older wells, casing or tubing size and integrity, and avoiding re-fracing old perforated zones in an attempt to stimulate only the new, "by-passed" pay zone.

Objectives

The primary focus of the proposed work is to combine geological surface outcrop studies with subsurface geological and engineering work for the purpose of improving reservoir architecture and subsequently, better define behind-pipe pay zones in tight-gas sand sequences. The proposed work will provide industry operators the means to better quantify and locate these gas-bearing sands or coals in the Menefee.

As a corollary component, background information to the effectiveness of stimulating behind-pipe pay zones is provided, including a discussion on research needed to address stimulation concerns.

The outcome is to provide a decision process to identify behind-pipe pay zones in existing wells and deduce the impact on gas recovery.

Significance

The significance of this work is the potential recovery of incremental reserves from complex pay zones in existing wells and in infill wells. The need in "existing wells" is driven by the request of independents, and reflects the preference to optimize existing wells over capital expenditures for new development. Subsequently, this work directly targets the segment of the U.S. industry which is responsible for natural gas development in the U.S. today. For the Menefee, the result could be the addition of several trillion cubic feet (Tcf) of reserves, with a high probability of success because operators are actively adding pay in existing wells and/or infill drilling the play. Operators will now have a resource available to them to assist in making decisions concerning the extensive Menefee Formation resources in the basin. Furthermore, this work impacts completion/stimulation strategy and effectiveness, subsequently leading to insights into future areas of research.

Chapter 2

Background

General Geology

The selected target for this research is the Menefee Formation of the Mesaverde Group in San Juan Basin, New Mexico. The advantages for investigating this formation are: (1) to provide additional reservoir information not previously available which is necessary to correctly characterize the Menefee, (2) the Mesaverde Group reservoir is the most prolific and economically important producing reservoir in the San Juan Basin region, (3) there is current industry interest and practice in this group, (4) and the Menefee is an excellent analog to other underdeveloped dual reservoir sand/coal opportunities in the San Juan Basin, Raton Basin and other basins in the United States.

The San Juan Basin, roughly circular in shape (Figure 2.1), is an asymmetrical syncline located in northwestern New Mexico and southwestern Colorado [Peterson *et al.*, 1965; Dutton *et al.*, 1993]. The basin extends approximately 100 miles north to south, and 90 miles east to west. Geological formations dip towards a low area in the northeastern part of the basin. The Cretaceous Formations are widespread gas reservoirs, with the target Mesaverde Group the most prolific. Figure 2.2 illustrates present day stratigraphy in the basin.

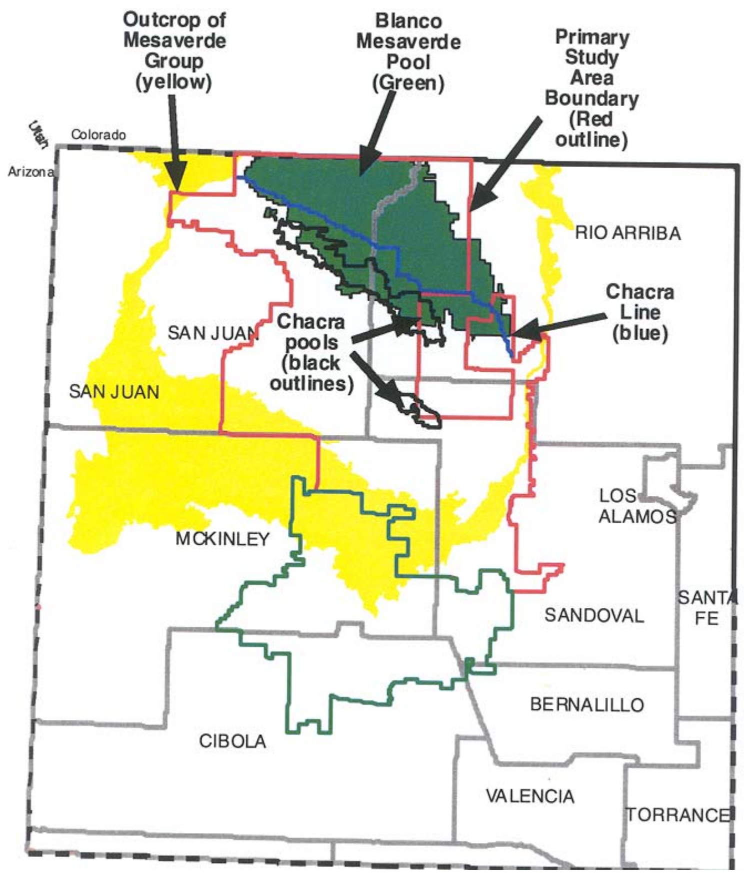

Figure 2.1: Map of New Mexico portion of San Juan Basin showing Mesaverde Group outcrop, Blanco Mesaverde pool, Chacra line and Chacra pools. (RFD, 2001)

ERA	SYSTEM	FORMATION	THICKNESS	PRODUCTION
CENOZOIC	TERTIARY	San Jose Formation	2500 ft	gas
		Nacimiento Formation	500-1300 ft	gas
		Ojo Alamo Sandstone	250 ft	gas
MESOZOIC	CRETACEOUS	Kirtland Shale / Farmington Sandstone	1500 ft	gas/oil
		Fruitland Formation	500 ft	gas
		Pictured Cliffs Sandstone	250 ft	gas
		Lewis Shale / Huerfanito bentonite	500-1900 ft	gas
		Mesaverde Group: Cliff House Sandstone	0-800 ft	gas
		Mesaverde Group: Menefee Formation	350 -2200 ft	gas
		Mesaverde Group: Point Lookout Fm.	100-300 ft	gas
		Mancos Shale: upper Mancos shale/Tocito Ss.	2300-2500 ft	gas/oil
		Mancos Shale: Gallup Sandstone/Carlile Sh.		gas/oil
		Mancos Shale: Greenhorn Limestone		
		Mancos Shale: Graneros Shale		
		Dakota Sandstone	150-200 ft	gas/oil
	JURASSIC	Morrison Formation	400-900 ft	
		Wanakah Formation / Todilto Limestone	50-200 ft	
		Entrada Sandstone	100-300 ft	oil
	TRIASSIC	Chinle Formation	500-1600 ft	
PALEOZOIC	PERMIAN	Cutler Formation	1500-2500 ft	
	PENNSYL-VANIAN	Hermosa Formatio: Honaker Trail Fm.		
		Hermosa Formatio: Paradox Formation	200-3000 ft	gas?
		Hermosa Formatio: Pinkerton Trail Fm.		
		Molas Formation	0-100 ft	
	Mississippian	Leadville Limestone	0-165 ft	
	Devonian	Elbert Formation	0-325 ft	
	Cambrian	Ignacio Quartzite	0-100 ft	
Precambrian				

Figure 2.2 Stratigraphic column for the San Juan Basin

The Mesaverde Group is bounded by the overlying Lewis Shale and the underlying Mancos Shale (Figure 2.3). It is subdivided into coastal shoreface sandstone formations (Cliff House Sandstone and Point Lookout Sandstone), and the alluvial to estuarine Menefee Formation (Collier, 1919). The basal unit, the Point Lookout Sandstone, represents a regressive, basinward (northeastward) migration of the shoreline. The Point Lookout blankets the basin northward into southern Colorado. The Menefee Formation, overlying the Point Lookout, resulted from back-barrier deposition and contains discontinuous sandstone, mudstone and coal beds. A turnaround from regional regression to transgression is marked by the deposition of the Lewis Shale above the Menefee Formation in the north and above the Cliff House Sandstone in the south. The Cliff House Sandstone represents temporary cessation of the regional transgression event so that shoreface sands could redevelop. The La Ventana Tongue of the Cliff House Sandstone ranges from nonmarine to offshore sand bodies deposited during later regressive/transgressive episodes in the southern part of the basin. The strandline-parallel, offshore sand bodies of the La Ventana Tongue are commonly termed “Chacra sands”.

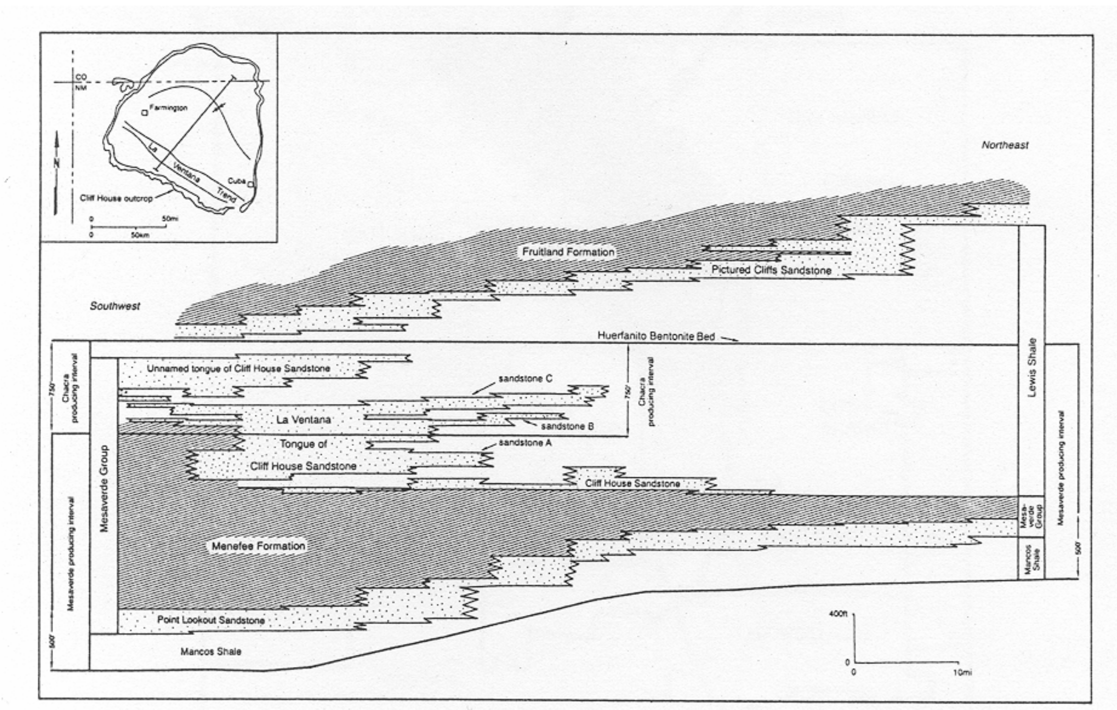

Figure 2.3 Cross-section depicting generalized stratigraphy for the Mesaverde Group and the statutory Mesaverde reservoir intervals north and south of the Chacra line (after Whitehead, 1993).

The Mesaverde Group reservoir includes the various producing intervals of the Blanco Mesaverde pool (New Mexico) and Ignacio-Blanco Mesaverde field (Colorado). In New Mexico, the upper vertical limit of the Mesaverde reservoir is defined differently in two areas separated on the basis of the “Chacra line” (Figure 2.1). North of the Chacra line, the upper limit of the Mesaverde reservoir is the Huerfanito bentonite, a marker within the Lewis Shale. In this northern area, the lower part of the Lewis Shale is statutorily within the Mesaverde reservoir. South of the Chacra line, the upper limit of the Mesaverde reservoir is 750 feet below the Huerfanito bentonite, thus the Mesaverde reservoir includes only the lowermost part of the Lewis

Shale. In this southern area, the Chacra reservoir lies within the 750 feet below the Huerfanito marker. In both the northern and southern areas, the lower limit of the Mesaverde reservoir is defined as 500 feet below the top of the Point Lookout Sandstone. The thickness of the Point Lookout varies within the basin, thus, the Mesaverde reservoir incorporates a variable portion of the uppermost Mancos Shale.

A range of reservoir characteristics is possible for the Mesaverde reservoir depending upon location. The Point Lookout Sandstone is a relatively uniform blanket-type, low permeability sandstone formation. The Cliff House is similar in reservoir characteristics, but less extensive. The Menefee Formation, on the other hand, although extensive, is highly variable in its characteristics, particularly in terms of sand content, thickness and continuity of sand bodies. The lower Lewis shale and upper Mancos "Point Lookout transition" range from shale to siltstone to sandstone.

For the main pay intervals, the Point Lookout and Cliff House, porosity averages approximately 10%. Matrix permeability is typical of "tight gas" reservoirs and is on the order of 10^{-3} md, requiring hydraulic fracture stimulation for economic production. North-northeast-oriented fractures are common in the Mesaverde and increase the formation permeability by several orders of magnitude in some areas. The best wells in the basin are interpreted to have intersected particularly well connected, through-going fracture sets.

Production/Development History

The Blanco Mesaverde Pool (field) in the San Juan Basin was discovered in 1927 and has grown in response to pipeline capacity, decreased well spacing, and price increases. Extensive development occurred in the 1950s on 320-acre spacing when the western gas market became available. In the late 1950s and early 1960s, EPNG conducted long term pressure buildup tests, indicating low permeability and low drainage efficiency from the Mesaverde reservoir (Maldonado, et al., 1983). This prompted the request for 160-acre infill development, which was approved in 1974 and began in January 1975 for the Blanco Mesaverde reservoir. Infill development for the Ignacio Blanco Mesaverde reservoir was approved in 1979. Prior to January 1975, approximately 2000 wells were producing on the 320-acre spacing.

In 1997, pilot tests were initiated to determine the feasibility of reducing spacing to 80 acres. A simulation study (Harstad, 1998) revealed the significance of permeability anisotropy to the location of infill wells. The results of the pilot tests coupled with the simulation study prompted the approval of 80-acre spacing for the Mesaverde in 1998. Cumulative production to date is greater than 10 Tcf, with an estimate of 7 Tcf of additional proven reserves . At this time more than 4,900 completions yield 0.75 Bcf/day. It is expected that within the next 20 years about 4,300 additional completions will occur, many of which will be dual completions with the deeper Dakota Sandstone.

Summary of Previous Work

Previous geologic studies regarding the Mesaverde Group have been primarily centered on natural resource development. The two areas of research that have received the most attention are coal seams and reservoir sandstones. Coal seams are abundant in the Menefee Formation, and have been historically examined as an extractable resource (Biewick et al. 1991, Fassett

1989, Hoffman 1994, 1995, 1999, Turner et al. 1997). Beginning in the late-1980's, the focus has shifted from mining to drilling as operators began to recognize the coals as a source for coalbed methane production (Bland 1992, Crist et al 1989, 1990, Fassett 1988, Johnson et al 1989, Mavor 1991, Mitchell et al. 1989, Tremain 1981, Young 1992). Several areas of research regarding coalbed methane reservoir development have been investigated, including structural controls (Century 1991), and also fracturing and other rock properties of coals in regards to CBM production (Gash 1991, Laubach et al 1991).

The sandstone units within the Mesaverde have been studied for a variety of reasons. The Cliffhouse and Point Lookout are often examined to illustrate the regressive/transgressive shifting of the interior seaway that occupied the San Juan Basin during the late-Cretaceous (Cavaroc et al. 1982, Donselaar, 1989, Dunbar et al. 1997, Fouch et al. 1991, Hicks 1991, Katzman 1990, Molenaar et al. 1991, 1992, Nummedal et al. 1990, 1992, Templet et al. 1991, Wright-Dunbar et al. 1992, Wright-Dunbar 1992, Young 1073). These formations have also been investigated in regards to reservoir potential (Harstad et al. 1998, Huffman 1989, Keighin et al. 1993, Raynolds et al. 1994, Van Wagoner et al. 1991).

As research into the development of CBM and tight-gas reservoirs in the Mesaverde Group continues, the complexities of the stratigraphy and reservoir system is becoming more and more evident. In 2002, Wright-Dunbar completed a project located in the Jicarilla Apache Indian Reservation that incorporated several aspects of the Mesaverde Group architecture with the objective of hydrocarbon exploration in the Dakota Sandstone unit in order to address such complexities. Wright-Dunbar incorporated surface observation with subsurface data to better classify the stratigraphy using various correlation techniques. This project will proceed in a similar fashion, addressing the stratigraphic complexities from a wider perspective and examining the detailed architectural properties as they occur on a regional scale.

Previous studies [Teufel et al., 2001; Espeland, 2001; Iden, 2001, Robinson, 2001] on the Mesaverde demonstrated the effect of reservoir permeability anisotropy on well performance and infill drilling strategies. Also, an outcome of the past work was the realization that simple reservoir models often do not capture the complexity of the Mesaverde and particularly the Menefee Formation. A further study [Engler et al., 2001], recognized the Menefee Formation play as a behind-pipe pay-add in potentially tens of thousands of wells in the basin and as perhaps the most significant opportunity for additional recovery of trillions of cubic feet of gas from the existing well inventory. This realization has led to the current study which addresses this potential.