RECEIVED
JAN 0 8 2001
OSTI

Naturally Fractured Tight Gas Gas Reservoir Detection Optimization

Prepared for:

**U.S. Department of Energy
Federal Energy Technology Center**

Contract No. DE-AC21-93MC30086

Quarterly Status Report

Period of Performance: October 1, 1997 – December 31, 1997

Date of Submission: September 30, 1998

Prepared by:

**Advanced Resources International, Inc.
1110 N. Glebe Road, Suite 600
Arlington, VA 2220**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Quarterly Status Report

CONTRACT NO.:

DE-AC21-93MC30086

CONTRACTOR:

Advanced Resources International, Inc.
1110 N. Glebe Road, Suite 600
Arlington, VA 22201

CONTRACT NAME:

Naturally Fractured
Tight Gas Reservoir
Detection Optimization

CONTRACT PERIOD:

10/01/97 – 12/31/97

CONTRACT OBJECTIVE: No change.

TECHNICAL APPROACH CHANGES: No change.

FIELD PERFORMANCE TEST PLAN:

The work plan for the quarter of October 1, 1997 – December 31, 1997 consisted of two tasks:

1. Present results of Rulison field test at various conferences, seminars, and to Barrett Resources and Snyder Oil Co. and,
2. Continue work into developing a predictive quantitative method for locating fault-related natural fractures.

The first task was completed during this reporting period. The second task continues the beginning of quantitative fracture mechanics analysis of the geologic processes that are involved for the development of fault-related natural fractures. The goal of this work is to develop a predictive capability of locating natural fractures prior to drilling.

TASK 1. Conference Presentations

Advanced Resources presented the results of the Rulison field test at three separate conferences. The first conference Advanced Resources presented at was the Innovative Applications of Petroleum Technology in the Rocky Mountain Area sponsored by the Rocky Mountain Association of Geologists. The conference was held during October 30, 1997 in Denver. The second conference was the Society of Exploration Geophysicists held in New Orleans, Louisiana on November 4, 1997 where we presented at a poster session. The third conference was the Greater Green River Symposium sponsored by the Department of Energy, the Gas Research Institute, and IPAMS held at Denver, Colorado during November 11, 1997. Copies of the first and third presentations are submitted with this report and can be found in Appendix A and B, respectively.

TASK 2. Development and preliminary tests of a predictive method

It has been well demonstrated in the laboratory, theory, and field observations that secondary structures such as natural fractures accompany local deformation such as faults. Advanced Resources has demonstrated that such a relationship exists in the southern Piceance basin tight gas play. Natural fracture clusters are genetically related to stress concentrations (also called stress perturbations) associated with local deformation such as faulting. The mechanical explanation of this phenomenon is that deformation generally initiates at regions where the local stress field is elevated beyond the regional. Numerous theoretical investigations support this interpretation and show the formation of secondary structures (fractures) as resulting from stress concentrations that involves both rotations in principal stress trajectories and changes in stress magnitudes.

The uncertainties of directly detecting the location of subsurface natural fractures propel us to develop a predictive method based on observable inputs. The genetic relationship between local faults, stress, and natural fractures provides an opportunity to predict the important criteria of location, orientation, and relative aperture of natural fractures using numerical models. Rock mechanics and a structural understanding of

associated deformation provides one with the means to assess quantitatively regions for natural fractures due to local deformation. These stress concentrations can be calculated given the remote stress field, fault/fold geometry, and displacement of the local structures. Simple relationships have been investigated numerically by either boundary element or finite element analysis. In the last decade, significant advances have occurred in the field of numerical analysis and modeling of geologic deformation, principally the development of three-dimensional capability. We are developing, as the next logical step, a technical demonstration and application of a numerical model that can calculate stress concentrations linking the mapped structures and faults to areas of natural fracture development.

The stress concentrations associated with fault systems can be used to determine the occurrence and orientation of natural fractures formed during the tectonic process of fault deformation. Numerical models, such as the Boundary Element or Finite Element Methods, can calculate 3-D stress variations over a defined volume. In addition, once the orientation of the subsequent fracture system is known, the aperture of natural fractures can be predicted by inputting present day stress magnitudes and orientations, leading to reasonable estimates of natural fracture-related permeability. Many numerical methods exist in the academic realm as well as commercial codes related to construction or mining engineering. Two methods are commonly employed in these models are the Boundary Element Method (BEM) and the Finite Element Method (FEM). For petroleum applications, it is essential that the numerical method handle the detailed geometry of faults responsible for producing the local fracture system.

The BEM uses a displacement discontinuity procedure that explicitly delineates boundary surfaces (faults in this application) whereas the surrounding media are considered more simply. This allows one to input realistic and complex fault geometry. The requirements for a geologically realistic numerical model are twofold. First, the critical input variables must be constrained, whenever possible, by appropriate observable geologic information. For example, both fault geometry and slip distribution along the fault plane can be determined from 3D seismic surveys and ideally, the numerical method

will use this information instead of inputting estimated paleostress directions and relative magnitudes. This permits the independent determination of critical variables that affect the outcome of the model. With the BEM method stress variations can be calculated as a result of prescribed slip along the fault, eliminating the need to guess at the paleostresses that historically drove fault slip. Second, the numerical method must be robust enough to allow default or invariant input on secondary rock mechanic variables such as stiffness, friction, etc.

Advanced Resources plans to investigate this opportunity by developing a process to predict natural fracture clusters (PNFC). We will use a public-domain BEM code and apply it to the situation found at the Rulison field as well as to the Hunter Mesa/Mamm Creek field. In the initial stages of investigation, we do not intend to change the public domain code but concentrate on developing a methodology for capturing the appropriate input information from the seismic survey. We then will compare the output of the program to reservoir permeability calculated from production history to test the success of the method.

The development effort for this quarter is to test the ability of the PNFC Model to identify areas of high and low natural fracture intensity. We established three field sites for this test, **Figure 1**:

1. Northern Rulison Area -- a 20 section established development area where the 3-D seismic survey was located.
2. Southern Rulison Area -- a 20 section step-out development area where new wells are being drilled by Barrett Resources, Snyder Oil and Tom Brown with 2-D seismic coverage.
3. Mamm Creek/Hunter Mesa -- a 40 section area under development with 2-D seismic coverage.

Inputs to the model are kept within the realm of observation such as fault geometry (from 3-D and 2-D seismic data), fault displacement, and material properties. Output for these test cases will be the location, intensity, and orientation of principal tensile stress.

Figure 1: Map of the Rulison-Mamm Creek Area.

For these test cases, we will examine the correlation of principal tensile stress concentrations with EUR and calculated permeability.

The north a Rulison test area provided the most complete information on the geometry and displacements of the mapped faults due to the high-quality 3-D seismic coverage. The faults obviously continue beyond the seismic survey boundaries and their lengths were extended by the amount deemed appropriate given the displacement amounts observed in the data. At the south Rulison test area, a single 2-D seismic line provided the means to map fault geometry. A single fault appears to cut the line in section 6, T7S, R93W. This fault was assumed to be the largest reverse fault in the Rulison area since it can be observed in 2-D data. The faults were modeled as elliptical discontinuities that have varying size, displacements and spatial orientation that match closely the observed geometry, **Figure 2**. These parameters were input into the model and the resulting output of principal tensile stress was set to an observation plane at the Cameo level, **Figure 3**. When compared to the calculated permeability of the wells in the test site, **Figure 4**, it is obvious that there is a definite spatial correlation though the permeability map shows greater variations than the model output. The correlation holds when the well characteristics within the stress concentration and those that fall outside are averaged and compared, **Table 1 and 2**.

Table 1. North Rulison 3-D seismic test results

	Wells Inside PNFC	Wells Outside PNFC
No. Wells	14	10
Average EUR/Well	2.38 Bcf	1.37 Bcf
Average Permeability	8 μ d	4 μ d
Average Net Pay	401 ft	412 ft

Table 2. South Rulison 2-D seismic test results

	Wells Inside PNFC	Wells Outside PNFC
No. Wells	4	17
Average EUR/Well	4.15 Bcf	1.97 Bcf
Average Permeability	42 μ d	7 μ d
Average Net Pay	267 ft	282 ft

Figure 2: Fault Locations, Rulison Field

Figure 3: Principal Tensile Stress Concentrations, Rulison Field

Figure 4: Calculated Permeabilities, Rulison Field

We examined the Mamm Creek area East of the Rulison field to determine the applicability of the concept beyond a one field analysis. The 2-D seismic data at Mamm Creek, guided by fault geometry analogs from the 3-D seismic at Rulison, established fault style, locations and displacement for two large faults mapped at Mamm Creek – MC1 and MC2, **Figure 5**. The fault data were placed into the PNFC Model to calculate the fault associated stress perturbation. Two stress perturbation envelopes were established: Area 1 in the west-central portion of T7S, R93W, encompassing about 4 sections and Area 2 in the north-west portion of T7S, R92W, encompassing about 5 sections, **Figure 6**. The regions of stress concentrations correlated very well with areas of increased permeability and related production, **Figure 7**. Similar to the Rulison field test sites, we averaged the well characteristics for those located within the stress concentration and those outside the area, **Table 3**.

Table 3. Hunter Mesa/Mamm Creek 2-D seismic test results

	Wells Inside PNFC	Wells Outside PNFC
No. Wells	15	16
Average EUR/Well	1.71 Bcf	0.83 Bcf
Average Permeability	13 μ d	6 μ d
Average Net Pay	189 ft	198 ft

The initial success of using a predictive model for locating natural fractures in advanced to drilling indicates a that the method has great potential for economic development of tight gas resources. Theoretically, locating wells using the PNFC Technology versus current practice could provide a \$40 million cost saving in the 20 section Southern Rulison Test Area (see Table 4).

Table 4. Cost-savings of PNFC technology.

	Current Practice	PNFC Technology
Target Reserves	200 Bcf	200 Bcf
Average EUR/Well	1.97 Bcf (17 wells)	4.15 Bcf (4 wells)
No. of Wells (200 Bcf of reserves)	102	48
Capital Costs (\$750,000/well)	\$76 million	\$36 million
Cost Savings		\$40 million

Figure 7: Estimated Ultimate Recovery, Mamm Creek Area

Appendix A.

Rocky Mountain Association of Geologists

Presentation

Using 3D Seismic to Characterize Natural Fractures in the Rulison Field, Piceance Basin

David J. Campagna, Ph.D.

Vello Kuuskraa

Advanced Resources International, Inc.

"Applications of Petroleum Technology in the Rocky Mountain Region"

RMAG Continuing Education Seminar

October 30, 1997 Denver, Colorado

Outline for Presentation

- 1. Introduction***
- 2. Project Setting***
- 3. 3D Seismic Survey***
- 4. Seismic Attributes***
- 5. Fault Mapping***
- 6. EUR Correlation***
- 7. Structural Analysis***
- 8. Conclusions***

1. Introduction: Rulison Field Project

Project Title:

**Naturally Fractured Tight Gas Reservoir
Detection Optimization**

Project Objective:

***Optimize geological and geophysical
techniques for economically detecting, mapping
and evaluating naturally fractured tight gas
reservoirs.***

1. Introduction: Project Participants

Sponsors:

***DOE Federal Energy Technology Center
Barrett Resources***

Co-investigators:

***Western Geophysical
Lynn & Associates
Basin Energy***

1. Introduction: Project Rationale

- ◆ Areas of natural fracture enhanced permeability exist in extensive low-permeability, gas-saturated basins
- ◆ Random drilling and shear wave seismic are high cost approaches for locating naturally fractured areas
- ◆ Lower cost methods utilizing satellite imagery, aeromagnetic data and modified P-wave seismic (applied in an integrated fashion) offer a new, powerful technology

1. Introduction: Today's Topic

Integrated fault mapping, azimuthal P-wave analysis, and structural analysis offers a new, powerful method for locating natural fractures in advance of drilling.

2. Project Setting

- ◆ The Piceance basin in Colorado contains a vast accumulation of gas in tight, massively stacked, lenticular sands.
 - 321 Tcf (USGS, 1987)
 - 311 Tcf (ARI, 1996)
- ◆ Considerable past and ongoing R&D sponsored by DOE/FETC and GRI has been directed at this basin (MWX and M Site)

2. Project Setting: Basin Character

Piceance basin is a gas-centered basin.

COLORADO

2. Project Setting: Rulison Field

- ◆ The area around the Rulison Field, southeast Piceance basin, holds the region's richest concentrations of gas in place:
 - 160 Bcf per section in Williams Fork Member, Mesaverde Fm.
 - 40 Bcf per section in the deeper Cameo and Coal Ridge coals.

20 Bcf contours

2. Project Setting: Rulison Field

- ◆ The Rulison / Williams Fork field in Garfield County, Colorado (T6 & 7S, 94W) was discovered in 1956 with the drilling of the Juhan #1 well. The field is estimated to have approximately 10 Tcf of gas in place in the Mesaverde tight sands, plus additional gas resources in the underlying and interfingering Cameo coals.
- ◆ In the next 36 years, through 1992, only 36 more wells were drilled, with generally poor to marginal reserves and numerous dry holes. Under these conditions (confirmed by the USGS assessment), the Rulison field was judged to be an uneconomic gas play:
 - Average EURs/successful well - 0.9 Bcf
 - Dry hole rates - 45%

2. Project Setting: Productivity History

2. Project Setting: Rulison Field

- ◆ Characterization of the massively stacked, lenticular tight sands (the DOE/GRI MWX site is located on the southern edge of the field), introduction of improved well completion practices by Barrett Resources and inference of areas with higher permeability and sand development revitalized this gas play.
- ◆ From 1993 through early 1997, 65 new wells have been drilled with significantly improved EURs and gas production rates; also, many of the older wells have been recompleted. At the end of 1996:
 - The field had produced 40 Bcf
 - Gas production in 1996 averaged 325 MMcfd

2. Project Setting: Stratigraphy

The Williams Fork Member is a massively stacked, lenticular nonmarine unit of the Mesaverde Fm. containing sandstones, shales, and coals.

ERA	SYSTEM	SERIES	STAGE	UNIT
CENOZOIC	TERTIARY	Eocene		Uinta Fm.
				Green River Fm.
				Wasatch Fm.
		Paleocene		
MESOZOIC	CRETACEOUS	Upper	Maestrichtian	
		Campanian		Mesaverde Group
				Williams Fork Fm.
				Illes Fm.
				Cameo coal zone
				Rollins Ss.
				Cozzette Ss.
				Capitolian Ss.
				Castlegate Ss.

Stratified from Meyer and Murray, 1955 and Lorenz, 1988

2. Project Setting: Reservoir & Matrix Permeability

Natural fractures enhance permeability by an order of magnitude

2. Project Setting: Fracture Evolution

2. Project Setting: Rulison Field

- ◆ The field operator, Barrett Resources, has plans to intensively develop the higher productivity portions of the field at 20 to 40 acres per well. This would provide, theoretically, one to two thousand locations.
- ◆ A significant high-productivity trend, plus smaller pockets of natural fractures, exists at Rulison and has been mapped. Assuming 20% of the area has higher productivity, 200 to 400 high quality new wells could be drilled.

2. Project Setting: Objectives

- ♦ The objective of our field study is to further delineate sweet spots at Rulison (and in the adjacent southern Piceance Basin). When done in advance of drilling, this will provide significant value in terms of higher recovery per well, lower dry hole rates and lower-cost gas reserves.

3. Project Setting: Integrated Technologies

1. *Basin Deposition and Tectonic History:*
Geologic Framework
2. *Satellite Imagery:*
Structural Framework
3. *High Resolution Aeromagnetic Data:*
Trend Definition
4. *Azimuthal 3D P-Wave Survey:*
Well Site Selection

2. Project Integration: Scale & Cost

3. 3D Seismic: Objectives

- ◆ Establish P-wave seismic attributes that reliably correspond to orientation and intensity of open natural fractures.
- ◆ Map subtle fault systems.

3. 3D Seismic: Acquisition

◆ Design

- Full-azimuth, high-fold, full-offset
- Receiver spacing of 220 feet (bin size of 110' by 110')

◆ Processing

- Entire volume was separated into two limited azimuth volumes, N150E and N60E (+/- 45°)

3. 3D Seismic: Location

The 3D seismic survey covers 4.5 sq. miles and was located over highly productive areas as well as less productive areas in the Rulison field

3. 3D Seismic Survey

Well control provided by Barrett 68-21 within the survey area established seismic correlation with the major horizons.

4. Seismic Attributes: Theory

Theory predicts that P-waves travel slower when propagating across open fractures; this effect is enhanced when fractures are gas-filled.

A 1500-2000' interval between the z and cameo coals is examined using seismic attributes of interval velocity, AVO gradient, and difference by azimuth of interval velocity.

4. Seismic Attributes

DIX INTERVAL VELOCITY - RATIO (N60E / N30W)
Z TO CAMEO COALS

Interval velocity analysis shows a distinct NW-trending zone of anisotropy indicating N30W fractures.

4. Seismic Attributes

SUM OF AVO GRADIENT - Z TO CAMEO COALS

Strong positive gradients occur in the SW and NE portions of the survey. Positive gradients indicate fractures.

5. Fault Mapping

3D seismic data reveal small reverse faults in Rulison Field:

- ◆ Previous mapping using 2D seismic revealed no faulting (Barrett Resources).
- ◆ Mapping 3D seismic identified subtle reverse faults.
- ◆ Reverse faults, e.g. the NW2 fault, intersect the pay interval at a relatively low angle at the top of Cameo coal and terminate below the gas-water transition zone in the Mesaverde.

5. Fault Mapping: NE-SW profile

5. Fault Mapping: Cameo Horizon

The NW2 reverse fault trends N40W, enters the seismic survey from the southeast and dies out laterally to the NW.

5. Fault Mapping: SS2 horizon

At the SS2 horizon, the NW2 reverse fault translates to the southwest and terminates at the horizon.

6. EUR Correlation

- ◆ Within the 3D seismic survey, 27 wells have been drilled.
- ◆ The EURs of these wells are compared with results of fault mapping and P-wave analysis.

6. EUR Correlation: Fault mapping

NW2 fault parallels
EUR trend with best
wells west of fault.

Projection of
NW2 fault plane
from Cameo to
SS2 horizons.

6. EUR Correlation: Fault Mapping

Correlation of NW2 Fault with Well Performance

	West of NW2 Fault Zone	East of NW2 Fault Zone
Number of Wells	17	10
Average EUR/Well	2.32 Bcf	1.37 Bcf
Range of EUR/Well*	1.57 to 3.26 Bcf	0.98 to 1.84 Bcf

*After eliminating best and worst wells.

6. EUR Correlation: Seismic Attributes

Multiple seismic attributes identify wells with EURs greater than 2.0 Bcf.

- + 0.5 PT / 100 POS GRAD SUM AVO
- +1 PT / 100 GRAD DIF AVO > 100
- VEL. ANIS.: +0.5 PT PER % >4%
- +1 PT IF MAX. INT. VEL. >13500'/S
- +1 IF CONSIST ORIENT AZIM & HI MAGN

7. Structural Analysis

We observe that the permeable fracture network is a local phenomenon related to small reverse faults, and that wells with high EUR values occur near a fault tip.

Structural analysis will combine field observations, data analysis, and experimental theory to provide a robust exploration strategy.

7. Structural Analysis: Fracture Theory

Stress around fault tip

Secondary structures

7. Structural Analysis: Experiments

Small incision cut into a photoelastic material and placed under biaxial stress. Stress concentration around tip and asymmetry due to orientation of cut to stress direction.

7. Structural Analysis: Experiments

Experiments deforming rocks under confining pressures result in the formation of numerous fractures during contractional strain. The fractures concentrate near fault tips and in the footwall of the reverse fault system.

from Logan and others, 1979

7. Structural Analysis: 3D Seismic

The Clough RMV 7-21 has an EUR > 3Bcf whereas the Clough 3 has an EUR ~1Bcf

The difference may be due to location with respect to fault tip where the greatest amount of fracturing occurs.

Clough RMV 7-21

Clough 3

7. Structural Analysis: Fracture Orientation

Consistent with theory, the orientation of fractures rotate 180° across reverse faults at the Cameo horizon.

Fracture Orientation

DIX INTERVAL VELOCITY - RATIO (N60E / N30W)
Z TO CAMEO COALS

7. Structural Analysis: 3D Seismic

Present-day stress, directed N80W, may cause offset of open fracture location to northwest lateral terminus of fault.

Other factors include sand thickness and location.

8. Conclusions

- ◆ Advanced Resources' natural fracture detection project at Rulison shows that it is possible to map subtle reverse faults responsible for permeability-based sweet spots in the tight, massively stacked sands.
- ◆ The information from structural analysis of the 3D seismic shoot has helped delineate the higher productivity trends
 - EUR's within the trend are 2+ Bcf
 - EUR's outside the trend are ~1 Bcf

8. Conclusions

- ◆ Natural fracture detection technology that combines 3D seismic fault mapping and 3D stress modeling may ultimately unlock the vast resources held in tight, lenticular-sand gas plays, as shown for the Rulison field:

	<u>EUR's</u>	<u>Dry Holes</u>
Historical Performance (1956-1972)	0.9 Bcf/well	45%
Recent Technology-Based Performance	2.0 Bcf/well	low

Appendix B.
GRI-DOE-IPAMS Presentation

Fault Mapping and Natural Fracture Detection Using 3D Seismic Data

David J. Campagna, Ph.D.

Advanced Resources International, Inc.

**"Advances in Seismic Technologies"
A Consortium for Emerging Gas Resources
in the Green River Basin**

IPAMS

November 11, 1997 Denver, Colorado

Outline for Presentation

- 1. Introduction**
- 2. Project Setting**
- 3. 3D Seismic Survey**
- 4. Seismic Attributes**
- 5. Fault Mapping**
- 6. EUR Correlation**
- 7. Structural Analysis**
- 8. Conclusions and Future Directions**

1. Introduction: Rulison Field Project

Project Title:

**Naturally Fractured Tight Gas
Reservoir Detection Optimization**

Project Objective:

***Optimize geological and geophysical
techniques for economically detecting, mapping
and evaluating naturally fractured tight gas
reservoirs.***

1. Introduction: Project Participants

Sponsors:

DOE Federal Energy Technology Center

Barrett Resources

Co-investigators:

Western Geophysical

Lynn & Associates

Basin Energy

1. Introduction: Today's Topic

Integrated fault mapping, azimuthal P-wave analysis, and structural analysis offers a new, powerful method for locating natural fractures in advance of drilling.

2. Project Setting

- ◆ The Piceance basin in Colorado contains a vast accumulation of gas in tight, massively stacked, lenticular sands.
 - 321 Tcf (USGS, 1987)
 - 311 Tcf (ARI, 1996)
- ◆ Considerable past and ongoing R&D sponsored by DOE/FETC and GRI has been directed at this basin (MWX and M Site)

2. Project setting: Basin Character

2. Project Setting: Rulison Field

- ◆ The Rulison / Williams Fork field in Garfield County, Colorado (T6 & 7S, 94W) was discovered in 1956 with the drilling of the Juhan #1 well. The field is estimated to have approximately 10 Tcf of gas in place in the Mesaverde tight sands, plus additional gas resources in the underlying and interfingered Cameo coals.
- ◆ In the next 36 years, through 1992, only 36 more wells were drilled, with generally poor to marginal reserves and numerous dry holes. Under these conditions (confirmed by the USGS assessment), the Rulison field was judged to be an uneconomic gas play:
 - Average EURs/successful well -- 0.9 Bcf

– Dry hole rates -- 45%

2. Project setting: Rulison Field

- ♦ The area around the Rulison Field, southeast Piceance basin, holds the region's richest concentrations of gas in place:

- 160 Bcf per section in Williams Fork Member, Mesaverde Fm.
- 40 Bcf per section in the deeper Cameo and Coal Ridge coals.

2. Project Setting: Stratigraphy

The Williams Fork Member is a massively stacked, lenticular nonmarine unit of the Mesaverde Fm. containing sandstones, shales, and coals.

ERA	SYSTEM	SERIES	STAGE	UNIT
CENOZOIC	TERTIARY			Uinta Fm
		Eocene		Green River Fm
				Wasatch Fm.
		Paleocene		
		Maestrichtian		
MESOZOIC	CRETACEOUS	Upper	Campanian	Mesaverde Group
				Williams Fork Fm.
				Rollins Ss.
				Cameo coal zone
				Cozzette Ss.
				Corcoran Ss.
				Castlegate Ss.

2. Project Setting: Reservoir & Matrix Permeability

2. Project Setting: Rulison Field

- ◆ Characterization of the massively stacked, lenticular tight sands (the DOE/GRI MWX site is located on the southern edge of the field), introduction of improved well completion practices by Barrett Resources and inference of areas with higher permeability and sand development revitalized this gas play.
- ◆ From 1993 through early 1997, 65 new wells have been drilled with significantly improved EURs and gas production rates; also, many of the older wells have been recompleted. At the end of 1996:
 - The field had produced 40 Bcf
 - Gas production in 1996 averaged 325 MMcfd

2. Project Setting: Rulison Field

- ♦ The field operator, Barrett Resources, has plans to intensively develop the higher productivity portions of the field at 20 to 40 acres per well. This would provide, theoretically, one to two thousand locations.
- ♦ A significant high-productivity trend, plus smaller pockets of natural fractures, exists at Rulison and has been mapped. Assuming 20% of the area has higher productivity, 200 to 400 high quality new wells could be drilled.

2. Project Setting: Objectives

- ♦ The objective of our field study is to further delineate sweet spots at Rulison (and in the adjacent southern Piceance Basin). When done in advance of drilling, this will provide significant value in terms of higher recovery per well, lower dry hole rates and lower-cost gas reserves.

3. 3D Seismic: Objectives

- ◆ Establish P-wave seismic attributes that reliably correspond to orientation and intensity of open natural fractures.
- ◆ Determine ability to map subtle fault systems.

3. 3D Seismic: Acquisition

- ◆ Design
 - Full-azimuth, high-fold, full-offset
 - Receiver spacing of 220 feet (bin size of 110' by 110')
- ◆ Processing
 - Entire volume was separated into two limited azimuth volumes, N150E and N60E (+/- 45°)

3. 3D Seismic: Location

The 3D seismic survey covers 4.5 sq. miles and was located over highly productive areas as well as less productive areas in the Rulison field

3. 3D Seismic Survey

Well control provided by Barrett 68-21 within the survey area established seismic correlation with the major horizons.

4. Seismic Attributes: Theory

Theory predicts that P-waves travel slower when propagating across open fractures; this effect is enhanced when fractures are gas-filled.

A 1500-2000' interval between the z and cameo coals is examined using seismic attributes of interval velocity, AVO gradient, and difference by azimuth of interval velocity.

4. Seismic Attributes

DIX INTERVAL VELOCITY - RATIO (N60E / N30W)
Z TO CAMEO COALS

Interval velocity analysis shows a distinct NW-trending zone of anisotropy indicating N30W fractures.

4. Seismic Attributes

SUM OF AVO GRADIENT - Z TO CAMEO COALS

Strong positive gradients occur in the SW and NE portions of the survey. Positive gradients indicate fractures.

5. Fault Mapping

3D seismic data reveal small reverse faults in Rulison Field:

- ◆ Previous mapping using 2D seismic revealed no faulting (Barrett Resources).
- ◆ Mapping 3D seismic identified subtle reverse faults.
- ◆ Reverse faults, e.g. the NW2 fault, intersect the pay interval at a relatively low angle at the top of Cameo coal and terminate below the gas-water transition zone in the Mesaverde.

5. Fault Mapping: NE-SW profile

5. Fault Mapping: Cameo Horizon

The NW2 reverse fault trends N40W, enters the seismic survey from the southeast and dies out laterally to the NW.

5. Fault Mapping: SS2 horizon

At the SS2 horizon, the NW2 reverse fault translates to the southwest and terminates at the horizon.

6. EUR Correlation

- ◆ Within the 3D seismic survey, 27 wells have been drilled.
- ◆ The EURs of these wells are compared with results of fault mapping and P-wave analysis.

6. EUR Correlation: Seismic Attributes

Multiple seismic attributes may be able identify wells with EURs greater than 2.0 Bcf - though results depend on arbitrary weights specific to the test well data set

- + 0.5 PT / 100 POS GRAD SUM AVO
- +1 PT / 100 GRAD DIF AVO > 100
- VEL. ANIS.: +0.5 PT PER % >4%
- +1 PT IF MAX. INT. VEL. >13500'/S
- +1 IF CONSIST ORIENT AZIM & HI MAGN

7. Structural Analysis

We observe that the permeable fracture network is a local phenomenon related to small reverse faults, and that wells with high EUR values occur near a fault tip.

Structural analysis will combine field observations, data analysis, and experimental theory to provide a robust exploration strategy.

7. Structural Analysis: Fracture Theory

Stress around fault tip

Secondary structures

7. Structural Analysis: Experiments

Small incision cut into a photoelastic material and placed under biaxial stress. Stress concentration around tip and asymmetry due to orientation of cut to stress direction.

7. Structural Analysis: Fracture orientation

Consistent with theory, the orientation of fractures rotate 180° across reverse faults at the Cameo horizon.

↔ Fracture Orientation

DIX INTERVAL VELOCITY - RATIO (N60E / N30W)
Z TO CAMEO COALS

7. Structural Analysis: 3D Seismic

Present-day stress is oriented N80W, oblique to NW2 fault, and causes an area of open natural fracture potential in the extensional quadrant of the fault.

○ Location of Extensional Quadrant

6. EUR Correlation: Fault Mapping

Correlation of NW2 Fault with Well Performance

	<u>West of NW2 Fault Zone</u>	<u>East of NW2 Fault Zone</u>
Number of Wells	30	18
Average EUR/Well	2.17 Bcf	1.27 Bcf
Range of EUR/Well*	1.28 to 3.58 Bcf	0.62 to 2.30 Bcf

*After eliminating best and worst wells.

7. Structural Analysis: 3D Seismic

Based on our results from the 3-D survey plus a 2-D interpretation, we expect that the highly productive area around Sec. 1 of T7S, R94W is also influenced by reverse faulting.

8. Conclusions and Future Directions

- ◆ Advanced Resources' natural fracture detection project at Rulison shows that it is possible to map subtle reverse faults responsible for permeability-based sweet spots in the tight, massively stacked sands.
- ◆ The information from structural analysis of the 3D seismic shoot has helped delineate the higher productivity trends
 - EUR's within the trend are 2+ Bcf
 - EUR's outside the trend are ~1 Bcf

8. Conclusions and Future Directions

- ◆ Natural fracture detection technology that combines 3D seismic fault mapping and 3D stress modeling may ultimately unlock the vast resources held in tight, lenticular-sand gas plays, as shown for the Rulison field:

	<u>EUR's</u>	<u>Dry Holes</u>
Historical Performance (1956-1972)	0.9 Bcf/well	45%
Recent Technology-Based Performance	2.0 Bcf/well	low

8. Conclusions and Future Directions

- ◆ The field experiment at Rulison shows that the link between natural fracture-related permeability and faulting mapped by 3D seismic provides a means to predict the occurrence of “sweet-spots” in low permeability reservoirs.
- ◆ By combining 3D seismic-based fault mapping with a numerical stress model, it may be possible to predict the location and key attributes of natural fractures:
 - Location and density
 - Orientation
 - Relative aperture

8. Conclusions and Future Directions

- ◆ Further field tests of the capability of a combined 3D seismic fault mapping and a 3D stress model for natural fracture evaluation are required to calibrate and demonstrate this technology.
- ◆ Additionally, the information derived from the stress model may help define the critical azimuths for using seismic attributes (e.g., P-wave velocity analysis) in detecting open natural fractures.