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Naturally Fractured Tight Gas Gas Reservoir Detection Optimization

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Quarterly Status Report

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Quarterly Status Report

CONTRACT NO.:

DE-AC21-93MC30086

CONTRACTOR:

Advanced Resources International, Inc.
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Arlington, VA 22201

CONTRACT NAME:

Naturally Fractured
Tight Gas Reservoir
Detection Optimization

CONTRACT PERIOD:

9/30/93 - 4/30/99

CONTRACT OBJECTIVE: No change.

TECHNICAL APPROACH CHANGES: No change.

FIELD PERFORMANCE TEST PLAN:

Introduction

In March, work continued on characterizing probabilities for determining natural fracturing associated with the GGRB for the Upper Cretaceous tight gas plays. Structural complexity, based on potential field data and remote sensing data, was completed. A resource estimate for the Frontier and Mesa Verde play was also completed. Further, work was also conducted to determine threshold economics for the play based on limited current production in the plays in the Wamsutter Ridge area. These analyses culminated in a presentation at FETC on 24 March 1999 where quantified natural fracture domains, mapped on a partition basis, which establish "sweet spot" probability for natural fracturing, were reviewed. That presentation is reproduced here as Appendix I.

The work plan for the quarter of January 1, 1999 - March 31, 1999 comprised five tasks:

1. Evaluation of the GGRB partitions for structural complexity that can be associated with natural fractures,
2. Continued resource analysis of the balance of the partitions to determine areas with higher relative gas richness,
3. Gas field studies,

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4. Threshold resource economics to determine which partitions would be the most prospective.
5. Examination of the area around the Table Rock 4H well

The following sections describe the tasks performed during this quarter as part of the GGRB analysis effort.

Task 1. Evaluation of the GGRB Partitions for Structural Complexity That Can Be Associated with Natural Fractures

As an integral part of identifying potential "sweet spots" of enhanced natural fracturing within the Greater Green River basin, Advanced Resources derived an index of structural complexity associated with natural fracture intensity, created based on the analysis of Landsat Thematic Mapper (TM) multispectral satellite imagery and potential field data, as follows:

1A. Linear Feature Analysis

This task was accomplished by applying a strict set of photogeologic criteria to map geomorphic features that indicate structural control of topography. Anomalous geomorphic features, such as straight linear valleys, ridges, or streambeds, indicate the presence of underlying fractures - faults or joints - in the bedrock, that affect erosion and landform morphology. Straight topographic features were interactively mapped on the satellite imagery using widely accepted techniques for photogeologic analysis. We separated linear features into three categories: straight escarpments, straight valley, and straight stream channels. Features were computer-mapped onscreen at a working scale of approximately 1:100,000 (at larger scales, individual TM image pixels become obvious, and no additional geologic detail is apparent). To minimize confusion with cultural influences - roads, fencelines, plowing patterns, etc. - no features shorter than about one kilometer were mapped. Two separate rounds of quality control review were conducted to refine this primary dataset.

1B. Basement Structural Analysis

The structural importance of surface linear features is assessed by comparing them with an analysis of the underlying basement configuration. For this study, Advanced Resources used regional aeromagnetic and isostatic residual gravity data from the U.S. Geological Survey, Digital Data Series 9. These data show variations in magnetic susceptibility and density of the crust. Low-frequency variations reveal changes in depth-to-basement or in basement composition. Abrupt changes create steep gradients in the potential field data that suggest the presence of a physical boundary in the basement, such as a major fault or shear zone that has juxtaposed different crustal blocks or caused a vertical offset in basement topography. The spatial coincidence of abrupt potential field gradients with surface linear features indicates the presence of an important structural feature that has affected the physical properties of the basement and the present-day land surface,

and presumably the intervening strata, including the reservoir rocks. To integrate the surface and basement analyses, we mapped the aeromagnetic and gravity data by assigning an 8-bit "rainbow" of colors to the range of data values found within the study area. Low magnetic intensity or negative gravity anomaly appears purple; high magnetic intensity or positive gravity anomaly appears red. The color-coded potential field data were then digitally merged with the satellite imagery for easier reference. Regionally extensive, abrupt gradients in the basement properties are shown by sharp changes in color. These gradients were delineated onscreen to show significant aeromagnetic and gravity alignments.

3C. Structural Complexity Ranking

Structural complexity was then determined by township. To determine the index of structural complexity (ISC), the presence or absence of abrupt potential field gradients within a given township was determined and weighted by a value of two-thirds. Surface linear features were summed for each township and weighted by a value of one-third. The township values were binned by ISC ranking with the highest 10% categorized as "best", the next 20% categorized as "good", the next 30% categorized as moderate and the 40% balance categorized as "poor".

Task 2. Continued Resource Analysis of the Balance of the Partitions to Determine Areas with Higher Relative Gas Richness

Using the partitions previously defined (see Appendix I), analysis for this task during this quarter culminated in a determination of the relative resource richness in the GGRB Upper Cretaceous tight gas play in overpressured areas. The purpose of the effort was to highlight those areas that would be most prospective for exploration. Work included further determination of the overpressured portions of the basin. Over 300 wells were analyzed as part of the investigation to define net pay, porosity, and other parameters necessary to the resource calculation.

Results show substantial resource present in the GGRB, approximately 850 Tcf GIP for the Mesa Verde play and 150 Tcf for the Frontier play. Results show that the Mesa Verde has an average drill depth of 10,300 ft, porosity of 9.5 %, and net sand thickness of 275 ft in the play. The Frontier has an average drill depth of 14,700 ft, porosity of 8.5 %, and net sand thickness of 32 ft in the play.

Task 3. Gas Field Studies

Further field studies were conducted to examine the reservoir settings for gas accumulation in the Upper Cretaceous section in the GGRB. During the quarter, we examined the Table Rock, Jonah, Siberia Ridge and Yampa-Lay fields.

Task 4. Threshold Resource Economics to Determine Which Partitions Would Be the Most Prospective

On the basis of the partitions, natural fracture ranking was related to resource richness for the GGRB. Resource recovery economics were run for the Mesa Verde and Frontier plays based on current technology (Case 1), advanced technology (use of advanced completions and horizontal wells, Case 2), and advanced technology with natural fracture ranking (Case 3). Among the most prospective partitions are the Pinedale, Farson Deep Sand Wash Deep and Wamsutter Arch partitions for the Mesa Verde play. For the Frontier play, prospective partitions include the Farson Deep, Sand Wash Deep, Pinedale and Green River Deep partitions.

Task 5. Examination of the Geology and Fault Systems Near the Table Rock 4H Well

A full 3D seismic data set that covers approximately 36 sections was extracted from the Table Rock and Continental Divide 3D surveys. It was decided to apply a coherency filter to further enhance the data. The coherency processing brings out in finer detail the fault-related discontinuities in the seismic data allowing for better analysis and fault mapping.

Using the fully processed 3D data, the thrust and strike-slip fault system north of Table Rock was shown in great detail. Furthermore, two small splay faults were identified in the data that occur in the region of the horizontal drilling location.

Using the more complicated fault system geometry, a geomechanical model was performed. This new model showed regions of possible tensile failure associated with the smaller faults. It is possible that the Table Rock 4H horizontal well may have crossed into one of these tensile failure zones. The success of the horizontal well in encountering clusters of natural fractures near small faults is in agreement with the fault mapping and geomechanical model.

Appendix 1

Optimizing The Exploration Process for Naturally-Fractured Gas Reservoirs in the Greater Green River Basin

*"Developing and demonstrating high value E&P technology for
unlocking natural gas resources in low permeability basins."*

Presented to:

DOE/FETC

Prepared by:

Advanced Resources International, Inc.

March 24, 1999

Outline

- **Greater Green River Basin Regional Partitioning and High-Grading**
 - Resource-in-Place
 - Structural Characterization
 - Resource Recovery Economics
- **Prospect Delineation**
 - Table Rock Horizontal Drilling Project
- **Conclusions & Discussion**

Project Evolution for Naturally-Fractured Deep Gas Exploration

Regional High-Grading

Prospect Delineation

Prospect Test

Project Evolution for Naturally-Fractured Deep Gas Exploration

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Prospect Test

Essential Data and Tools

- **Geologic Database**
 - Existing well information (completion, production)
 - Existing borehole data (logs and core)
 - Outcrop studies of natural fractures
- **Potential Field and Image Data**
 - Basement mapping from potential field surveys (both standard and high-resolution aeromagnetics plus gravity data)
 - Regional and local structures from satellite imagery analysis
- **Seismic Surveys**
 - regional 2-D regional data

Greater Green River Basin

The overpressured sands of the Mesaverde Group and the deep Frontier Formation gas play in the Greater Green River basin of SW Wyoming serves as the case study.

Greater Green River Basin Regional Partitioning and High-Grading

Resource-in-Place

Resource Assessment

- To high-grade areas with potential, Gas-in-Place was determined for the various partitions that make up the Upper Cretaceous tight gas play
- Methodology based on partitioning provides a quick but robust assessment
- Results show substantial resource present in the GGRB, approximately
 - 850 Tcf GIP for the Mesaverde play and
 - 150 Tcf for the Frontier play

Resource Assessment (cont'd)

Methodology

- Gas-in-Place was assessed, by partition, for each of the requisite parameters
 - Area
 - Net pay thickness
 - Porosity
 - Gas saturation
 - Temperature
 - Gas compressibility

Primary database was derived from well control, selecting the deepest, complete well in a township to represent the many of the parameters for that township.

Resource Assessment (cont'd)

Methodology

Significant well data were available, but some infilling of townships was performed by means of generated contour maps.

Resource Assessment (cont'd)

Methodology

Field studies
helped to
constrain
parameters for
the plays.

Upper Cretaceous Tight Gas Play

JAF01069.CDR

Upper Cretaceous Tight Gas Play

Determination of the top of the overpressure of tight gas play was accomplished by examination of mudweights, DSTs, pressure of gas vitrinite reflectance, and seismic velocities.

JAF01071.CDR

Mesaverde Drill Depth

Average properties for the MV:

- Drill depth 10,300
- porosity = 9.5%
- net sand = 275 ft.

Mesaverde Production

Study is limited to Mesaverde section below the Upper Almond in overpressured areas.

Defining Overpressured Volumes

Mesaverde Overpressured Areas

Overpressuring of the Mesaverde Group is not present throughout the basin.

Porosity Cut-offs

- The following cut-offs were used to define net pay in both the Mesaverde and Frontier strata.

Depth Upper (ft.)	Bound Lower (ft.)	Porosity (%)
0	2,500	12
2,500	5,000	10
5,000	7,500	8
7,500	10,000	7
10,000	15,000	6
15,000	20,000	5
20,000	25,000	4

Mesaverde Parameters (cont'd)

Porosity

Net Sand Isopach

Mesaverde GIP by Partition

Gas-in-Place totals
about 850 Tcf.
Resource
concentration is
greatest along the
Wind River Thrust,
Wamsutter Arch
and Deep Sand
Wash.

1

This map displays the geographical distribution of producing frontier fields within the Bakken region. The map is overlaid with a grid of latitude and longitude coordinates. Latitude lines are marked at 48°N, 49°N, and 50°N. Longitude lines are marked at 106°W, 105°W, 104°W, 103°W, 102°W, 101°W, 100°W, 99°W, 98°W, 97°W, 96°W, 95°W, 94°W, 93°W, 92°W, 91°W, 90°W, 89°W, 88°W, 87°W, 86°W, 85°W, 84°W, 83°W, 82°W, 81°W, 80°W, 79°W, 78°W, 77°W, 76°W, 75°W, 74°W, 73°W, 72°W, 71°W, 70°W, 69°W, 68°W, 67°W, 66°W, 65°W, 64°W, 63°W, 62°W, 61°W, 60°W, 59°W, 58°W, 57°W, 56°W, 55°W, 54°W, 53°W, 52°W, 51°W, 50°W, 49°W, 48°W, 47°W, 46°W, 45°W, 44°W, 43°W, 42°W, 41°W, 40°W, 39°W, 38°W, 37°W, 36°W, 35°W, 34°W, 33°W, 32°W, 31°W, 30°W, 29°W, 28°W, 27°W, 26°W, 25°W, 24°W, 23°W, 22°W, 21°W, 20°W, 19°W, 18°W, 17°W, 16°W, 15°W, 14°W, 13°W, 12°W, 11°W, 10°W, 9°W, 8°W, 7°W, 6°W, 5°W, 4°W, 3°W, 2°W, 1°W, 0°W, 1°E, 2°E, 3°E, 4°E, 5°E, 6°E, 7°E, 8°E, 9°E, 10°E, 11°E, 12°E, 13°E, 14°E, 15°E, 16°E, 17°E, 18°E, 19°E, 20°E, 21°E, 22°E, 23°E, 24°E, 25°E, 26°E, 27°E, 28°E, 29°E, 30°E, 31°E, 32°E, 33°E, 34°E, 35°E, 36°E, 37°E, 38°E, 39°E, 40°E, 41°E, 42°E, 43°E, 44°E, 45°E, 46°E, 47°E, 48°E, 49°E, 50°E, 51°E, 52°E, 53°E, 54°E, 55°E, 56°E, 57°E, 58°E, 59°E, 60°E, 61°E, 62°E, 63°E, 64°E, 65°E, 66°E, 67°E, 68°E, 69°E, 70°E, 71°E, 72°E, 73°E, 74°E, 75°E, 76°E, 77°E, 78°E, 79°E, 80°E, 81°E, 82°E, 83°E, 84°E, 85°E, 86°E, 87°E, 88°E, 89°E, 90°E, 91°E, 92°E, 93°E, 94°E, 95°E, 96°E, 97°E, 98°E, 99°E, 100°E, 101°E, 102°E, 103°E, 104°E, 105°E, 106°E, 107°E, 108°E, 109°E, 110°E, 111°E, 112°E, 113°E, 114°E, 115°E, 116°E, 117°E, 118°E, 119°E, 120°E, 121°E, 122°E, 123°E, 124°E, 125°E, 126°E, 127°E, 128°E, 129°E, 130°E, 131°E, 132°E, 133°E, 134°E, 135°E, 136°E, 137°E, 138°E, 139°E, 140°E, 141°E, 142°E, 143°E, 144°E, 145°E, 146°E, 147°E, 148°E, 149°E, 150°E, 151°E, 152°E, 153°E, 154°E, 155°E, 156°E, 157°E, 158°E, 159°E, 160°E, 161°E, 162°E, 163°E, 164°E, 165°E, 166°E, 167°E, 168°E, 169°E, 170°E, 171°E, 172°E, 173°E, 174°E, 175°E, 176°E, 177°E, 178°E, 179°E, 180°E. The map shows several large, irregularly shaped areas shaded with a stippled pattern, representing producing fields. These fields are primarily located in the central and eastern portions of the map, with some smaller fields scattered throughout. The map also includes a legend in the top left corner, which identifies the shaded areas as 'Producing Frontier Fields' and the solid black lines as 'Field Outline'.

Frontier Drill Depth

Data control for the Frontier is less than that for the MV.

Average properties for the Frontier:

- Drill depth 14,700 ft**
- porosity = 8.5%**
- net sand = 32 ft**

Frontier Overpressured Areas

**Majority of
nonconventional
areas contain
overpressured
Frontier Fm.**

Frontier Parameters (cont'd)

Porosity

Net Sand Isopach

Frontier GIP by Partition

Gas-in-Place totals
about 150 Tcf.
Most resource is
found in the
northerly partitions.

Resource Assessment

- While knowledge of the distribution of the resource is fundamental, additional work is needed to high grade areas of permeability in the tight gas basin where the gas is amenable to economic recovery.

Greater Green River Basin Regional Partitioning and High-Grading

Structural Characterization

Regional Structural High-Grading

- **Basin-wide analysis for structural high-grading**
- **Structural high-grading for the GGRB was accomplished by utilizing:**
 - aeromagnetic and gravity data for basement mapping, and
 - outcrop and/or image analysis for surface manifestations of structure.
- **Risk mitigation using probability assessment of structural complexity**

Structural Control of Natural Fractures

- Natural fractures are typically classified as “regional” and “tectonic” (local).
 - Regional fracture systems are comprised of a dominant set with consistent spacing parallel to maximum horizontal stress.
 - Local fracture systems are typically formed as secondary features to larger structures such as faulting and folding.
- Local natural fracture sets are responsible for the highly productive “sweet spots.”

Natural Fracture Settings

Types of Natural Fractures Observed In Cores

The type of natural fracture observed in core is important information that will help determine the method of quantitative stress modeling.

extension fracture

shear fracture with
extensional component
(mixed mode)

shear fracture

Structural High-Grading

- **Goal:**
 - Delineate regions of significant structural “complexity.”
- **Rationale**
 - Since local natural fracture development is directly related to local structural features, mapping regions with significant occurrences of basement and surface structures identify areas prone to local natural fracturing.
- **Results**
 - Regions graded by density and correlation of significant structures.

Major Structural Elements of the Greater Green River Basin

The Greater Green River Basin is surrounded by major thrust faults that formed a series of foreland-style sub basins separated by regional arches.

Regional Basement Anomalies: Isostatic Gravity

Gravity data reveal the architecture of the Greater Green River Basin and facilitated basin partitioning.

Regional Basement Anomalies: Aeromagnetic Data

Aeromagnetic data also reveal significant basement-related structures. For example, in the Pinedale/Hoback sub-basin the data contain several north- and northwest-trending basement anomalies.

Regional Surface Features: Image Analysis

A seven scene
Landsat-TM
satellite image
mosaic was
constructed and
provides the basis
of the surface
linear features
analysis.

Regional Surface Trends: Geomorphic Linear Analysis

The geomorphic linear features were mapped according to specific criteria that account for the type of geomorphic linear feature and minimum length of the feature.

Farson Deep Partition

Density of Surface Linear Features

Density of surface linear features was calculated as one indication of structural complexity within the basin.

Red = high density.

Procedure for Identifying Areas of Structural Complexity

- High-grading procedure depends on spatial distribution and spatial correspondence:
 - Surface linear features are summed by township.
 - Density of surface linear features is spatially compared to basement anomalies.
- Township Rankings
 - (Best) 1. Basement anomalies and dense surface linear features
 - (Good) 2. Basement anomalies and nominal surface linear features
 - (Moderate) 3. Basement anomalies or dense surface linear features
 - (Poor) 4. No basement anomalies and sparse to nominal surface linear features

Structural Complexity Map

High structural complexity is inferred for partitions with both basement anomalies and high density of surface linear features.

Partition Structural Characteristics

- As the final step in the structural high-grading, the distribution of structural ranks in each partition is calculated.
- Distribution is analogous to EUR distribution since well productivity is related to local fracture systems.
 - This distribution is necessary for developing appropriate well distribution for each partition, especially those partitions with limited well information.

Natural Fracture Rank and Distribution of Selected Partitions

Partition	Ranking			
	Best	Good	Moderate	Poor
	Township Count			
Pinedale	4	5	7	12
Green River Deep	4	3	20	36
Sand Wash Deep	4	2	13	7
Hoback	4	1	3	20
Farson Deep	2	1	2	17
Cherokee Arch	1	2	2	13
Wamsutter Arch	1	1	6	7
Red Desert	0	7	6	51
Vermilion	0	3	2	12

Greater Green River Basin Regional Partitioning and High-Grading

Resource Recovery Economics

Integration of Natural Fracture Prospectivity with Resource Assessment

- **On a partition basis, the natural fracture ranking was related to resource**
- **Simple resource recovery economics were run for the Mesaverde and Frontier plays:**
 - (Case 1) current technology
 - (Case 2) advanced technology (use of advanced completions and horizontal wells)
 - (Case 3) advanced technology plus natural fracture prospecting

Resource Economics were Analyzed for Prospective Partitions

<u>Partition</u>	<u>Mesaverde</u>	<u>Frontier</u>
• Wamsutter Arch	☒	
• Cherokee Arch	☒	
• Sand Wash Deep	☒	
• Hoback	☒	☒
• Pinedale	☒	☒
• Farson Deep	☒	☒
• Red Desert	☒	☒
• Vermillion		☒
• Green River Deep		☒

Integration Methodology

Parameter/ Technology Case	Current	Advanced	Advanced w/ Natural Fracturing
• Structural Complexity	All Ranks	All Ranks	Best, Good
• EUR,Bcf/well	<i>varied by partition dependent on resource magnitude</i>		
• O&M	\$.40	\$.30	\$.30
• well cost, x\$1000 MV	650	1300	1300
• well cost, x\$1000 Ftr	800	1600	1600
• NRI	85%	85%	85%
• spacing, acres	160	320	320
• dry hole rate, MV	30%	22.5%	17.5%
• dry hole rate, Ftr	50%	37.5%	25%

Data were modeled to define a relative cost for production in \$/mcf

Calibration of Structural Complexity Ranking to Production

**Wamsutter area
is the only area
with significant
MV production.**

**EUR/well was
developed based
on 5x highest full
year of
production.**

Calibration of Structural Complexity Ranking to Production

Resource within
the Wamsutter
area correlates
positively with
structural
complexity.

Calibration of Resource Variation to Production--Current Technology Case

Wells in the Wamsutter area show a positive correlation with GIP, which was used to help define the relative EUR/well form partition to partition.

Calibration of Resource Variation -- Advanced Technology Cases

Higher potential wells provide a basis for describing potential of advanced technology wells.

Calibration of Horizontal Wells -- Advanced Technology Cases

Estimated Gas Recovery: 30 Years
(Blue Rim 31-1 Reservoir Assessment)

Permeability (μ d)	Vertical Well ¹ (Small Frac) (Bcf)	Vertical Well Horizontal Laterals (Bcf)	
		1,000 ft. ²	2,000 ft. ³
10	1.9	4.1	-
20	-	5.6	-
25	2.8	-	8.3

¹ Uses 160 acre spacing per well

² Uses 320 acre spacing per well

³ Uses 640 acre spacing per well

Federal 31-1 Megas Field, Frontier Completion

FRONTIER 31-1

($Y_e/X_e=1$)

Horizontal Well Projection
K=10 micro-d, Lw=1000 feet

Horizontal Well Projection
K=20 micro-d, Lw=1000 feet

Horizontal Well Projection
K=25 micro-d, Lw =2000 feet

Mesaverde Partitions with Potential

	Technology Case	Current	Advanced	Advanced w/ Natural Fracturing
Hoback	\$2.63	\$1.62	\$0.80
Pinedale	\$2.05	\$1.29	\$0.82
Farson Deep	\$2.86	\$1.76	\$0.84

Mesaverde Partitions with Potential

Technology Case	Current	Advanced	Advanced w/ Natural Fracturing
<p>Sand Wash Deep</p>	\$2.91	\$1.79	\$1.05
<p>Wamsutter Arch</p>	\$3.30	\$2.07	\$1.07
<p>Cherokee Arch</p>	\$4.74	\$2.84	\$1.23
<p>Red Desert</p>	\$6.40	\$3.80	\$1.58

Frontier Partitions with Potential

	Technology Case	Current	Advanced	Advanced w/ Natural Fracturing
Hoback	\$2.04	\$1.60	\$0.86
Farson Deep	\$2.08	\$1.64	\$0.87
Sand Wash Deep	\$2.91	\$1.79	\$1.05

Frontier Partitions with Potential

Technology Case	Current	Advanced	Advanced w/ Natural Fracturing
Red Desert	\$2.66	\$2.14	\$1.09
Pinedale	\$2.45	\$1.96	\$1.12
Green River Deep	\$3.71	\$3.05	\$1.40
Vermilion	\$3.99	\$3.30	\$1.55

Where Do We Go From Here?

- Methodology presented here provides a basis for economical assessment of tight gas sand resources for high grading basins
- But we aren't done yet...we need to take the next step, based on high graded areas, to delineate prospects using tools such as seismic and geomechanical modeling.

Prospect Delineation

Table Rock Horizontal Drilling Project

Prospect Identification

- Next stage in exploration process is to delineate prospects within high-graded regions.
- The prospect delineation process for naturally-fractured reservoirs involves
 - Characterizing the local natural fractures present in target reservoir
 - Mapping local structural features such as faults
 - Predicting the location, intensity and orientation of the fractures.

Project Evolution for Naturally-Fractured Deep Gas Exploration

Regional High-Grading

Geologic Database

Subsurface Mapping
using Well Data

Reservoir Character
and Extents

Regional Structure and
Stress Regime

Surface Structure from
Field and Imagery

Basement Mapping
using Potential Field Data

Prospect Delineation

Local Reservoir
Characteristics

Offset Core and Log
Observations

Subsurface Mapping
using Seismic Data

Fault Mapping and
Stress Modeling

Prediction of
Fracture Occurrence

Prospect Test

Exploration Drilling
Program

Coring & Logging
Program

Well Testing

Reserve Estimates

Table Rock Prospect Delineation

- The Table Rock Horizontal Drilling Project by DOE/UPRC provides an opportunity to demonstrate an optimized prospect delineation.

Prospect Delineation

The steps necessary for a prospect delineation at Table Rock:

- A. Characterizing Natural Fractures in the Frontier Fm.**
 - Examine Govt. Union #4 and Frewen Deep cores.
- B. Fault Mapping using 3-D Seismic Data**
 - Post-stack depth-conversion of 3D data.
 - Map and develop structure and isopach maps.
 - Coherency processing for fault identification.
 - Map fault geometry for input to stress model.
- C. Predicting Fault-Related Natural Fractures**
 - Assemble fault geometry and displacements.
 - Determine area(s) of enhanced natural fracturing based on geomechanical model.

Natural Fractures Observed In Frontier Fm. Core

Types of natural fractures identified in the Govt. Union #4 core include:

- Shear fractures with an extensional component exhibiting oblique-reverse slip
- Large voids located between overlapping shear fractures
- Bitumen-filled splay fractures
- Minor calcite- and quartz-filled extensional fractures

Govt. Union #4 Core

Natural Fractures Observed In Cores

Shear(ed) fractures are identified in core by:

Natural Fracture Characterization

- The natural fractures present are fault-related showing dominantly oblique-reverse shear with an extensional component.
- Open isolated voids in core result from step-overs in the shear fractures.
- The voids are connected by single fractures that are typically filled with mineral deposits.
- Open voids represent storage for gas whereas the connecting shear fractures provide the deliverability (i.e., the controlling factor in permeability).

Fault Mapping Using 3-D Seismic Data

- **Two-stage interpretation of the 3D seismic data**
 - “Regional” mapping of fault system using 2D slices from the 3D cube
 - Local fault mapping of 21 sections around Table Rock 4H horizontal drilling project.

Regional Fault Mapping Using 3-D Seismic Data

Selected seismic lines in the Table Rock and Continental Divide Phase II 3-D seismic surveys at 1/2 mile spacing were post-stack depth converted and mapped to:

- 1) Examine a 5 township area around the horizontal drilling location for structure and history of deformation associated with fault systems and,**
- 2) Provide a regional fault geometry in spatial coordinates for use in stress model.**

Extents of 3-D Seismic Survey

Approximately
180 square
miles of 3-D
seismic were
post-stack
depth-converted
and analyzed
for fault
geometry and
displacements.

3-D Seismic: Regional Fault Mapping

The Table Rock thrust system contains two major faults; (1) a thrust fault that trends N30E; and, (2) an oblique reverse-strike-slip fault that trends approximately N60E

3-D Seismic: Regional Fault Mapping

The northward extension of the thrust system terminates below the Frontier Fm.

The strike-slip fault acts as an oblique tear fault accommodating strain on the thrust.

Subsea structure of the Frontier Fm.

3-D Seismic: Regional Fault Mapping

The thrust and the NE trending strike-slip fault (to the right in this profile) are separated as one moves North in the seismic data.

Natural Fracture Prediction

Objectives : To predict location and orientations of shear fractures created by the Table Rock thrust system.

Methodology: Using a 3-D boundary element numerical model, solve linear elastic equations for stress and displacement. This method is limited to modeling failure due to displacement and stress perturbations along a discontinuity (fault, fracture).

3-D Stress Model: Failure Criterion

To evaluate the mechanical genesis of secondary shear fractures, the maximum Coulomb shear stress (S_c) is used as an indicator of failure.

$$S_c = ((\sigma_1 - \sigma_3)/2) * (1 + \mu^2)^{1/2} + \mu * \{(\sigma_1 + \sigma_3)/2\}$$

As compression (negative sign convention) increases from tectonic forces, the rock will fail in shear. The failure envelope is influenced by frictional forces, μ .

3-D Stress Model: Input Criteria

- Inputs into model include fault geometry, orientation of remote stresses deduced from displacement geometry, and material properties.
- Remote stress orientations were calculated based on displacement amounts of the fault system. The greatest compression stress is N30W, nearly perpendicular to the thrust fault, and given a relative value of twice the other applied stresses.
- Frictional component, μ , was assigned 0.6, typical value for sandstones.

3-D Stress Model: Results

Predicted location of shear fractures covers 8 miles².

Greatest intensity of natural fractures should occur between Govt. Union #4 and Table Rock #104.

Predicted shear orientations are N27W and N87W.

3-D Stress Model: Results

Predicted location of shear fractures is consistent with the production rates.

Govt. Union #4 produces 6,000 mcf, Table Rock #104 IP'd at 4,300 mcf and currently produces at 300 mcf. Initial tests of Table Rock Units #22 and #43 were discouraging and the wells are shut-in.

3-D Seismic: Regional Fault Mapping

Conclusions

- Analysis of seismic and structural data suggest a two-stage deformation.
 - The strike-slip fault moved once the level of thrust-related strain needed accommodating.
 - The accommodation occurred on a pre-existing basement shear zone, causing the strike-slip tear to be slightly oblique to the thrust fault.
 - A mechanically-connected geometry of the thrust and strike-slip faults should be used in the stress model and the northern continuation of the thrust ignored.

3-D Seismic: Local Fault Mapping

- A full 3D data set was extracted around the horizontal drilling location to map the local fault geometry.
 - Depth-converted to map faults in space rather than time.
 - Use coherency processing to optimize fault identification.
- Local geometry of fault systems permit the prediction of local natural fracture development.

3D Seismic: Depth Slice 16,000'

- Frontier horizon shown in yellow.

3D Seismic: Coherency Slice 16,000'

- The coherency processing highlights the fault-related discontinuities in the data

3D Seismic: Local Fault Mapping

- Using coherency as a tool, subtle faults and complex geometry of the main thrust and strike-slip system are revealed.

3D Seismic: Local Fault Mapping

- Displacements across faults can be observed in depth slice.

3D Seismic: Depth Slice 16,500'

- A depth-slice further below the Frontier Fm. shows consistency of structure.

3D Seismic: Coherency Slice 16,500'

- Again, the faults are detected by the coherency processing.

3D Seismic: Local Fault Mapping

- The fault mapping of the deeper slices show a consistent geometry to the fault systems.

3D Seismic: Local Fault Mapping

- The fault mapping of the deeper slices show a consistent displacement to the fault systems.

Detailed 3-D Stress Model: Results

The results of the geomechanical modeling of the detailed fault geometry indicate a tensile region northeast of the Table Rock 4H horizontal well.

This result was confirmed when the well encountered numerous fractures in the horizontal leg.

Summary of Prospect Delineation at Table Rock

- **Depth-converted 3-D seismic data shows a connected thrust and strike-slip fault system in the region of Table Rock Field.**
- **Regional analysis of fault-related stress concentrations, using a quantitative numerical model, predicts that natural fractures exist in a prospective area of 8 mile² for the Frontier Fm. at 13,500' to 15,500'.**

Summary of Prospect Delineation at Table Rock

- Detailed analysis of 3D data, aided by coherency processing, reveals a complex fault geometry:
 - small northwest-trending faults in the vicinity of Table Rock horizontal well.
- Geomechanical modelling this more complex system indicates a more diverse and expanded potential for naturally fractured “sweet spots”
 - It is predicted that the Table Rock horizontal well has encountered an area of increased probability for tensile fractures.
 - Other prospects are indicated such as Section 36 of T20N, R97W

Conclusion

Conclusions for Prospecting

- Natural fractures are controlled by local structural complexity such as faults.
- Structural complexity of the play necessitates a two-stage methodology as outlined by Advanced Resources that must include a prospect delineation phase before drilling.
- Prospect delineation stage requires detailed natural fracture characterization, fault mapping using 3D seismic, and geomechanical modelling.
- Complexity of the play is retained at the well-bore scale
 - A single vertical drilling does not necessarily test the play

Conclusions (cont'd)

- **Prospect Delineation Is Driven by Critical Technologies....**
 - Seismic attributes
 - Structural imaging
 - Geomechanical modeling
 - Which must be integrated to define drillable prospects

Lessons Learned

- A “tank” concept is too simplistic for determining success in tight gas plays--resource variation should be defined.
- Fracture-related permeability is localized as “sweet spots” and controlled by structure complexity such as faults. Such structural complexity can be tractably, statistically delineated within a basin.
- Needs remain, however defining the true *local* nature of fracturing--heterogeneity which can result in highly variable EUR values within a developed gas field -- is a critical step.
- Success be use of 3D seismic and geomechanical modeling is confirmed by Table Rock.