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**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

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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:

1/01/98 - 9/30/98

CONTRACT OBJECTIVE: No change.

TECHNICAL APPROACH CHANGES: No change.

FIELD PERFORMANCE TEST PLAN:

The goal of the work this quarter has been to partition and high-grade the Greater Green River basin for exploration efforts in the Upper Cretaceous tight gas play and to initiate resource assessment of the basin. The work plan for the quarter of July 1-September 30, 1998 comprised three tasks:

1. Refining the exploration process for deep, naturally fractured gas reservoirs,
2. Partitioning of the basin based on structure and areas of overpressure,
3. Examination of the Kinney and Canyon Creek fields with respect to the Cretaceous tight gas play and initiation of the resource assessment of the Vermilion sub-basin partition (which contains these two fields),
4. Initiation analysis of the Deep Green River Partition with respect to the Stratos well and assessment of the resource in the partition.

Introduction

During this quarter, work continued on the regional structural and geologic analysis of the greater Green River basin (GGRB) in southwestern Wyoming, northwestern Colorado and northeastern Utah. The goal of the work performed in this quarter has been to divide the basin into partitions and then perform geological analysis and resource assessments in each partition. As part of the assessment of the partitions, selected fields are being examined in detail to determine specific reservoir characteristics (porosity, thickness, fracturing, etc.) and assess gas production potential. Geological analysis of the partitions is being conducted in the context of structural attributes conducive to natural fracture formation and enhanced tight gas production. Resource assessments will include estimating the resource in place and its technical recoverability.

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

Task 1. Refining the Exploration Process for Deep, Naturally-Fractured Gas Reservoirs

Building on the work from prior quarters, the exploration and prospect delineation process for naturally-fractured reservoirs continued to be refined. As part of our technology transfer responsibilities, we presented the results of our on-going work at the GRI-sponsored Deep Gas Forum (Series #2) in Denver on October 15 and 16 (see Appendix 1).

The Upper Cretaceous Frontier Formation gas play in the GGRB is being studied to establish the correlation between gas production and natural fractures. As a result of this process -- the determination of areas of fracture generation based on Columb failure for shear fractures -- we delineated an eight township area in the Table Rock region of the GGRB for horizontal well development. The presentation in Appendix 1 illustrates this process.

Task 2. Basin Partitioning

Building on fundamental fracture characterization work (See Task 1 above) and prior work performed under this contract, namely structural analysis using satellite and potential field data, the GGRB is being divided into partitions that will be used to analyze the resource potential of the Frontier and Mesaverde Upper Cretaceous tight gas play. The GGRB partitions are shown in Figure 1, using townships as the unit of analysis.

FIGURE 1

Greater Green River Basin Partitions

Federal Energy Technology Center
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A total of 20 partitions were developed, which will be instrumental for examining the Upper Cretaceous play potential. The rationale for the individual partitions (in alphabetical order) is as follows:

Cherokee Arch. The Cherokee Arch is a structurally high feature located in the southwest part of the GGRB, separating the Washakie Deep from the Sandy Wash area. The Cherokee Arch displays oblique right lateral faulting and is likely a counterpart to the Wamsutter Arch to the north for accommodating stresses across the Washakie Deep. The partition covers an area of eight townships.

Dad Dixon Platform. Located in the east-central part of the GGRB, the Dad Dixon Platform is in a foreland position relative to thrusting associated with basin-bounding Park Range. Structurally the platform dips at a relatively shallow angle toward the Washakie Deep. It sits in an equivalent structural position to LaBarge platform, although exploration maturity and established production levels are not as great. The partition covers an area of 21 townships.

East Sand Wash. Located south of the Cherokee Arch but in similar structural position to the Dad Dixon Platform, the East Sand Wash ramps toward the Sand Wash Deep. The partition is also located at the southern terminus of the upthrust Park Mountains where a tear fault likely separates the two domains. The partition displays fairly constant homoclinal dip and is lightly explored. Thirty one townships are covered by the partition.

Farson Deep. The Farson Deep sits in a foreland position to thrusting which uplifted the Wind River Mountains. The Farson Deep exhibits a strong gravity signature that is likely the result of basement structuring. Depth to the Frontier formation in the reaches over 16,000 feet (subsea). On the partition's southeast side may be bounding by a fault which separates it from the RockSprings Uplift. The Farson Deep is relatively unexplored and comprises an area of 25 townships.

Green River Deep. Located between the Moxa Arch and the Rock Springs uplift, the partition is bounded by a steep flank on the west and is fault-bounded on the east. The northern end of the partition includes the Sandy Bend Arch, a structurally high feature that separates the partition from the Farson Deep to the north. The partition, in the area of the Sandy Bend Arch, is the site of the Stratos 1 well, drilled by DOE and UPR. Northwest-trending basement faults occur interior to the partition. The partition is bounded on its southern end by the upthrust Uinta Mountains. The Green River Deep partition is a locus of basin-centered gas and is largely overpressured. Exploration maturity in the partition is relatively low. The partition covers an area of 61.5 townships.

Hoback. The Hoback partition is an asymmetric foreland deep located between the upthrust Wind River Mountains to the east and the Wyoming thrust belt to the west. The axis of the deep is located adjacent to the Wind River Mountains and has a strong gravity expression. Depth to the Frontier formation in the partition is over 20,000 feet (subsea). On its southwestern side, the partition is transitional to the LaBarge Platform. The partition is lightly explored and covers an area of thirty one townships.

LaBarge Platform. The LaBarge Platform is a foreland area to the Wyoming thrust belt to the west where the thrust belt displays a left-stepping tear. The tear fault has set the partition up as a sub-regional structural high. On its south side the partition transitions to the more homoclinal shallow dip of the Moxa Arch and is surrounded by deeps on the east and northeast sides. Similar to the Moxa Arch, reservoirs of the Upper Cretaceous section in the partition are dominated by nonmarine sediments. The partition is the site of intense drilling, especially in the Mesa Verde section. It covers 39 townships.

Moxa Arch. The Moxa Arch is also foreland to the Wyoming thrust belt to the west. The partition is the site of generally shallow, southward dipping strata, gently folded into an arch. In contrast to much of the rest of the GGRB, the Upper Cretaceous section here is nonmarine and was deposited in a fluvial-dominated environment. The level of exploration for the Upper Cretaceous section in the partition is high. Reservoirs in the partition are generally normally pressured. The partition covers an area of 62 townships.

Pinedale. The Pinedale partition is the site of a foreland deep relative to the upthrusting of the Wind River Mountains. The partition shows a pronounced gravity low, but is differentiated from the Hoback and Farson deeps to the northwest and southeast, respectively, by the presence of the Pinedale anticline. The partition is the site of the Jonah field, an upfaulted, overpressured Lance Formation producer discovered in the early 1990s. Overall, the partition has had relatively little exploration activity. Twenty four townships are covered by the partition.

North Rock Springs. This partition comprises the northeast flank of the Rock Springs Uplift and displays relatively homoclinal northeast-dipping strata. The partition is separated from the Farson Deep on the northwest by a fault and ramps to the northeast into the Red Desert partition. The partition is the site of moderate exploration activity production, especially in the Mesa Verde Group. The partition covers 22 townships.

Red Desert. This partition is a steeper complement to the North Rock Springs partition. Where it abuts the southern edge of the Wind River Mountains to the north, the partition is a foreland deep and displays a gravity signature. To the northeast, the partition grades into the Red Desert Deep. Exploration activity in the partition has been moderate. The partition covers 48 townships.

Red Desert Deep. The Red Desert Deep is a foreland deep to the Rawlins Uplift. The partition shows a pronounced gravity signature and has a depth of over 18,000 feet (subsea) to the Frontier formation. Lightly explored, the partition covers 11 townships.

Rock Springs Crest. The Rock Springs Crest partition sits atop the north-south striking Rock Springs Uplift, which is bounded by late Laramide faulting on west side. The uplift displays a pronounced (high) gravity signature. Transverse, northeast-southwest trending faults are present in the crest. Because of the uplift the Upper Cretaceous section is normally pressured in this part of the GGRB. The Frontier formation is found at depths above sea level in this partition. The partition is heavily explored and comprises 24 townships.

Rock Springs East. This partition comprises the eastern and southeastern flank of the Rock Springs Uplift as it dips toward the Washakie and Red Desert areas. Moderate drilling has taken place in the partition. The Rock Springs East partition covers 21 townships.

Sand Wash Deep. The Sand Wash Deep partition is a foreland deep found at the eastern terminus of the Unita Mountains uplift. Adjacent to the uplift, in the southwest portion of the partition is the site of a pronounced gravity low. Depth to the top of the Frontier Formation is over 15,000 feet (subsea) in the deepest part of the partition. It is separated from the Washakie Deep to the north by the Cherokee Arch. The partition is immaturely explored and covers an area of 34.5 townships.

Vermilion Sub-basin. The Vermilion Sub-basin is sandwiched between the Washakie and Sand Wash deeps to the east, the Rock Springs Uplift to the northwest and the upthrust Unita Mountains to the south to which it lies in a foreland structural position. Overthrusting is present in fields (Kinney, Canyon Creek and Trail) of the partition, but overall the strata are relatively flat-lying compared to adjacent partitions. The partition is relatively heavily explored and comprises 14.5 townships.

Wamsutter Arch. The Wamsutter Arch is situated in a structurally high position relative to the Red Desert partition to the north and the Washakie Deep to the south. The arch may be the site of right-lateral oblique faulting, complementary to the Cherokee Arch. The partition comprises 12 townships and has been drilled fairly extensively.

Washakie Deep. The Washakie Deep may represent a rhombochasm between the Wamsutter and Cherokee arches. The partition displays a northeast-southwest gravity-low signature and is the site of basin centered gas. Depth to the top of the Frontier Formation in the partition reaches over 18,000 feet (subsea). The partition is lightly explored and comprises 28.5 townships.

Washakie West. This partition comprises the eastern dip flank of Rock Springs uplift transitional to Washakie Deep. It is relatively heavily explored, especially in the Mesa Verde section. The partition covers 13.5 townships.

Washakie East. The Washakie East partition comprises the steeper dip ramp into Washakie deep from the Dad Dixon Platform. Drilling activity, especially in the Mesa Verde section has been fairly heavy. The partition comprises 13 townships.

Using these partitions, analysis was begun on the resource associated with the Cretaceous tight gas play to attempt to highlight those areas that would be most prospective. As part of our ongoing analysis, the boundaries of the partitions are being modified slightly as we refine our models and concepts for the GGRB and as we examine the boundaries of the overpressured zone within the basin. Figures 2 and 3 show well penetrations of the Frontier and Mesa Verde formations. These data are being used to define transects of pressure profiles, which will be utilized to further adjust the partition boundaries. Also as part of this task, regional cross sections of the Frontier formation were made to develop an idea of the thickness variation of the formation.

FIGURE 2
FRONTIER PENETRATIONS

Greater Green River Basin
Wells that Penetrate the Frontier Fm.

U.S. Department of Energy
Federal Energy Technology Center

- Wells that TD in the Frontier Fm.
- Wells that TD @ or deeper than the Dakota Fm.

□ Basin Partition

■ Transect

Analysis performed by:
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FIGURE 3
MESAVERDE PENETRATIONS

**Greater Green River Basin
Wells that Penetrate the Frontier Fm.**

U.S. Department of Energy
Federal Energy Technology Center

- Wells that TD in the Mesaverde Fm.
- Wells that TD @ or deeper than the Mesaverde Fm.

□ Basin Partition

■ Transect

Analysis performed by
Advanced Resources International, Inc.
Member of the Consortium

Task 3. Examination of the Vermilion Sub-Basin Partition

The Vermilion Sub-Basin is located in the southern part of the Greater Green River Basin, foreland to the southern bounding thrust of the Unita Mountains and comprises the SE flank of the Rock Springs uplift. The southern portion of the partition displays oblique slip surface faulting that is transitional between the Unita thrusting and the Cherokee Arch. The Vermilion Sub-Basin shows no distinctive features on gravity data. Folding within the partition generally trends NE-SW, reflecting the partition's structural position relative to the Rock Springs Uplift, the Cherokee Arch and the Unita front. Folds within the partition are thrust fault bounded.

We examined two fields within the partition: Kinney and Canyon Creek (Figures 4 and 5). During the quarter, these fields were examined with respect to the overpressured Upper Cretaceous section, primarily the Frontier and Dakota sandstones. Examination of the Mesa Verde section was also initiated during the quarter but not completed.

Geological Setting. As part of our field descriptions, we researched the depositional environments and diagenesis of the Frontier Formation in an effort to differentiate the various facies present in the formation. Type logs for the Kinney and Canyon Creek fields are shown in Figures 6 and 7.

The Cretaceous Frontier Formation at Kinney and Canyon Creek Fields contains marine shale, offshore sand bars, fluvial deposits and coastal marine sandstones which were deposited along the western shoreline of the Cretaceous Interior Seaway during middle Turonian time (92 - 89 M.Y.). The clastic sediments of the Frontier Formation were derived from emerging uplifts in Idaho and western Utah and were transported eastward through an extensive fluvial system in central Utah and western Wyoming.

The basal part of the Frontier Formation consists of several hundred feet of marine shale beds, which were deposited on a shallow marine shelf. This section overlies the Cenomanian-age Mowry Shale along an unconformable submarine erosion surface dated at 96 M.Y. (Molenaar and Wilson, 1990). The lower Frontier shale section thins to the south onto the Cretaceous-age "Vernal High" where it is thinnest near the Uinta uplift.

The marine shelf deposits are overlain by regressive lower shoreface deposits and prograding coastal shoreline sandstone beds. The shoreface contains massive to cross bedded fine grained sandstone beds. These marine sandstones are generally sub-litharenites containing quartz sand, clays and rock fragments. These sandstones have been highly compacted and cemented with quartz, calcite and clay cements (Dutton and Hamlin, 1992). Sandstone porosity ranges from 4 to 13 % and is typically 8 to 10% (Dickinson, 1992). Permeability is generally very low (0.02 - 0.1 md). Higher permeability can be found in localized naturally fractured zones.

The main Frontier marine sand is overlain by a scoured, erosional contact and a thin non-marine delta plain and fluvial section which occasionally contains coal beds and fluvial sandstone channels. This non-marine interval corresponds with the Middle Turonian sea level fall dated at 90 M.Y. (Mieras, 1992).

ADVANCED RESOURCES INT'L.

Kinney-Canyon Creek Area
FRONTIER STRUCTURE
Sweetwater Co., WY and Moffat Co., CO

RWB 1/10/92
C 1 300 feet 1"=800' BYC

- LEGEND
- Shallow Well
 - o Frontier Penetration
 - Frontier Producer
 - ⊙ Dakota Producer
 - ⊙ Deep Test Location

FIGURE 4

FIGURE 5

LEGEND	
•	Shallow Well
○	Frontier Penetration
●	Frontier Producer
●	Dakota Producer
●	Deep Test Location

ADVANCED RESOURCES INT'L.		
Kinney-Canyon Creek Area FRONTIER STRUCTURE Sweetwater County, Wyoming		
MSW		11/30/98
RWB	Scale 1:160000.	BTK

FIGURE 6

TYPE LOG FRONTIER AND DAKOTA FORMATIONS WINNEN FIELD WEST WASHAKIE BASIN, WYOMING

FIGURE 7
 TYPE LOG
 FRONTIER AND DAKOTA FORMATIONS
 CANYON CREEK FIELD
 WEST WASHAKIE BASIN, WYOMING

STRATIGRAPHIC CORRELATIONS AND AGES
 AFTER MOLENAAR AND CULSON, 1990

ROUGH
 DRAFT
 MSW 10/98

In some localities, Frontier sand bar deposits and shale beds overlie the non-marine delta plain deposits. These discontinuous, lenticular offshore sandstones are intensely bioturbated, and usually have poor porosity and relatively high clay content. The sand bars are conformably overlain by thick marine shales of the Upper Cretaceous Mancos (Baxter) Shale section. The Frontier sandstones in the West Washakie Basin have been buried to depths of 13,000 to 16,000 feet. Present day reservoir temperatures range from 250 - 350 deg. F. Regional thermal maturity trends indicate dry gas window conditions with vitrinite reflectance measurements ranging from 1.5 to 2.0% in this depth range (Scott, 1994). Mudlogs, drilling mud weights and pressure data indicate gas-charged overpressures in the Frontier-Mowry section at Kinney and Canyon Creek fields and throughout most of the West Washakie area.

Several basement-reverse faults and folds have created anticlinal structures within the basin-center gas system. To date, most exploration has been focused along the deep structural highs. The Frontier has been tested occasionally, but has frequently been bypassed in favor of the deeper Nugget and Dakota reservoirs and shallower Mesa Verde section.

Kinney and Canyon Creek fields are found in anticlinal structures above basement reverse faults. Structural maps were completed on the Frontier and Dakota horizons for both fields (Figures 8 through 11).

Kinney Field Description. Kinney Field is located on a Laramide-age fault-fold anticlinal structure located above a west-directed basement reverse fault on the east flank of the Rock Springs Uplift.

Gas-prone carbonaceous shales and coal beds in the Cretaceous Mancos-Frontier-Mowry shale section are buried to 12,000 to 15,000 ft deep in this region. Published %Ro data (Tyler et al, 1994) indicates Ro = 1.0 % at 10,000 ft and Ro = 2.0 % at 15,000 ft, indicating thermally mature conditions. These source rocks are in the gas window and have expelled gas into nearby sandstone reservoirs including the Blair (Airport) sandstones, Frontier Formation and Dakota Sandstone. Increases in drilling mud weights, gas kicks, blowouts, and DST pressure data indicate the top of a gas-charged overpressured zone at 10,000 to 11,000 ft depth in this area. The top of overpressure cuts across stratigraphy and is part of the larger basin-centered gas system in the Washakie Basin.

An early well was drilled to evaluate the Frontier Fm and Dakota Sandstones at the Kinney anticline (Superior Butterwick Gov't #1-18, 18-13N-99W, TD 14,060', 1957). This well was located along the crest of the structure, probably by mapping surface geology and seismic data. High mud weight (14.5 ppg) was needed to maintain control of the well in the Frontier-Mowry-Dakota section below 13,500 feet. Gas shows were encountered in the Frontier SS and several cores were cut. The cores contained quartzitic Frontier sandstone beds with no to slight visible porosity. Some coaly shale was recovered. Gas bubbles and "rainbows" were noted as well as gilsonite (pyrobitumen?) inclusions. Vertical fractures "filled with gypsum" were noted. One core was cut in the Mowry shale section. No formation tests were made of this interval. These cores are stored at the USGS Core Research Center in Lakewood, Colorado, inventory #D896.

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

The Dakota Sandstone was penetrated at 13,996' and two cores were cut. The cores contained hard, quartzitic sandstone with slight to no visible porosity and several vertical fractures, bleeding gas. Most of the cored Dakota sandstone beds were described as "non-porous". The well was drilled to 14,060' TD in the upper Dakota section, but did not penetrate the lower Dakota, Entrada or Nugget sandstones. No formation tests were made to evaluate the Dakota or Frontier reservoirs.

A deep wildcat well (Mountain Fuel Supply Kinney Unit #1, 18-19N-99W, TD 18,636', 1974) was drilled to evaluate the Nugget, Weber and Madison potential at the Kinney anticline. This well was probably located using seismic data and surface geology. A gas kick was encountered in the Blair Fm (Airport Sandstones) at 10,360 feet and was controlled by raising the mud weight to 11.5 ppg. This appears to be the transition into gas-charged overpressure in this area. The Frontier was penetrated at 13,400 ft with 14.9 ppg mud. The Frontier sands show high resistivity and good SP deflection on the well logs. A gas kick and blowout occurred at 13,561', just below the thick Frontier marine sandstones. The Dakota sandstone was encountered at 13,886 ft, and a thick basal conglomerate with about 8 ft of 14-20% density porosity was found at 14,055 ft, just above the Jurassic Morrison Fm. Another gas blowout was reported at 14,320' in the Morrison Fm, with gas to surface at 10-20 mmcf/d rates. This gas may have been gas from the basal Dakota channel reservoir.

Deeper drilling and testing in the Kinney #1 well discovered a significant natural gas reservoir in the fractured Nugget sandstones at 14,722-14,940 ft. Initial production from the Nugget was 13.1 mmcf/d in 1975. The Madison, Morgan and Weber reservoirs were also tested, but were found to be wet or non-productive. A dual completion was established in 1977 to produce gas from the Frontier sandstones as well as the Nugget. A packer was set at 14,620' just above the Nugget, and tubing was set at 13,240'. The Frontier was perforated at 13,405-416' and 13,444-474' and was tested at a rate of 2,837 mcfg/d at 750 psi FTP, without stimulation. Records from BLM files indicate a static Frontier reservoir pressure of 9,373 psig, indicating strong overpressure at 0.70 psi/ft gradient. The reported reservoir data include average porosity of 10%, average water saturation of 58%, and average net pay of 50' in this zone. The Frontier produced 564 mmcf/g within about two years, but then ceased abruptly in late 1978. The cause of the end of production was not reported, however it may have been related to problems with liner leaks and water flows behind pipe. Poor cement jobs can occur with high BHT and depth. The water may have come from the Nugget and Entrada water drive reservoirs downhole. Two PDST's (#15 and 16) were run to evaluate liner problems. This Frontier completion was the only production from the Frontier at Kinney Field. The well was eventually abandoned in 1992.

Following the drilling of Kinney #1, it was clear that the Superior Butterwick #1 well had not been drilled deep enough to penetrate the entire Dakota section and had missed a 'sweet spot' with high porosity in the basal Dakota conglomerate. So the well was re-entered by Mountain Fuel Supply in 1975 and was deepened into the Morrison Fm. Four Dakota sandstone beds from 14,015' to 14,209' were selectively perforated, and the well was put on production as Kinney Unit #2. Flow rates of 6716 mcfg/d were reported during testing. Final shut in pressures of 4853, 6204 and 6295 psig were measured (0.44 psi/ft, normal pressure). This reservoir compartment may be connected to the approximately normally pressured Nugget reservoir system. The measured reservoir temperature was 280 F. No stimulation or fracture treatments were applied. Initial production in 1975 was 3,798

mcfg/d with 31 bwpd. The well was typically produced during the winter heating season and shut in during the summer for pressure buildup. Cumulative production has been 3,664 mmcf through mid-1998.

Following the successful production tests from the Nugget at Kinney #1 and the Dakota at Kinney #2, several additional field extension wells were drilled. Kinney Unit #3 was drilled along the south-plunging nose of the anticlinal structure in 1975, but encountered the Dakota in an irregular structural position. The Entrada produced gas to surface with water recovered during testing. The Nugget was found to be tight, with no gas flows during several PDST's. A Hygel and sand frac was applied, but gas was produced at very low, sub-commercial rates (1170 mcf/d) during production tests. The Dakota flowed 500 mcf/d gas and water during testing. The Frontier was perforated and acidized, but water was recovered by swabbing. The well was plugged and abandoned in 1975. Recent mapping indicates that this well may be in a separate fault block, isolated from the rest of the field. In addition, there may have been problems with zone isolation and water flows behind pipe due to difficulties with cement jobs in the high temperature, high pressure boreholes.

Kinney Unit wells #4, #5 and #6 were more successful, and were completed to produce gas from the Dakota sandstones. Kinney #4 had initial production of 11, 117 mcf/d with 0.8 bwpd, but declined rapidly and produced only 331 mcf from 1984 to 1992, when it was shut in. Kinney #5 had initial production of 5490 mcf/d and has produced 4509 mmcf through mid-1998. Kinney #6 had initial production of 8810 mcf/d and has produced 5489 mmcf through mid-1998. These wells were typically produced during the winter heating season and shut in during the summer for pressure buildups. No hydraulic fracture treatments were applied to the Dakota sandstones in these wells.

The Frontier sandstones have not been tested since Kinney #3 (1975) and Kinney #1 (1977-78 production), and are bypassed behind pipe. Well logs and core descriptions indicate quartzitic sandstone beds with 3 - 14% porosity, with variable natural fractures due to structural flexures. These tight gas reservoirs are surrounded by thermally mature, overpressured, gas-charged carbonaceous shale source rocks within a regional basin-center gas system. A recent neutron-density log (marathon VCD #3) shows strong neutron-density crossover effects in the Frontier sandstones, indicating gas saturation.

Structure maps and cross sections based on well data and field reports from BLM files indicate a sharply folded, doubly plunging anticline located above a north-south trending, west-directed basement reverse fault. The displacement on the thrust appears to be sufficient to juxtapose Nugget sandstones in the hanging wall against overpressured, gas generating Mowry Shale source rocks in the footwall, thus charging the Nugget sandstone reservoir and basal Dakota fluvial channels. The anticlinal structure may be cut by several cross faults, creating separate reservoir compartments.

The problems encountered in Kinney #3 at the south end of the structure may be due to inadequate charge in a separate fault block. Water recoveries from the Frontier at Kinney #1 and Kinney #3 may be due to faulty cement bond and water leakage behind pipe, or may indicate complexities due to water movements along fault zones within the structure.

In 1995, the field operator, Celsius Energy (formerly Mountain Fuel Supply Company) formed an agreement with Marathon Oil Corporation to acquire 3-D seismic data across the Kinney, Canyon Creek and Trail area. Marathon has drilled two new infill wells at Kinney, based on the 3-D seismic data. Marathon Vermillion Creek Deep #1 was drilled into the Nugget Sandstone and was completed open hole, with casing set in the Morrison Formation. Initial production from the Nugget reservoir was 12,300 mcf/d with 25 bwpd.

Another well has been drilled by Marathon in early 1998 to extend production downdip on the north-plunging nose of the structure. Marathon Vermillion Creek Deep #3 was also completed in the Nugget, open hole without casing. This well tested only 665 mcf/day from the Nugget.

Several additional new locations have been proposed at Kinney as well as two locations to the west at Trail anticline.

Canyon Creek Field Description. Canyon Creek is a Laramide-age fault-fold anticlinal structure located above a west-vergent basement reverse fault on the east flank of the Rock Springs Uplift. The NE-SW trending basement reverse fault extends at least 12 miles under canyon Creek and Trail fields, with variable displacement. The anticlinal structure may be cut and compartmentalized by several cross faults.

Gas-prone black shales, carbonaceous shales and coal beds in the Cretaceous Mancos-Frontier-Mowry shale section are buried 12,000 to 15,000 ft deep in this region. Published %Ro data (Tyler et al, 1994) indicates $R_0 = 1.0\%$ at 10,000 ft and $R_0 = 2.0\%$ at 15,000 ft, indicating thermally mature conditions. These source rocks are in the gas window and have expelled gas into nearby sandstone reservoirs including the Blair (Airport) sandstones, Frontier Formation and Dakota Sandstone. Increases in drilling mud weights, gas kicks, blowouts, and DST pressure data indicate the top of a gas-charged overpressured zone at 10,000 to 11,000 ft depth in this area. The top of overpressure cuts across stratigraphy and is part of the larger basin-centered gas system in the Washakie Basin.

An early well was drilled to evaluate the Frontier Fm and Dakota Sandstones at Canyon Creek anticline (Stanolind Canyon Creek Unit #1, 3-12N-101W, TD 13,322', 1949). This well was located along the crest of the structure, probably by mapping surface geology and seismic data. High mud weights (14.7 - 15 ppg) were needed to maintain control of the well in the Frontier section below 12,000 feet. Gas shows were encountered in the Frontier sandstone below 12,685' and several cores were cut. The cores found poor to good porosity in quartzitic Frontier sandstones. Several thin coal beds were penetrated. Several cores were cut in the Mowry shale section. No formation tests were made of this interval.

The Dakota Sandstone was penetrated at 13,108' and several cores were cut. The cores contained "dry" sandstone with "some" porosity and dead oil stain. The core analyses show 3 to 11 % porosity and 0.01 to 1.64 md permeability in the upper Dakota Sandstones. A "sweet spot" with unusually good core porosity and permeability (14-19%, 0.22 to 3.34 md) was discovered in the basal Dakota chert pebble sandstone at 13,236-248', just above the Jurassic Morrison Formation. A gas kick occurred while drilling at 13,264'. Liner was set at 13,185 ft in the lower Dakota, and the basal Dakota sandstone channel was evaluated with an open hole test. The zone flowed gas to surface at

1,115 mcfg per day rate, without stimulation. A shut in pressure of 5800 psi was recorded after a 14 hour buildup. If this was a shut-in tubing pressure, it indicates a possible bottom hole reservoir pressure of 7720 psi at 13, 240' = 0.58 psi/ft (moderate overpressure). The well was suspended and eventually abandoned without additional testing of the Dakota zone. Cuttings samples (and probably core chips?) from this well were donated to the AMSTRAT collection and are now stored at the USGS Core Research Center, Inventory # CZ8167.

The Frontier, Dakota, Entrada and Nugget reservoirs were penetrated in 1964 by Mountain Fuel Supply Canyon Creek #17 (3-12N-101W). this well was drilled with gas down though the Entrada sandstone where a water flow was encountered and drilling mud was added to control the water flow. 5-1/2" liner was set at 13, 845 ft just above the Nugget Sandstone. Several cores were cut in the Nugget which apparently indicated a water-saturated or non-productive reservoir. The Nugget was plugged off without testing. The Canyon Creek structural cross section, based on the 1990 Madison structure map from BLM files, indicates insufficient displacement on the reverse fault to juxtapose Nugget against Cretaceous source rocks. The Nugget reservoir is apparently un-charged and wet at this location.

The basal Dakota sandstone channel which had flowed gas to surface at the Stanolind Unit #1 well was tested in the MFS #17 in 1964 along with a Morrison sandstone, by perforations through casing (13,155-170' and 13,330-345') and a sand-diesel oil frac job ("Vis-0-Frac"). After the frac job, the well flowed gas to surface at 396 mcfg per day. Traces of frac diesel oil and 1/4 barrels of water per hour, at surface flowing tubing pressure of 60 psi and csg pressure of 400 psi. The wellbore was plugged back after this low rate test in favor of better zones in the Mesaverde section uphole.

The sand and diesel oil frac technique was popular in the 1960's, but was later abandoned after formation damage studies discovered that the frac did more harm than good to most tight sandstone reservoirs. These fracs frequently created gas-oil emulsions which impaired production rates.

A deep wildcat well was drilled at Canyon Creek in 1990 (Exxon Canyon Creek Dome Unit #34, 9-12N-101W). This well penetrated the Nugget, Weber and Madison reservoirs, and evaluated the deep prospects, which were wet or non-productive. No cores or tests were made in the Frontier or Dakota reservoirs, although logs show high resistivity.

In 1995 Celsius Energy and Marathon formed an agreement for the acquisition of 3-D seismic data and drilling exploratory wells. Marathon has drilled two wells (VCD #3, VCD #1) at Kinney Field to test the Nugget. The Frontier and Dakota have been bypassed without coring or testing in these new wells. Marathon has proposed and staked two locations at Trail anticline.

The Frontier and Dakota sandstones at Canyon Creek and Trail Fields have been penetrated by only three deep wells. The sandstones are adjacent to overpressured, gas-charged shales folded by a twelve-mile long anticlinal structure within a basin-centered gas system. Folding along the crest of the Canyon Creek anticline as well as possible cross faults may have created zones with enhanced natural fracturing, however no fracture finder logs have been run in the previous wells. The Exxon #34 well logs show strong neutron-density crossover effects in both the Frontier and Dakota sandstones, and the resistivity log shows zones with high deep resistivity. Cores from the Stanolind well contained unusually good porosity and permeability in a 'sweet spot' within the basal Dakota

sandstone. This zone flowed gas to surface at low rates after a sand-diesel oil frac job which may have caused formation and skin damage.

In general, the magnitude of displacement on basement reverse faults is critical. At Kinney Field, the Nugget was thrust over Mowry source rock and filled with gas down to a gas/water contact. At Canyon Creek, fault displacement was probably less, so Nugget is wet and unproductive. Gas shows and gas production is from basal Dakota chert pebble conglomerates with good porosity and may be due to faulting of this section up and over Mowry source rocks.

The concept of drilling wells in or near fault zones seen on 3-D seismic to find the best fracture systems in tight gas sand reservoirs has not yet been tried here--although there are rumors that MVKD #3 "fell off the front edge" of the structure and ended up near the reverse fault by accident.

Log Analysis of Frontier and Dakota Sandstones. As the Kinney and Canyon Creek Fields are Laramide-age anticlinal structures, which contain tight gas sandstone reservoirs in the Lower Cretaceous Frontier and Dakota Formations at depths of 12,800 to 15,000 feet, reservoir temperatures range from 230 to 300 degF. High drilling mud weights (14-15 ppg) and high measured reservoir pressures (0.58 - 0.71 psi/ft) indicate overpressured conditions.

Early wells at each field (1949, 1957) were logged with electrical logs and micrologs. Several Frontier and Dakota cores were collected. The core descriptions indicate quartzitic sandstones with generally low porosity, shale laminations and localized natural fracturing. Lenses with unusually high porosity (12 - 19 %) were found occasionally in chert conglomerate fluvial channels of the Dakota Fm along the crests of the structural highs.

Additional wells were drilled in the 1970's to test the Dakota and Nugget reservoirs at Canyon Creek and Kinney Fields. These wells were logged with DIL, Sonic and/or Density logs. Wexpro Kinney #6 (1980) has a dual induction log and a density-neutron log, and was selected for log analysis.

Two recent wells (Exxon #34 (1990) and Marathon VCD#3 (1997) have modern log suites with dual induction and/or high resolution induction logs and neutron-litho-density logs. These logs are available on Dwigths/PI microfiche. These two wells with modern logs were selected for log analysis.

The Simandoux equation was selected for calculating water saturations in shaly sandstones. The Simandoux equation was used according to procedures outlined in Asquith, Log Evaluation of Shaly Sandstones: A Practical Guide, AAPG CECNS #31.

Vclay calculations and corrections to porosity logs were made according to procedures using gamma ray logs outlined in Asquith and Gibson, 1982. The Vclay calculations for the Frontier and Dakota ranged from 10 to 14%. These may be somewhat low, due to the subjective selection of the GRfm value in the Vclay process. There are no special core analyses available in the public data set to calibrate clay contents or M and N values in this area.

Strong neutron-density crossover effects were observed in several Frontier and Dakota zones, indicating gas effects on the neutron logs. Sonic porosities are also affected by overpressured gas and clay content, and were observed to be unrealistically optimistic compared to density porosity readings.

Density porosity measurements were preferred over neutron or sonic porosity readings. Corrected porosity values ranged from 8 to 17 % for the Frontier and Dakota sandstones. The highest porosity (17%) is in a basal Dakota chert pebble conglomerate zone which produced gas. Core data substantiates this high porosity 'sweet spot'.

Resistivity readings were made from the Deep Resistivity logging tool. R_w data for the Dakota and Frontier reservoirs at Kinney Field was found in a Wyoming Geological Association guidebook: Frontier $R_w = 0.37$ at 68F; Dakota $R_w = 0.45$ at 68F. These R_w values were converted to R_w at Fm temperature using a conversion chart (Merkel, AAPG CECNS #14, Figure 7). Regional R_w data for the Frontier and Dakota are available from the 1985 Rocky Mountain Formation Water Resistivities catalogue (Denver Well Logging Society), but there are no data listed near Kinney or Canyon Creek.

Accurate R_w values are extremely important in the Simandoux equation, but the available R_w data for Kinney field is limited, and there are no R_w data available for the Frontier and Dakota sandstones at Canyon Creek Field. R_w values are the least constrained inputs to the Simandoux equation. Errors in saturation calculations are probably due to incorrect R_w inputs.

Simandoux water saturations ranged from 8 to 59 %, with most values between 26 to 45 %. These values are generally reasonable for low porosity, tight gas sandstones in high temperature, thermally mature and overpressured conditions. Water saturations calculated by the Archie equation are also listed for comparison, however these are not "Archie rocks".

Based on examination of well logs from the Kinney and Canyon Creek fields, the reservoir characteristics for these two field areas are shown in Table 1.

Table 1

Well	Yr	Fmn	Field	Depth (ft.)	Vclay	Dporcor	Rdeep	Rw at BHT	Rshale	Archie Sw	Simandoux Equation Sw	Comments
Exxon 34	90	Fr	CC	12843	0.11	0.106	140	0.1	15	0.26	0.26	
Exxon 34	90	Fr	CC	12888	0.11	0.12	85	0.1	15	0.31	0.29	
Exxon 34	90	Dak	CC	13320	0.1	0.14	220	0.12	3	0.17	0.39	
Exxon 34	90	Dak	CC	13249	0.1	0.08	150	0.12	3	0.35	0.15	
Exxon 34	90	Dak	CC	13236	0.1	0.083	300	0.12	3	0.24	0.08	Very high Rdeep, Sw is too low?
Mar. VCD #3	97	Fr	K	13506	0.13	0.078	40	0.1	7	0.64	0.45	
Mar. VCD #3	97	Fr	K	13510	0.13	0.065	70	0.1	7	0.58	0.59	WGA Report Rw = .37 at 68F
Mar. VKD #3	97	Dak	K	13942	0.14	0.087	55	0.1	3	0.49	0.26	WGA Report Rw = .45 at 68F
Mar. VKD #3	97	Dak	K	14173	0.12	0.86	40	0.1	7	0.58	0.44	
WXPR K #6	80	Dak	K	14200	0.1	0.17	45	0.1	4	0.27	0.21	MFS memo, Avg Sw = 0.30

Task 3. Initiation Analysis of the Deep Green River Partition with Respect to the Stratos Well and Assessment of the Resource in the Partition.

Examination of the Green River Deep partition which contains the Stratos Federal No. 1 well was also initiated late in the quarter (results will be reported with the next quarters' report). The Stratos well was part of a project to evaluate the natural gas potential of the Upper Cretaceous Frontier Formation in the central portion of the Green River Basin below a depth of 15,000 feet. Drilled to offset two deep Frontier wells (No. 31-1 Blue Rim Federal and No. 1-30 Blue Rim Federal), the Stratos well failed to meet expectations. Examination of the Green River Deep partition will address the Stratos well results.

Examination of the Green River Deep partition will be followed by the Rock Springs Crest and successive partitions. Future work will also entail determination of recoverable resource in the Vermilion partition, examination of representative fields in the balance of the partitions on the GGRB, and an assessment of the resources contained in each partition.

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Figures

- Figure 1. GGRB Partition Map
- Figure 2. GGRB Frontier Fm Penetrations
- Figure 3. GGRB Mesa Verde Fm Penetrations
- Figure 4. Frontier Fm Structure map-Kinney-Canyon Creek Area
- Figure 5. Frontier Fm Structure map-Kinney-Canyon Creek Fields
- Figure 6. Type Log - Kinney Field
- Figure 7. Type Log - Canyon Creek Field
- Figure 8. Kinney Field - Top Frontier Structure Map
- Figure 9. Kinney Field - Top Dakota Structure Map
- Figure 10. Canyon Creek Field - Top Frontier Structure Map
- Figure 11. Canyon Creek Field - Top Dakota Structure Map

Appendix 1

Presentation to be made to the Deep Gas Forum

The Exploration Process for Deep, Naturally-Fractured Gas Reservoirs

*Integrating Multiple Data and Analyses
for Successful Exploration Programs*

David J. Campagna, Ph.D.
Advanced Resources International, Inc.

GRI's Deep Gas Forum Series #2

15-16 October 1998 Denver, Colorado

Outline

This presentation will cover the following topics:

- **Exploration Program & Tools for Deep Gas**
- **Exploration Case Study**
 - **Regional Work and Play Definition**
 - **Prospect Delineation**
- **Conclusions & Discussion**

Cost of Exploration Tools

• Geologic database	In-house costs
• Potential Field Surveys	
– Existing survey of 200 townships costs approx. \$60,000 or	~\$8/mile ²
– New survey of 200 townships costs approx. \$140,000 or	~\$20/mile ²
• Seismic Surveys	
– 2-D surveys may cost approx.	~\$1,000/mile
– 3-D surveys may cost approx.	~\$30,000/mile ²
• Exploration Well Costs	
– Drilling to 15,000+'	~\$3,000,000+
– Coring approximately 100'	~\$25,000 +rig time
– Logging (full suite)	~\$25,000

Project Evolution for Naturally-Fractured Deep Gas Exploration

Regional High-Grading

Data Costs ~\$200,000

Prospect Delineation

Data Costs ~\$1,000,000

Prospect Test

Costs ~\$5,000,000

Gas Production and Net Pay

Net pay and hydraulic fracs in the Frontier shows little correlation with EUR. This is not to imply that net pay and hydraulic fracs are unimportant; rather, this shows that thick pay and fracs are not sufficient to make an otherwise geologically-poor area productive.

Correlation of Net Sand and EUR

Pounds of Sand vs. EUR

Gas Production and Natural Fractures

Permeability is the most important production controlling mechanism in the Frontier Fm, with the presence (or absence) of natural fractures controlling permeability in this formation.

Permeability vs. EUR

Tight Wells - Permeability vs. EUR

Basin Basement Trends

Gravity data reveal the structural complexity within the Greater Green River Basin. Three major east-trending basement arches are clearly visible: the well-known Wamsutter and Cherokee arches in the east; and Sandy Bend arch in the west that separates the Green River sub-basin from the Hoback sub-basin.

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Basement Trends

Aeromagnetic data also reveal significant basement-related structural trends. For example, in the Hoback sub-basin the aeromag reveals NW and NE trending basement structure.

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High-Resolution Aeromagnetic and Imagery Data

- High-resolution aeromagnetic and imagery data covering 19 townships were examined along northern margin of the Washakie basin along the Wamsutter arch.
- The goals in the analysis of these data were to provide relevant information on:
 - regional basement-related structural trends
 - local patterns of surface fractures
 - structural partitions and any control over fracture trends.

2. Prospect Delineation

The prospect delineation process for naturally-fractured reservoirs involves predicting the location intensity and orientation of the fractures. The steps necessary for a prospect generation in the northern Washakie Basin include:

- A. Characterize Natural Fractures in the Frontier Fm.
 - Examine Govt. Union #4 core.
- B. Fault Mapping using 3-D Seismic Data
 - Post-stack depth-conversion of selected lines.
 - Map and develop structure and isopach maps.
 - Map fault geometry for input to stress model.
- C. Prediction of Fault-Related Natural Fractures
 - Assemble fault geometry and displacements.
 - Determine area(s) of enhanced natural fracturing based on stress calculations.

2A. 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

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).

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.

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3-D Seismic: 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

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3-D Seismic: Fault Mapping

Three profile views of the fault system from south to north show the characteristics of the thrust fault, intersection with strike-slip fault, and where the faults diverge in the north.

Subsea structure of the Madison Fm

3-D Seismic: Fault Mapping

Profile view of Table Rock thrust fault near Govt. Union #4.

Thrust fault is steeply dipping and an asymmetrical fold is well developed on the hanging wall.

3-D Seismic: Fault Mapping

- 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.

2C. 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).

To capture effects of folding, one would need to include other methods such as a Finite Element Model.

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.

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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.

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Conclusions

- Once a resource has been established the next critical exploration step is the search for permeability; particularly in deep basin-centered gas reservoirs.
- Detailed natural fracture characterization and fault mapping will aid in delineating prospective targets.
- A series of exploration methods and tools are available for economically predicting natural fracture permeability as demonstrated by case studies in the Greater Green River and Piceance Basins.

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