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Final

**INCREASED OIL PRODUCTION AND RESERVES
UTILIZING SECONDARY/TERTIARY RECOVERY
TECHNIQUES ON SMALL RESERVOIRS
IN THE PARADOX BASIN, UTAH**
(Contract No. DE-FC22-95BC14988)

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TECHNICAL PROGRESS REPORT

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Utah Geological Survey
Salt Lake City, Utah 84114
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Contract Date: February 9, 1995
Anticipated Completion Date: February 8, 2000
Government Award (fiscal year): \$448,800
Program Manager: Thomas C. Chidsey, Jr.
Principal Investigator: M. Lee Allison

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PRELIMINARY
Subject to Review

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Utah Geological Survey (UGS), Salt Lake City, Utah 84114-6100

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Objectives

The primary objective of this project is to enhance domestic petroleum production by demonstration and technology transfer of an advanced oil recovery technology in the Paradox basin, southeastern Utah. If this project can demonstrate technical and economic feasibility, the technique can be applied to approximately 100 additional small fields in the Paradox basin alone, and result in increased recovery of 150 to 200 million barrels of oil. This project is designed to characterize five shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation and choose the best candidate for a pilot demonstration project for either a waterflood or carbon dioxide- (CO₂-) flood project. The field demonstration, monitoring of field performance, and associated validation activities will take place in the Paradox basin within the Navajo Nation. The results of this project will be transferred to industry and other researchers through a petroleum extension service, creation of digital databases for distribution, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and publication in newsletters and various technical or trade journals.

Summary of Technical Progress

Four activities continued this quarter as part of the geological and reservoir characterization of productive carbonate buildups in the Paradox basin: (1) interpretation of outcrop analogues, (2) reservoir mapping, (3) reservoir engineering analysis of the five project fields, and (4) technology transfer.

Interpretation of Outcrop Analogues

Outcrops of the Paradox Formation evaluated in the Wild Horse Canyon area along the San Juan River of southeastern Utah provide small-scale analogues of reservoir heterogeneity, flow barriers and baffles, depositional facies, and geometry. These characteristics can be used in reservoir-simulation models for secondary/tertiary recovery of oil from small fields in the basin.

Morphologically, algal buildups within the Ismay zone of the Paradox Formation consist of large, northwest-trending algal banks separated by interbank troughs or channels. Smaller, secondary algal mounds and intermounds define the upper surfaces of the algal banks. Cyclic sedimentation is recorded by four dominant facies recognized in a single, shoaling-upward sequence: (1) substrate carbonate, (2) phylloid algal, (3) intermound, and (4) skeletal capping. An outcrop in the Wild Horse Canyon area displaying these and additional facies was selected for detailed study.

The Wild Horse Canyon study site is interpreted as consisting of three principal features: (1) a phylloid-algal mound with grainstone buildups deposited at or near sea level, (2) a 'reef wall' that formed in a higher energy, more marginal setting than the mound, and (3) a carbonate detrital wedge and fan consisting of shelf debris (Fig. 1).¹ This interpretation is not only based on observations made at the outcrop, but also incorporates subsurface core data which are documented and discussed in Chidsey and others.²

Bafflestone and *Chaetetes*- and rugose-coral-bearing grainstone and packstone textures observed in the northern part of the Wild Horse Canyon complex represent the main phylloid-algal mound. A texturally and compositionally similar algal buildup constitutes the primary reservoir facies in oil and gas fields to the east of the study site. A flooding surface recognized on top of the buildup in outcrop and probable low-permeability lithotypes (packstone and cementstone) within the buildup might act as barriers or baffles to fluid flow in the subsurface. The Wild Horse Canyon outcrop appears to be only a portion of a larger algal-bank complex, or one of a series observed in the San Juan Canyon. Although not documented at this outcrop locality, observations from core in similar areas in the subsurface suggest an interior-lagoon and other associated facies likely formed west of the study area as part of this complex.² Hypothetical facies relationships are illustrated in the schematic block diagram (Fig. 1).

The rudstone, cementstone, and lumpstone depositional textures represent deposits which were part of, or near, what might be interpreted as a 'reef wall' (Fig. 1). The presence of internal sediments in these rocks indicates an influx of mud during storms or mud routinely distributed by stronger currents. The reef wall records deposition and intense sea-floor cementation as a result of reflux of large pore volumes of water through sediments occupying a high-energy marginal setting between shallow-shelf and deeper, open-marine conditions. The reef wall may have served as a barrier behind which algal buildups could develop and thrive in a more protected setting that facilitated preservation of primary shelter porosity. The presence of reef-wall facies in a well core

Figure 1. Block diagram displaying depositional interpretation of the Wild Horse Canyon mound complex and associated features. This interpretation is a composite of inferences made from outcrop and subsurface data.¹

might serve as a proximity indicator for a more prospective drilling target. Examples of this relationship have been observed in the Blue Hogan and Brown Hogan fields, southwest of the Greater Aneth field.²

An intermound trough in the center of the mound could represent a tidal channel flowing across the reef wall (Fig. 1). Material shed from the mound and reef wall and subsequently carried through the tidal channel might have been deposited as a detrital wedge or fan on open-marine carbonate muds. These features are recorded by the grainstone and transported material observed in outcrop on the east side of the complex. Coralline-algal buildups may have also developed near the carbonate detrital fan but were not observed at this locality in the canyon. Reservoir-quality porosity may have developed in troughs, detrital wedges, and fans identified from core and facies mapping. If these types of deposits are in communication with mound-reservoir facies in the subsurface, they could serve as conduits facilitating sweep efficiency in secondary/tertiary recovery projects. However, the relatively small sizes and the abundance of intermound troughs over short distances, as observed along the river, suggests caution should be used when correlating these facies between development wells. Facies that appear correlative and connected from one well to another may actually be separated by low-permeability facies which inhibit flow and decrease production potential.

Reservoir Mapping

Structure contour maps on the top of the Desert Creek zone of the Paradox Formation and gross Desert Creek interval isopach maps were constructed for the Anasazi, Blue Hogan, Heron North, Mule, and Runway project fields, San Juan County, Utah.³⁻⁷ These maps were combined to show carbonate buildup trends, define limits of field potential, and indicate possible combination structural and stratigraphic traps (Fig. 2). Well names and total depths are given for project field wells. The maps indicate Desert Creek completions, completion attempts, and drill-stem tests and display the Desert Creek subsea top and gross thickness for each well. These maps incorporated correlations from all geophysical well logs in the areas, and regional Chimney Rock shale structure maps and gross Desert Creek isopach maps generated from closely spaced seismic lines.

Reservoir Engineering Analysis of the Five Project Fields

Basic reservoir parameters for the Anasazi, Blue Hogan, Heron North, Mule, and Runway fields were compiled from the following sources: (1) geophysical well logs, (2) core analyses, (3) compressibility tests on carbonates from the Anasazi Nos. 1 and 6H-1 wells, (4) pressure-volume-temperature tests, (5) oil and gas analyses, (6) reservoir mapping, and (7) monthly production reports.⁸ The results are summarized on Tables 1-3. Production histories were also plotted for each field. These plots include monthly oil, gas, and water production, and number of producing wells (Fig. 3).

The information and plots compiled during this quarter have been merged with geological characterization data and incorporated into reservoir statistical models and simulations. Utilizing the results, sweep efficiencies for various secondary/tertiary recovery methods and the ultimate enhanced recovery will be estimated for all five fields.

Figure 2. Combined Desert Creek zone structure contour and gross interval isopach map, Runway field, San Juan County, Utah, Navajo Nation.⁷ Hachured lines separate carbonate depositional facies.

TABLE 1

Petrophysical Properties and Pressure Data for Project Fields

Field	Average Porosity (%)	Average Permeability (md)	Pore Volume Compressibility ($C_p \times 10^{-4}$, psi)		Reservoir Pressure		Water Saturation (%)	Initial Gas-Oil Ratio (scf/STB)	Initial Formation Volume Factor (reservoir bbls/STB)	Bubble Point Pressure (psig)	Type of Drive
			Limestone	Dolomite	Initial (psig)	Present (psi)					
Anasazi	14.1	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	1,945	200-300	15	364:1	1.199	1,023	Gas Expansion
Blue Hogan	9.1	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	1,800	200-300	15	487:1	1.260	1,590	Gas Expansion
Heron North	15	17.7	ND	ND	1,934	200-300	15	644:1	1.328	1,922	Gas Expansion
Mule	13	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	2,050	200-300	15	478:1	1.240	1,478	Gas Expansion
Runway	11.9	17.3	ND	ND	2,162	200-300	15	967:1	1.511	2,141	Gas Expansion

ND = No data

TABLE 2

Cumulative Production and Estimated Primary Recovery

Field	Carbonate-Buildup Facies Type	Spacing (acres)	Productive Area (acres)	Net Pay (ft)	Cumulative Production			Approx. Recovery Factor (%)	Estimated Primary Recovery	
					Oil (bbls)	Gas (MCF)	Water (bbls)		Oil (bbls)	Gas (BCF)
Anasazi	Phylloid Algal	80	165	46	1,692,117	1,339,281	25,922	20	2,069,392	1.89
Blue Hogan	Phylloid Algal	80	89	82	286,161	262,620	1,699	20	645,000	0.968
Heron North	Platform-Margin Calcarenite	40	110	60	202,776	316,289	25,124	20	990,000	2.65
Mule	Phylloid Algal	80	48	47	352,919	212,794	19,408	20	430,603	0.288
Runway	Phylloid Algal/Bryozoan	40	193	50	760,726	2,344,321	3,420	20	720,000	2.83

*Utah Division of Oil, Gas and Mining Monthly Production Report, May 1996

Runway field includes commingled Desert Creek and Ismay zones

ND = No data

Table 3**Oil, Gas, and Water Properties**

Field	Bottom-hole Temperature (°F)	Resistivity of Water (ohm-m @ BHT)	Oil Gravity (°API)	Oil Viscosity (cP @ initial reservoir conditions)	Gas Heating Value (BTU/ft³)	Gas Specific Gravity (decimal fraction)
Anasazi	138° @ 5,777'	0.035	41	0.951	1,400.3	0.8080
Blue Hogan	128° @ 5,613'	0.035	40.6	0.811	1,497.0	0.8992
Heron North	126° @ 5,752'	0.035	44.0	0.475	1,321.0	0.8335
Mule	128° @ 5,804'	0.035	44.0	ND	1,539.0	0.8890
Runway	126° @ 6,203'	0.070	40.5	0.314	1,356.5	0.7790

ND = No Data

Figure 3. Annual production graph for the Anasazi field, San Juan County, Utah, Navajo Nation.

Technology Transfer

Project material was displayed at the Utah Geological Survey (UGS) booth during the American Association of Petroleum Geologists (AAPG) Rocky Mountain Section meeting held in Billings, Mont., July 28-31, 1996. A paper was presented describing the outcrop reservoir analogues along the San Juan River.⁹

The UGS co-sponsored a symposium entitled the *Geology and Resources of the Paradox Basin* held in Durango, Colo., September 20-21, 1996. Other co-sponsors were the U.S. Bureau of Indian Affairs, Utah Geological Association, U.S. Geological Survey, Colorado Geological Survey, Four Corners Geological Society, Fort Lewis College, Ute Mountain Ute Indian Tribe, and U.S. Department of Energy. A UGS workshop presenting the results of phase 1 (budget period 1) of the Paradox basin project included the following poster displays: (1) project field summaries, (2) regional facies belts and analysis, (3) outcrop studies, (4) statistical models and reservoir simulations, and (5) technology transfer. The workshop also included a computer demonstration of the UGS-developed project database showing production data, petrophysical analysis, core descriptions, formation tops, completion results, and other information. A representative conventional core from the Anasazi No. 1 well was displayed for examination by the 120 participants. The UGS and its industry partners published the results of reservoir characterization and outcrop work in the symposium guidebook.^{1,2}

A field trip through the Paradox basin with 50 participants was also conducted on September 17-19 as part of the symposium. Project team members made presentations during visits to outcrops in Wild Horse Canyon along the San Juan River and the production facilities at the Mule field.¹⁰

Field summaries for the five project fields were also published in the second edition of the Utah Geological Association guidebook entitled *Oil and Gas Fields of Utah*.³⁻⁷ An abstract presenting the results of reservoir modeling of the Anasazi field was submitted for presentation at the 1997 AAPG Annual Convention in Dallas, Tex.

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Next Quarter Activities

Activities planned for the next quarter (October 1 through December 31, 1996) include:

1. Prepare catalog of the major Desert Creek facies in the region and field reservoirs.
2. Produce ideal diagrams of vertical sequence, based of core descriptions, vs. geophysical log response for each project field.
3. Continue data collection. Well information such as oil, gas, and water analyses; core descriptions; reservoir tops; and other data will be entered into the UGS database for manipulation.
4. Continue work on various reservoir maps for project fields. Complete seismic interpretations at Mule field.
5. Complete Mule area seismic processing and complete interpretation.
6. Prepare report deliverable describing sequence stratigraphic framework, depositional patterns, and reservoir flow units, barriers, and baffles based on published studies and UGS outcrop work.
7. Conduct first pass reserve assessment of CO₂ floods on project fields.
8. Evaluate geologic/seismic data for placement of Mule horizontal well design.
9. Evaluate Runway field potential for CO₂ flood simulation in addition to Anasazi field.
10. Generate new geostatistical descriptions of internal architecture and porosity/permeability distribution for reservoir flow simulation modeling. Write up report on geostatistical modeling.
11. Finalize plotting of mechanistic one-dimensional (i.e. slim tube) simulation runs to define the nature of CO₂ displacement and compare to ternary phase plots developed from multiple contract runs using phase behavior prediction software.
12. Finalize full field simulation runs for history matching of field production performance and initiate prediction phase simulation work.
13. Conduct the following technology transfer activities: (a) present a project overview at the Utah Indian Cooperative Council/Utah Tribal Leaders meeting, Goshute Indian Reservation, Ibapah, Utah, October 11, 1996, (b) present a lecture on reservoir heterogeneity and outcrop analogues to the Department of Geology, Brigham Young University, Provo, Utah,

November 21, 1996, and (c) submit an abstract to the AAPG for presenting the geology and reservoir characteristics of the Heron North field at the Rocky Mountain Section meeting in Denver, Colo., August 1997.