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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)

TECHNICAL PROGRESS REPORT

Submitted by

Utah Geological Survey
Salt Lake City, Utah 84109

January 15, 1996

UGS

Contract Date: February 9, 1995
Anticipated Completion Date: February 8, 2000
Government Award (fiscal year): $786,880
Program Manager: Thomas C. Chidsey, Jr.
Principal Investigator: M. Lee Allison

Contracting Officer's Representative

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Reporting Period: October 1 - December 31, 1995

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PRELIMINARY
Subject to Review

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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 (Fig. 1) in the Pennsylvanian (Desmoinesian) Paradox Formation and choose the best candidate for a pilot demonstration project for either a waterflood or carbon dioxide-(CO_2-)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

Five activities continued this quarter as part of the geological and reservoir characterization of carbonate mound buildups in the Paradox basin: (1) regional facies evaluation, (2) evaluation of outcrop analogues, (3) field-scale geologic analysis, (4) reservoir analysis, and (5) technology transfer.

Regional Facies Evaluation

Establishment of the general facies belts and stratigraphic patterns within the shallow-shelf carbonate Desert Creek zone of the Paradox Formation for the southern Paradox basin is critical to: (1) understanding reservoir heterogeneity and capacity of the five fields being evaluated for the pilot demonstration and (2) exploring areas in the basin that have the greatest petroleum potential. During this quarter, generalized regional facies belts for the Desert Creek zone (Fig. 1) were mapped utilizing conventional cores (more than 30), rotary sidewall cores, cuttings descriptions, and geophysical log interpretations. Various facies within these regional facies belts are being described in a catalog which includes photographs of representative slabbed conventional core.

Three generalized regional facies belts are identified (Fig. 1): (1) open marine, (2) shallow-shelf and shelf-margin, and (3) intra-shelf, salinity-restricted facies. The open-marine facies belt includes open-marine mounds (typically crinoid-rich buildups), open-marine crinoidal- and brachiopod-bearing carbonate muds, euxinic black shales, and detrital fans. Open-marine facies were deposited at water depths between 90 and 120 ft.

The shallow-shelf and shelf-margin facies belt includes shallow-shelf mounds (phylloid algal, coralline algal, bryozoan and marine-cemented buildups), calcarenite (beach, dune, and stabilized grain flats), and platform interior carbonate muds and sands. These facies were deposited at water depths between 0 and 40 ft. Karst characteristics are occasionally present over mounds. Tempestites (burrows filled with coarse sand as a result of storm pumping) are found in some carbonate muds and sands.

The intra-shelf, salinity-restricted facies belt includes platform-interior evaporites, dolomitized tidal-flat muds, bioclastic lagoonal muds, tidal-channel carbonate sands and stromatolites, and euxinic dolomites. These facies were deposited at water depths between 20 and 45 ft. Euxinic dolomites often display karst characteristics.

Mounds, tidal channel carbonate sands, and other features often appear promising on seismic records. However, if these carbonate buildups are located within the open-marine and intra-shelf, salinity-restricted facies belts, the reservoir quality is typically poor. Porosity and permeability development is limited or, if present, plugged with anhydrite in these respective facies belts. Mounds and calcarenite in the shallow-shelf and shelf-margin facies belt can have excellent reservoir properties; all five project fields are located within this facies belt.

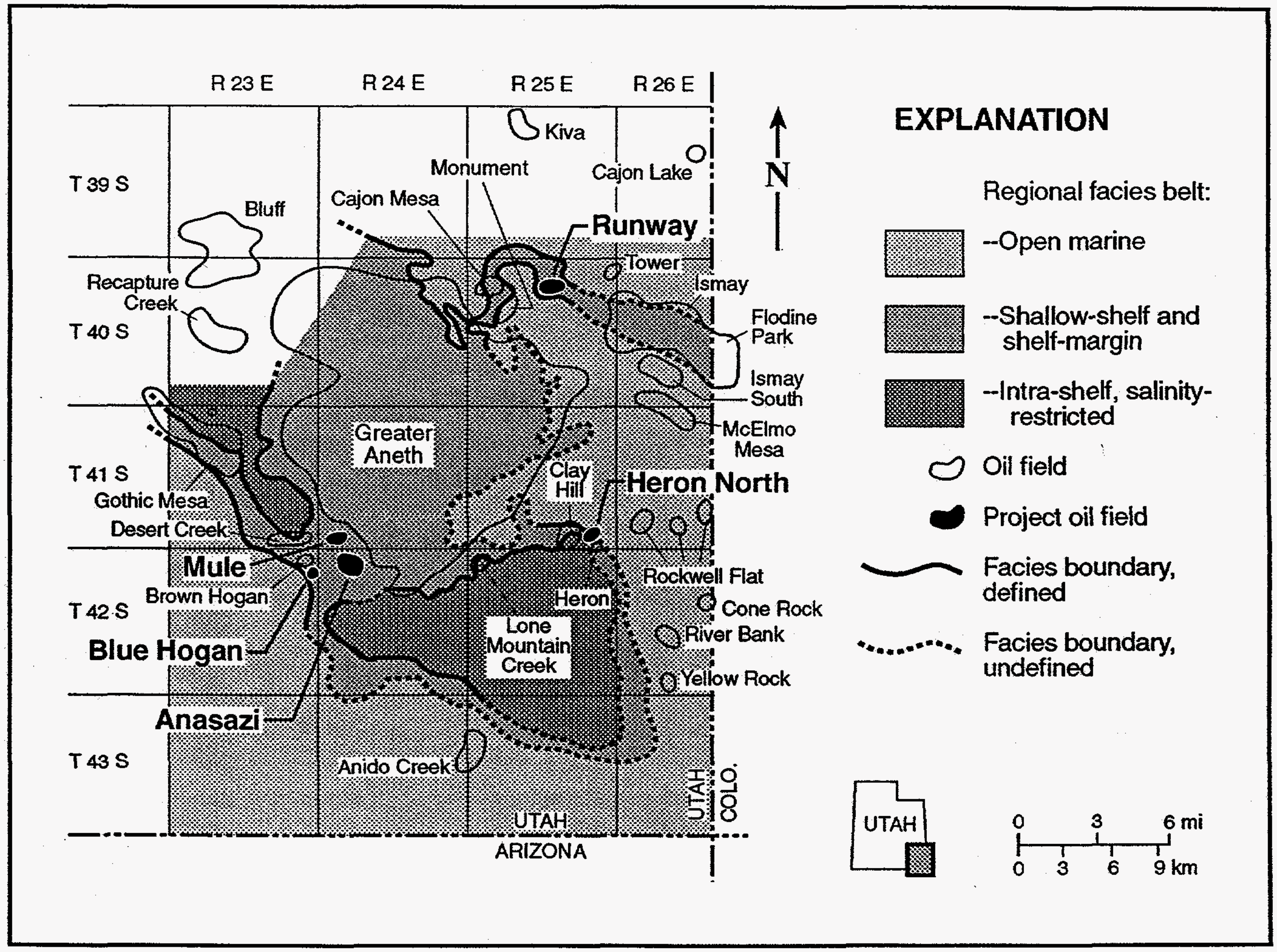

Figure 1. Generalized regional facies belts for Desert Creek zone, Pennsylvanian Paradox Formation, southeastern San Juan County, Utah.

Evaluation of Outcrop Analogues

Outcrops of the Paradox Formation Ismay zone in the Wild Horse Canyon area along the San Juan River of southeastern Utah (Fig. 2), provide small-scale analogues of reservoir heterogeneity, flow barriers and baffles, lithofacies, and geometry. These characteristics can be used in reservoir simulation models for secondary/tertiary recovery of oil from small fields in the basin. Quantitative data was gathered from several selected outcrops. These data included: (1) the sizes, shapes, orientations, and stratigraphic positions of units within the mounds, (2) facies relationships, and (3) gross reservoir properties of the key mound storage units, flow units, and permeability barriers. The outcrop work involved: (1) photographing mounds to create interpretive photomosaics, (2) measuring and describing stratigraphic sections, (3) mapping the areal extent of the mounds and associated facies, and (4) collecting representative samples for thin-section analysis. Major elements of reservoir architecture, lateral variations in reservoir properties, and definition of an internal "representative elementary volume" for modeling fluid storage and flow in each key facies were particularly emphasized.

From this work, it was determined that exposures of the Ismay zone (Fig. 3A) display lateral facies changes from phylloid algal mounds to off-mound detrital wedges or fans bounded at the top by a flooding surface. The phylloid mounds are composed of bafflestone (Fig. 3B), skeletal grainstone, packstone, and cementstone. Algal plates, brachiopods, bryozoans, and rugose corals are commonly found in the phylloid mounds. The mound wall is composed of rudstone, lumpstone, and cementstone. The detrital fan consists of transported algal material, grainstone, and mudstone with open-marine fossils. Within the mound complex is an inter-mound trough tentatively interpreted to be a tidal channel. The geometry and composition of the rocks in the trough significantly add to the overall heterogeneity of the mound.

The results of these field investigations have been incorporated into the geological constraints on facies distributions in the geostatistical models. Reservoir models are being developed for possible water- and carbon-dioxide floods of small Paradox basin fields to determine the most effective secondary/tertiary recovery method. The models will include lithologic fabrics, flooding surfaces, and inter-mound troughs, based on the mound complex exposed at Wild Horse Canyon.

Field-Scale Geologic Analysis

A detailed interpretation of the time-stratigraphic facies relationships among the four wells in the Anasazi field, San Juan County, Utah (Fig. 1), was developed from conventional cores and geophysical logs as a basis for layering the geostatistical model, and for representing facies equivalents in the on-mound and peripheral portions of the reservoir. Reservoir properties (porosity and permeability) were determined from log and core analysis. Petrophysical analysis for lithology, porosity, and initial water saturation were carried out on the Anasazi wells, plus four additional peripheral wells for which complete suites of modern geophysical logs are available. Crossplots of porosity and permeability data from core were generated for core-mound, peripheral-mound, and supra-mound facies, and a set of permeability predictors was determined (Fig. 4). Using a log porosity/core porosity transfer function, these predictors were used to estimate horizontal and vertical permeability over intervals in the four reservoir wells where lab data are lacking. The same predictions also will be used in conjunction with a suitable spatial scaling function to generate estimates of block-effective permeability for the geostatistical

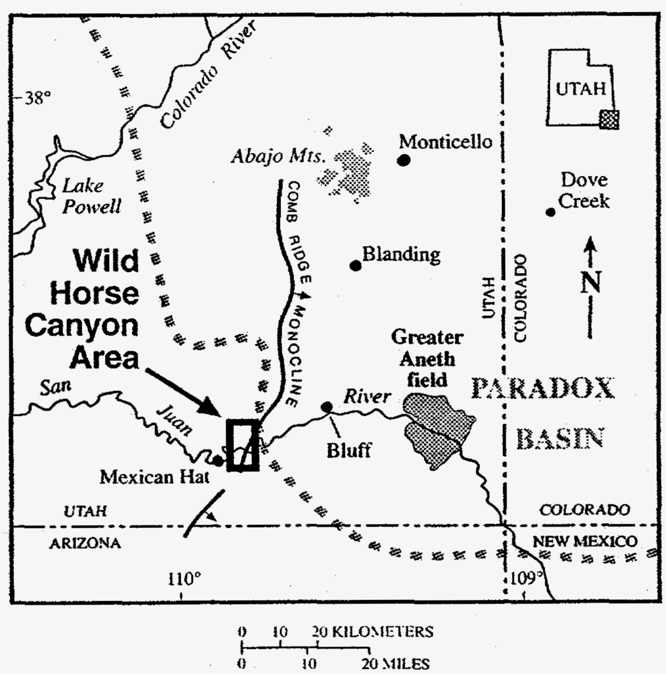

Figure 2. Location of Paradox Formation outcrops in the Wild Horse Canyon area along the San Juan River, southeastern Utah.

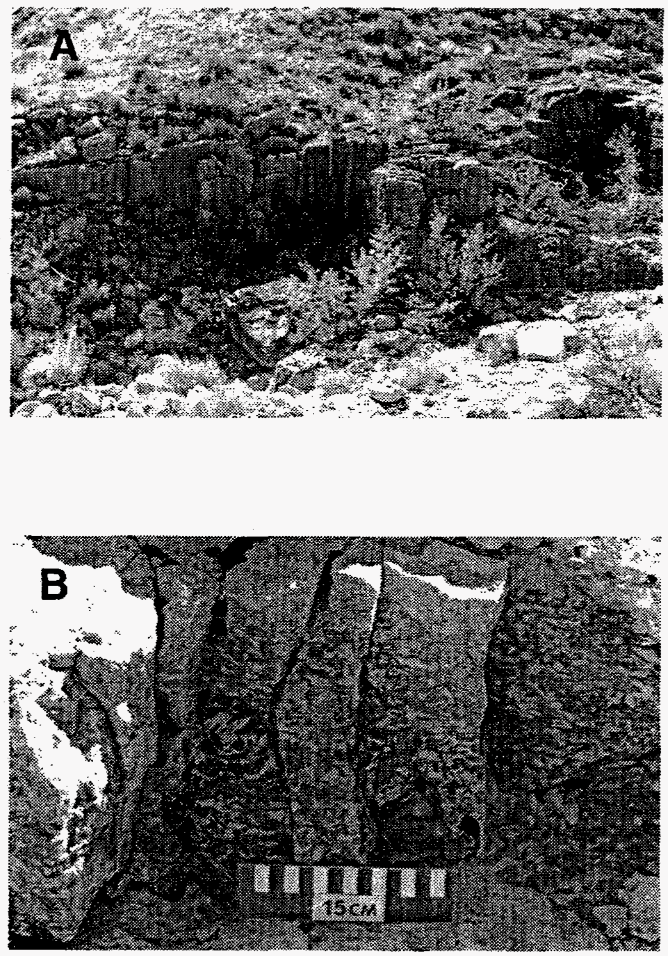

Figure 3. Outcrops in the Ismay zone of the Paradox Formation, Wild Horse Canyon near the San Juan River, southeastern Utah. (A) Typical phylloid mound composed of algal bafflestone, skeletal grainstone, and packstone. A flooding surface is present at the top of the mound. (B) Cement-rich algal bafflestone exposed in a phylloid mound. Original sheltered pore spaces were filled with mud; cement rinds are developed around algal plates.

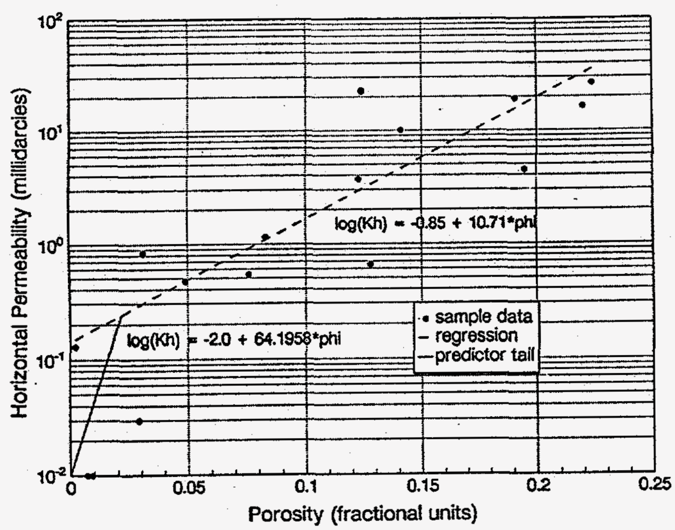

Figure 4. Porosity/permeability plot, upper dolomites, Anasazi No. 5L-3 well (SE1/4NE1/4 section 6, T. 42 S., R. 24 E.), in the Anasazi field, Navajo Nation, San Juan County, Utah.

reservoir models.

Based on the results of the core interpretations, analogue field studies, core analysis, and petrophysical investigations, sets of 20 and 30 equal-thickness layers were defined for the core-mound/peripheral-mound and the supra-mound sequences, respectively. These layers average about 2 ft thick in the four Anasazi wells, and conform closely to the minimum thicknesses of the principal reservoir storage and flow units. Reservoir thickness away from these wells was mapped from six two-dimensional seismic lines. This isolith map was gridded into 50 x 30 105-ft-square blocks for the initial geostatistical model (Fig. 5). In addition, the six seismic sections were visually examined for "reservoir quality" (porosity-ft), coded, and the results mapped over the reservoir (Fig. 6). This average reservoir quality map is designed as a constraining variable for the geostatistical models, in which a code of "10" corresponds to an average porosity-thickness of 18 phi-ft, and "0" to 10.5 phi-ft ($\pm$10%).

The initial characterization of conditional ("hard") data and constraining ("soft") data required for modeling the Anasazi reservoir is now completed, and generation of stochastic realizations commenced.

Reservoir Analysis

Three major experimental projects were completed during this quarter in preparation for compositional simulation studies. These include detailed relative permeability, capillary pressure, and wettability measurements on the dolomite facies, and reservoir fluid compositional characterization, carbon dioxide (CO_2) swelling tests, and rock compressibility measurements on both limestone and dolomite samples from the Anasazi Nos. 5L-3 and 6H-1 wells.

Relative permeability work consisted of determining oil-brine and gas-oil capillary pressure employing ultra centrifuge technology. These tests were conducted at reservoir temperature (130° F). Ultra centrifuge was used to determine core-plug wettability and relative permeability values. Core plugs were prepared in three ways to determine the influence of core handling procedures and wettability. The three core preparation procedures consisted of: (1) core solvent cleaned but not aged, (2) use of preserved core directly from wellsite, and (3) core solvent cleaned and aged with Anasazi field crude oil at reservoir temperature.

These data indicate a mixed wetting condition typical of carbonate systems with a slightly stronger oil wetting tendency in the preserved core and nearly neutral wetting for the cleaned and unrestored core, with the restored core falling between the others. The dominant feature of the cores is the lack of trapping sites yielding very low residuals in both oil and brine phases. This feature overwhelms the slight differences in the wetting states of core preparation techniques and yields capillary pressure and relative permeability curves that are essentially the same from a reservoir fluid-flow calculation standpoint (Fig. 7).

The insensitivity of relative permeability to core preparation procedures provided the basis for conducting additional relative permeability measurements from previously unpreserved limestone core samples. Oil-brine and gas-oil relative permeability from the limestone facies are currently on-going.

Crude oil compositional measurements and CO_2 swelling tests were conducted on wellhead-gathered samples from the Anasazi No. 5L-3 well. Fluid sample preparation consisted of recombining separator oil and gas mixtures to the current producing gas-oil ratio of 1208 standard cubic ft/barrel. The recombined sample was equilibrated to a specific bubble point pressure of 2050 pounds per square inch absolute at a reservoir temperature of 130° F. Using

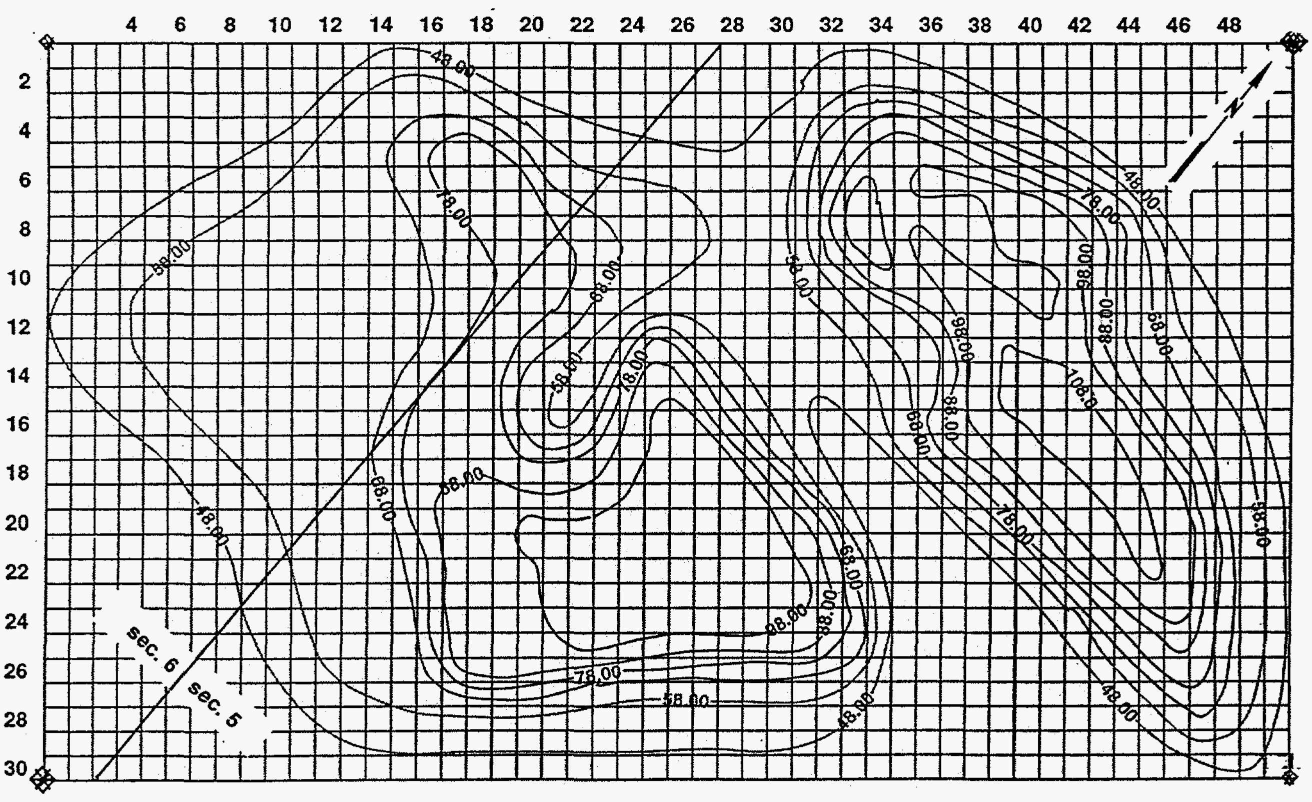

Figure 5. Simulator grid design and Desert Creek zone reservoir isolith, Anasazi field (sections 5 and 6, T. 42 S., R. 24 E., Salt Lake Base Line), San Juan County, Utah. Contour interval = 10 ft.

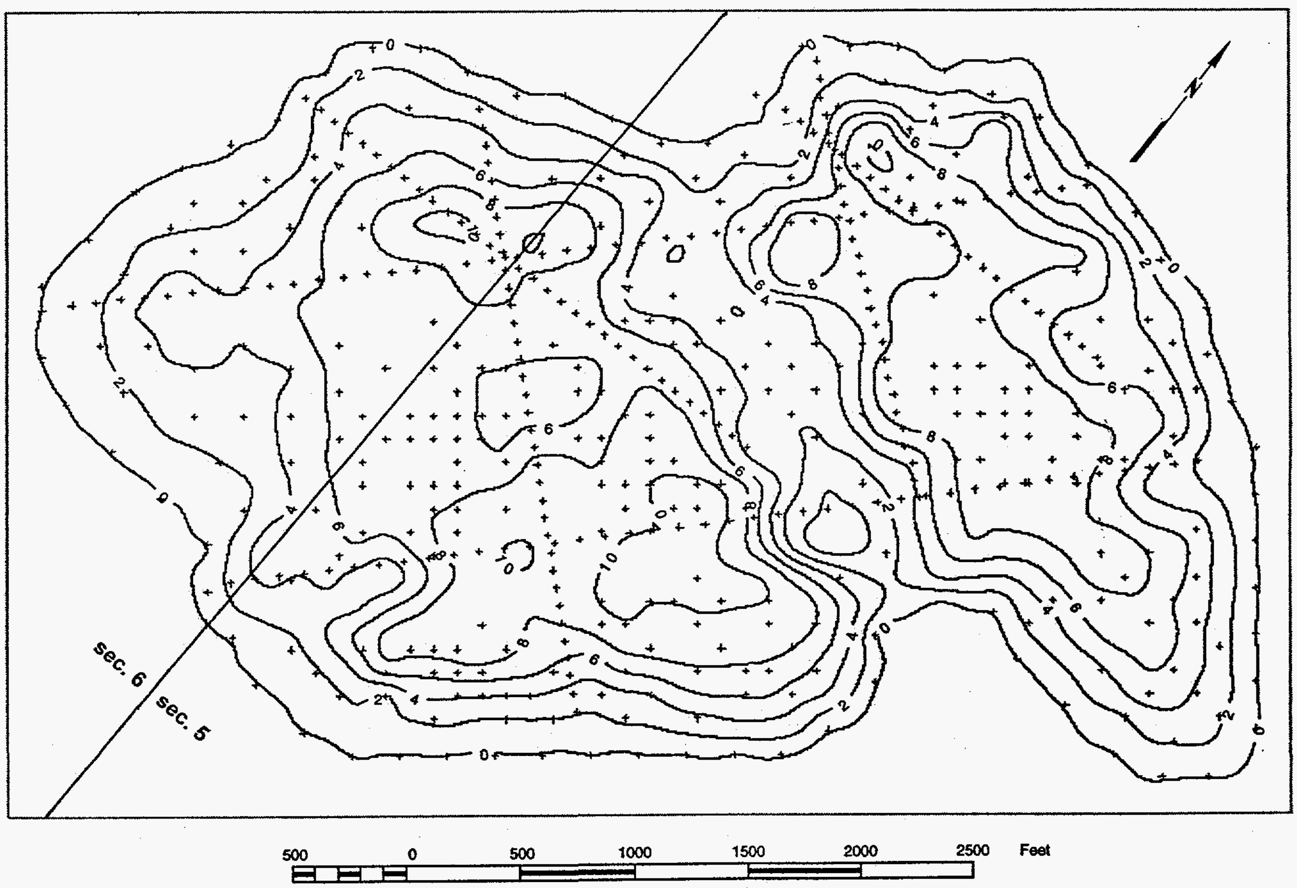

Figure 6. Map of seismic-coded indicator for average reservoir quality, Anasazi field (sections 5 and 6, T. 42 S., R. 24 E., Salt Lake Base Line), San Juan County, Utah. A code of "10" corresponds to an average porosity-thickness of 18 phi-ft, and "0" to 10.5 phi-ft ($\pm$10%).

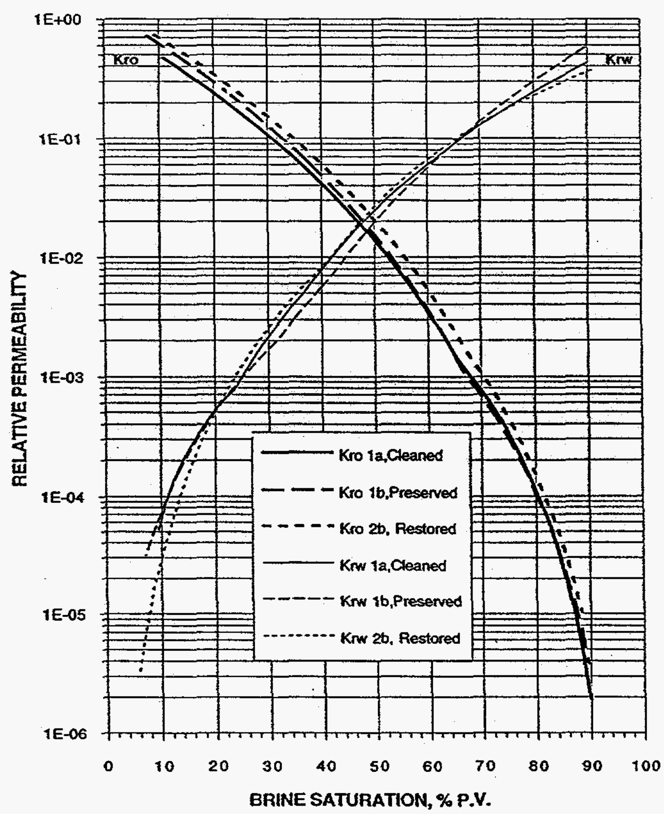

Figure 7. Oil-brine relative permeability curves, Anasazi No. 6H-1 well.

this fluid sample, CO_2 swelling tests at CO_2 concentrations of 20.0, 40.0, and 75.0 mole percent were conducted. Swelling factors range from 10 to 30% for the CO_2 concentrations used with oil viscosities reduced by a factor of two. The swelling data, fluid compositional analysis to carbon 30+, and original black oil pressure/volume/temperature experimental phase behavior data will be used to tune an equation of state that will be employed in the compositional simulation studies to be conducted on the Anasazi reservoir.

Rock compressibility measurements were performed on two core samples (one limestone sample from the Anasazi No. 1 well and a dolomite sample from the Anasazi No. 6H-1 well). Three types of compressibilities were measured: bulk compressibility, solid (grain) compressibility, and pore-volume compressibility. These tests were conducted using a servo-controlled triaxial testing apparatus which subjected the samples to the designated stress states at controlled strain rates.

Simulated *in-situ* conditions were used for the compressibility and triaxial compression tests. The testing scenario was based on an approximate average horizontal stress gradient of 0.65 pounds per square inch/ft (psi/ft), a reservoir (pore pressure) of 2000 psi, and a vertical stress gradient of 1 psi/ft (overburden stress). Pore volume compressibility measurements were made using a simulated reservoir pressure drawdown from an initial reservoir pressure of 2000 psi to 200 psi.

Values of Young's modulus, bulk modulus, shear modulus, and Poisson's ratio as well as compressibility were obtained for both samples. Pore volume compressibility values determined for the reservoir limestone and dolomite were 2.3×10^{-6}/psi and 3.2×10^{-6}/psi, respectively.

Technology Transfer

During this quarter, abstracts presenting the results of the five-field reservoir characterization and the outcrop reservoir analog were submitted for presentation at the 1996 American Association of Petroleum Geologists (AAPG) annual convention in San Diego, California and the AAPG Rocky Mountain Section meeting in Billings, Montana. These same abstracts were also submitted to the Utah Geological Association for papers to be published in a 1996 guidebook entitled *Geology and Resources of the Paradox Basin.*

A presentation entitled "Composition of Seismically Identified Upper Pennsylvanian Mounds Surrounding Greater Aneth Field: Implications for Increased Oil Production Utilizing Secondary and Tertiary Recovery" was given at the Fort Worth Geological Society's monthly meeting, Fort Worth, Texas, November 13, 1995. The Paradox Formation reservoir types, reservoir controls, and project objectives were discussed.

Next Quarter Activities

Activities planned for the next quarter (January 1 through March 31, 1996) include:

1. Prepare a report on the major facies in the field reservoirs and produce a map of the general facies belts in the region.

2. Continue to define layers or units with bounding surfaces for the Desert Creek reservoir in Anasazi field for statistical models.

3. Continue thin section petrography of Anasazi wells in order to: (a) establish a catalog of grain types and depositional facies, (b) develop a display and catalog of major porosity types as seen in thin sections, (c) develop a display of typical porosity types and lithology as a function of log response, and (d) construct a diagenetic history for the reservoir zones.

4. 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.

5. Continue work on various reservoir maps for project fields. Complete seismic interpretations at Mule field.

6. Conduct Mule area seismic permitting.

7. Evaluate and interpret data collected from outcrop reservoir analogues along the San Juan River. Prepare a report describing sequence stratigraphic framework, depositional patterns, and reservoir flow units, barriers, and baffles.

8. Evaluate petrophysical models of the five project fields utilizing geophysical logs and conventional core data on new petrophysical software. Integrate pressure transient work with petrophysical work.

9. Produce table of basic reservoir parameters for each field.

10. Complete development of software to generate internal architectural and reservoir properties for the mound and supra-mound intervals.

11. Generate geostatistical description of internal architecture and porosity/permeability distribution for reservoir flow simulation modeling.

12. Direct and monitor relative permeability work for a representative limestone interval at Westport Lab. Analyze data and develop curves for simulator.

13. Update EOS using new data generated by Robinson's Lab. Compare current tuned EOS and original compositions to revised EOS and new compositions.

14. Complete relative permeability measurements on limestone sample from Anasazi No. 1 core at Westport Lab.

15. Developed full field VIP compositional data files and initiate preliminary simulation runs in preparation for history matching of field production performance.

16. Deliver all lab results (permeability, rock compressibility, CO_2 swelling tests, etc.).

17. Conduct the following technology transfer activities: (a) complete and submit papers on the five project fields for the Utah Geological Association (UGA) Publication 22 entitled *Oil and Gas Fields of Utah*, second edition, (b) prepare the March issue of the UGS *Petroleum News*, (c) continue planning for the *Geology and Resources of the Paradox Basin* symposium sponsored by the Bureau of Indian Affairs, UGS, UGA, U.S. Geological Survey, Colorado Geological Survey, Four Corners Geological Society, Fort Lewis College, and Ute Mountain Indian Tribe. A UGS workshop presenting the results of phase 1 (budget period 1) and a field trip to outcrops and Anasazi field facilities will be part of this symposium, (d) submit papers on the outcrop analogues and reservoir characterization for the Paradox basin symposium guidebook entitled *Geology and Resources of the Paradox Basin*, and (e) develop a project home page within the UGS's Internet home page.