

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
April 30, 1996



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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Reporting Period: January 1 - March 31, 1996

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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-(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.

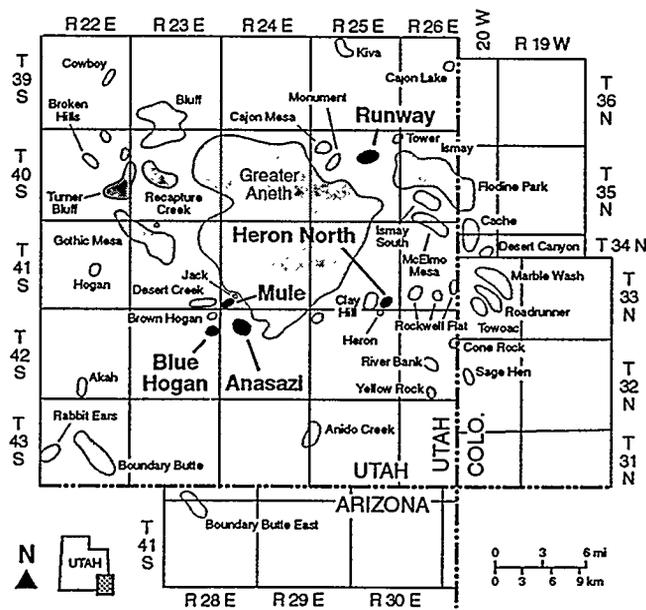


Figure 1. Shallow-shelf carbonate fields (the five project fields are indicated by dark shading with names in bold type) in the Paradox basin, Navajo Nation, San Juan County, Utah.

Summary of Technical Progress

Three activities continued this quarter as part of the geological and reservoir characterization of productive carbonate buildups in the Paradox basin: (1) reservoir facies characterization, (2) reservoir engineering analysis, and (3) technology transfer.

Reservoir Facies Characterization

Three generalized regional facies belts, each with unique types of facies, are identified in the Desert Creek zone of the Paradox Formation (Fig. 2): (1) open marine, (2) shallow-shelf and shelf-margin, and (3) intra-shelf, salinity-restricted facies belts. All five project fields, as well as the other Desert Creek fields in the region, are located within the shallow-shelf and shelf-margin facies belt. This facies belt includes shallow-shelf carbonate buildups, platform-margin calcarenites, and platform-interior carbonate muds and sands.

Carbonate Buildups

The productive carbonate buildups are located in the shallow-shelf and shelf-margin areas. This facies can be divided into three types: (1) phylloid algal, (2) coralline algal, and (3) bryozoan.

Phylloid algal buildup facies. Phylloid algal buildup facies can be subdivided into shelter, mud-rich, and solution breccia facies. The shelter, phylloid algal buildup facies represents a moderate energy environment with well-circulated water. Water depths ranged from 1 to 40 ft. The depositional fabric is bafflestone. Rocks representing this facies contain *in-situ* phylloidal algal plates (*Ivanovia* and *Eugonophyllum*), encrusting forams (for example *Tetrataxis*), soft peloidal mud, and minor amounts of internal sediment (mud or grains deposited after storms [suspended load]). These rocks have a high faunal diversity.

The mud-rich, phylloidal algal buildup facies represents a moderate to low energy environment where the buildup was in a protected position with poorly circulated water. Water depths ranged from 3 to 40 ft. The depositional fabrics include bafflestone, wackestone, and mudstone. Rocks of this facies contain *in-situ* phylloidal algal plates surrounded by lime mud, fine skeletal debris, and microfossils.

The solution breccia, phylloidal algal buildup facies represents a moderate to low energy environment modified by meteoric solution and collapse (karst to microkarst settings). Water level ranged from 3 ft above sea level to 30 ft below sea level. The depositional fabrics of this facies include disturbed rudstone and floatstone with some packstone. Rocks of this facies contain chaotic phylloid algal and exotic clasts, peloids, and internal sediments (muds).

The best stratigraphic hydrocarbon traps in the region are associated with phylloid algal facies. These traps are widely distributed, are small to moderate in size, and can be readily identified on seismic records. Shelter, phylloid algal buildup facies is observed in Anasazi, Mule, and Runway fields (Fig. 1). Mud-rich, phylloid algal buildup facies are also present in Anasazi, Runway, and Jack fields. The solution breccia, phylloid algal buildup facies is observed in Mule, Runway, and Monument fields. Variable amounts of early marine cement are found in mud-rich (Monument field) and shelter (Blue Hogan and Brown Hogan fields), phylloid algal facies. Bafflestone within these facies traps have excellent reservoir properties where primary shelter porosity is well-developed.

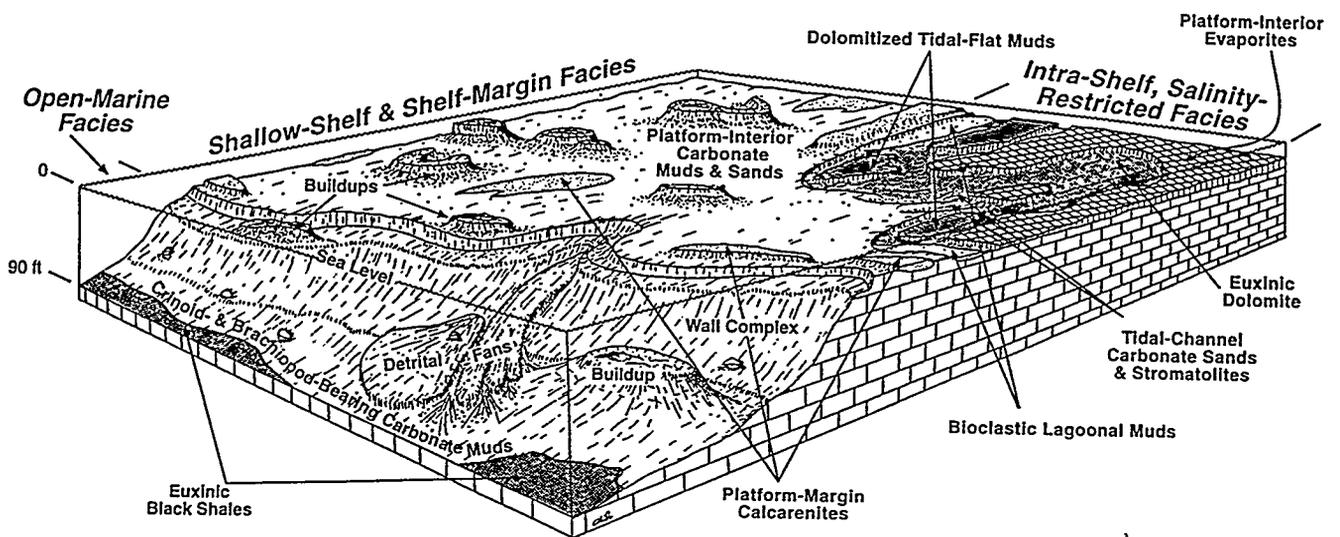


Figure 2. Block diagram displaying major facies within regional facies belts for the Desert Creek zone, Pennsylvania Paradox Formation, southeastern San Juan County, Utah.

However, anhydrite and early marine botryoidal to fibrous cements occasionally plug pores.

Coralline algal buildup facies. Coralline algal buildup facies are located along the shallow-shelf margins facing open-marine waters or within the intra-shelf, salinity-restricted facies belt (where they are non-productive). On the shallow shelf, this facies represents a low to high energy environment with well-circulated water. Water depths ranged from 25 to 45 ft. These buildups are a component of the wall complex (Fig. 2) in association with early marine cementation and are stacked vertically. They may surround other types of buildup complexes.

The depositional fabrics of coralline algal buildup facies are bindstone, boundstone, and framestone selectively dolomitized. Rocks representing this facies contain calcareous, encrusting and bulbous coralline (red) algae, variable amounts of lime mud, microfossils, and calcispheres.

Coralline algal buildup facies are poor stratigraphic hydrocarbon traps, and contribute minor amounts of oil to the production at Cajon and Runway fields (Fig. 1). These traps are rare, small, and identification on seismic records is difficult, requiring good well control for delineation. Although these reservoirs may appear good on geophysical logs, porosity and permeability are generally low.

Bryozoan buildup facies. Bryozoan buildup facies are located on the deeper flanks of phylloid algal buildup complexes. This facies represents a low energy environment with well-circulated water. Water depths ranged from 25 to 45 ft. These facies were prevalent on the northeast part of the shallow shelf where winds out of the east and paleotopography from Mississippian-aged normal faulting produced better marine conditions for bryozoan colony development.

The depositional fabrics are bindstone, bafflestone, and packstone which are rarely dolomitized. Rocks of this facies contain the following diagnostic constituents: bryozoan colonies (*Chaetetes*), small rugose corals, occasional small calcareous sponges and phylloidal algal plates, microfossils, and lime muds.

The bryozoan buildup facies are fair to poor stratigraphic hydrocarbon traps. This facies is productive at Cajon Mesa and Runway fields (Fig. 1). These traps are small and their geometry is difficult to determine. Porosity is good but pores (intrasketal) are isolated unless connected by bryozoan sheets; permeability is variable. Minor to abundant amounts of early marine botryoidal to fibrous cement plugs pores.

Platform-Margin Calcarenites

The platform-margin calcarenite facies are located along the margins of the larger shallow shelf or the rims of phylloid algal buildup complexes. This facies represents a high energy environment where shoals and/or islands developed as a result of regularly agitated, shallow marine processes on the shelf. Characteristic features of this facies include medium-scale cross bedding and bar-type carbonate sand body morphologies. Stabilized calcarenites occasionally developed subaerial features such as beach rock, hard grounds, and soil zones. Water level ranged from 5 ft above sea level to 20 ft below sea level.

The depositional fabrics of the calcarenite facies include grainstone and packstone. Rocks representing this facies typically contain the following diagnostic constituents: coated grains, hard peloids, bioclastic grains, shell lags, and intraclasts.

Calcarenite facies are moderately good stratigraphic and diagenetic hydrocarbon traps, like those observed in Heron North, Heron, and Anasazi fields for example (Fig. 1). However, these traps

have limited distribution, are relatively small, and identification on seismic records is difficult. Grainstones within calcarenite facies traps have excellent reservoir properties where primary interparticle and secondary intercrystalline porosity (from dolomitization) are well-developed. However, some calcarenites have exclusive moldic pores which result in classic "heart break" reservoirs. In addition, bitumen (or solid hydrocarbons) sometimes plug intercrystalline and interparticle pores.

Platform-Interior Carbonate Muds and Sands

The platform-interior carbonate muds and sands facies are wide-spread across the shallow shelf. This facies represents a low to moderate energy environment. Muds and sands were deposited in subtidal (burrowed), inter-buildup, and stabilized grain-flat (pellet shoals) settings intermixed with tubular and bedded tempestites. Water depths ranged from 5 ft to 45 ft.

The depositional fabrics of the platform-interior carbonate muds and sands facies include grainstone, packstone, wackestone, and mudstone. Rocks representing this facies typically contain the following diagnostic constituents: soft pellet muds, hard peloids, grain aggregates, crinoids and associated skeletal debris, and fusulinids.

The platform-interior carbonate muds and sands facies can contain reservoir-quality rocks if dolomitized. This facies is present in Anasazi, Heron, Heron North, and Runway fields (Fig. 1).

Reservoir Engineering Analysis

During the quarter team members performed the following reservoir engineering analysis tasks: (1) finalization of the experimental program with the completion of capillary pressure and relative permeability measurements on the mound-core interval (lower part of the carbonate buildup) from the Anasazi No. 1 well, Anasazi field, (2) finalization of well test analysis with the completion of a successful analysis and interpretation of the well tests conducted on the Big Sky No. 6E well near Clay Hill field (Fig. 1), and (3) initialization and completion of equation of state tuning using original black oil pressure-volume-temperature (PVT) data from the Anasazi No. 1 well and the CO₂ swelling test data obtained on fluids from the Anasazi No. 5L-3 and Anasazi No. 6H-1 wells, Anasazi field.

Relative permeability work consisted of determining oil-brine and gas-oil capillary pressure data employing ultra centrifuge technology. These tests were conducted at reservoir temperature (130°F). Ultra centrifuge data was used to determine core-plug wettability and relative permeability values. Restored state core plugs were used for the experimental study. The data indicates a mixed wettability condition with a slightly stronger water wetting tendency than previously found for the supra-mound interval (upper part of the carbonate buildup) samples from the Anasazi No. 6H-1 well. An oil/gas imbibition experiment provided data on the value of the trapped gas saturation. A value of 11.2% was determined from the experiment.

Well test analysis of various Paradox basin wells was finalized with the completion of analysis work on the Big Sky No. 6E well. The test was successfully interpreted using a homogeneous model, which is consistent with production data since only the supra-mound interval is present and should behave as a single-porosity system. To successfully analyze other wells (for example the Anasazi No. 1), a dual-property model was required to represent the fluid communication between the supra-mound and mound-core intervals. Figures 3 and 4 illustrate the quality of the match (computed responses are represented by solid lines and measured pressure data by the + symbol) and the

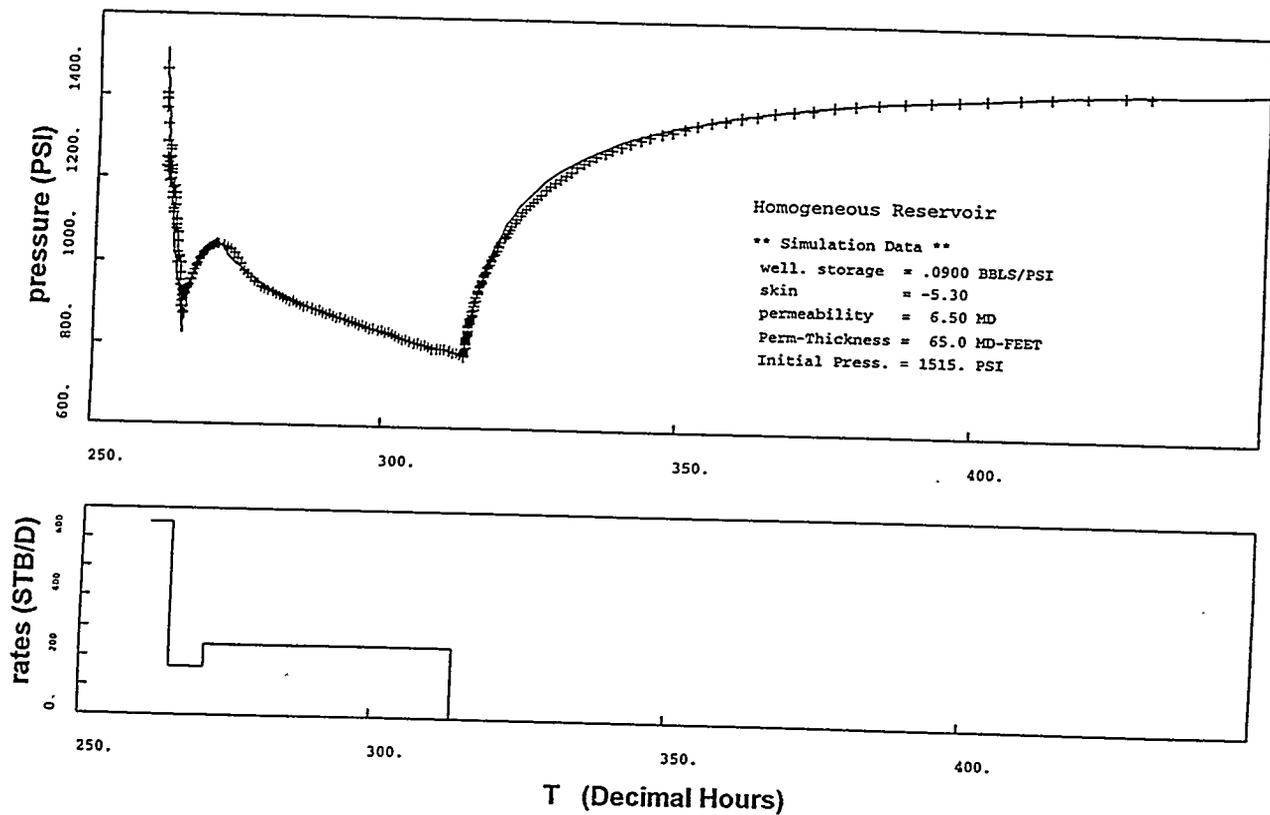


Figure 3. Well flow buildup test analysis of the Big Sky No. 6E well near Clay Hill field (see Fig. 1 for field location) displaying pressure vs. time match.

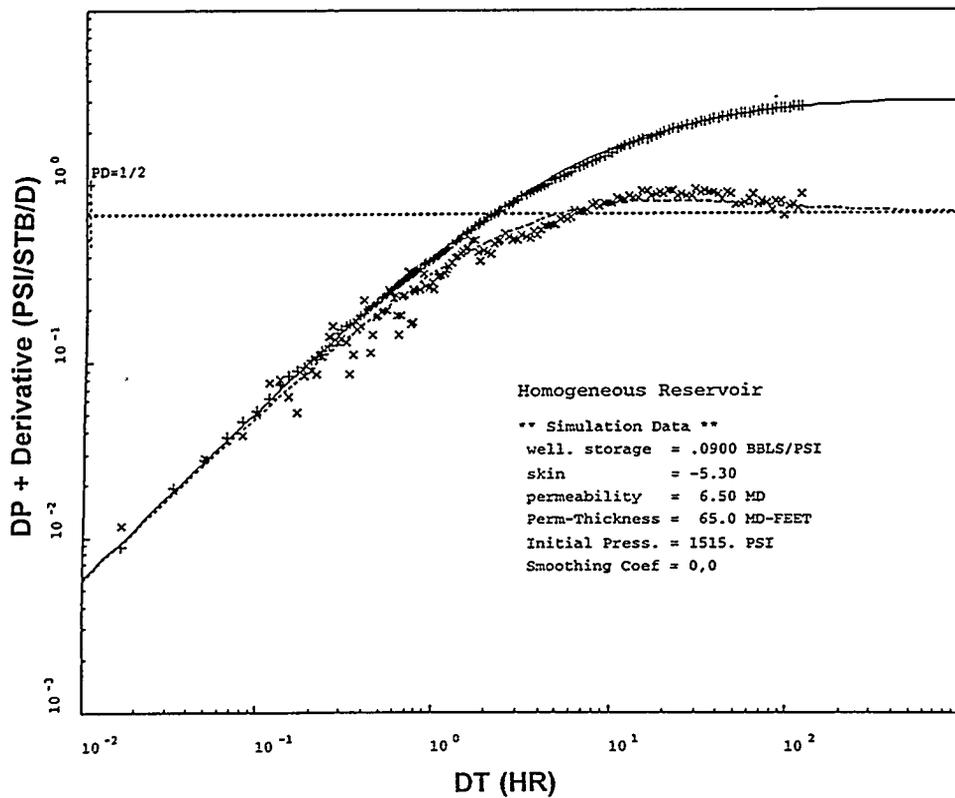


Figure 4. Well flow buildup test analysis of the Big Sky No. 6E well displaying pressure difference and pressure derivative match.

reservoir parameters required to achieve this match.

One of the first steps in conducting a compositional simulation study of the Anasazi reservoir is the calibration or tuning of an equation of state to provide a means of calculating or predicting the complex phase behavior associated with CO₂ displacements processes. A Peng-Robinson equation of state was tuned using all the experimental fluid property data available on the Anasazi reservoir. This included the original black oil PVT fluid study and the recently completed CO₂ swelling tests data. Two fluid characterizations employing 11 and 13 pseudo components were successfully used in the calibration work. Both characterizations, using equation of state parameters derived from the tuning work, have been used to reliably match all experimental data. Also, the calibrated equation of state was used to conduct a series of multiple contact experiments designed to approximately model a CO₂ displacement process. Results of this work provide insight into the conditions (compositions and pressures) required to develop miscibility.

Technology Transfer

Regulatory Issues

The UGS Director and Energy Section Chief were invited to meet with county commissioners from every oil producing county in the State, representatives from the State Tax Commission, and Utah Association of Counties to address regulatory issues affecting future oil production and activities. State tax incentives for enhanced oil-recovery (EOR), particularly CO₂ floods, and horizontal-drilling projects were discussed. The UGS explained technical aspects of such projects using the DOE-sponsored Bluebell and Monument Butte projects (both Class I), and Paradox basin project (Class II) as examples of the economic potential of EOR and horizontal drilling.

UGS personnel also met with the Utah Department of Natural Resources Executive Director and representatives of the Utah Office of Energy and Resource Planning. That meeting helped establish the Department's position on a state legislative bill that provides tax incentives for EOR and horizontal-drilling projects.

The UGS is preparing a white paper in cooperation with the Utah Office of Energy and Resource Planning outlining a state strategic initiative to increase oil production in Utah. The strategy will focus on encouraging government/industry partnerships similar to those established in the Paradox basin and Bluebell projects, and modifying tax philosophies and regulatory processes to take into account varying reservoir conditions.

UGS on the Internet

The UGS has established a home page on the Internet. The address is <http://utstdpwww.state.ut.us/~ugs/>. The site includes a page under the heading *Utah's Petroleum Resources*, describing the UGS/DOE cooperative studies (Paradox basin, Bluebell field, and Ferron Sandstone) and *Petroleum News*.

Next Quarter Activities

Activities planned for the next quarter (April 1 through June 30, 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 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.
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. Continue to conduct Mule area seismic permitting.
6. 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.
7. 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.
8. Produce table of basic reservoir parameters for each field.
9. Evaluate Runway field potential for CO₂ flood simulation in addition to Anasazi field.
10. Generate geostatistical description of internal architecture and porosity/permeability distribution for reservoir flow simulation modeling.
11. Finalize 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. Developed full field VIP compositional data files and initiate preliminary simulation runs in preparation for well level calibration runs and history matching of field production performance.

13. Deliver all lab results (permeability, rock compressibility, CO₂ swelling tests, etc.).
14. 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 May 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*, (e) develop a project home page within the UGS's Internet home page, and (f) make technical presentations at the Class II workshop in Midland, Texas, and at the Annual Convention of the American Association of Petroleum Geologists in San Diego, CA.