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INCREASED OIL PRODUCTION AND RESERVES UTILIZING SECONDARY/TERTIARY RECOVERY TECHNIQUES ON SMALL RESERVOIRS IN THE PARADOX BASIN, UTAH

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By
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Work Performed Under Contract No. DE-FC22-95BC14988

Utah Geological Survey
Salt Lake City, Utah

National Petroleum Technology Office
U. S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

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Increased Oil Production and Reserves Utilizing Secondary/Tertiary Recovery Techniques on Small Reservoirs in the Paradox Basin, Utah

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ABSTRACT

The Paradox basin of Utah, Colorado, and Arizona contains nearly 100 small oil fields producing from carbonate buildups or mounds within the Pennsylvanian (Desmoinesian) Paradox Formation. These fields typically have one to four wells with primary production ranging from 700,000 to 2,000,000 barrels (111,300-318,000 m^3) of oil per field at a 15 to 20 percent recovery rate. At least 200 million barrels (31,800,000 m^3) of oil is at risk of being unrecovered in these small fields because of inefficient recovery practices and undrained heterogeneous reservoirs. Five fields (Anasazi, Mule, Blue Hogan, Heron North, and Runway) within the Navajo Nation of southeastern Utah were evaluated for waterflood or carbon-dioxide (CO_2)-miscible flood projects based upon geological characterization and reservoir modeling. The results can be applied to other fields in the Paradox basin and the Rocky Mountain region, the Michigan and Illinois basins, and the Midcontinent.

Geological characterization on a local scale focused on reservoir heterogeneity, quality, and lateral continuity as well as possible compartmentalization within each of the five project fields. This study utilized representative core and modern geophysical logs to characterize the reservoirs of the five fields.

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each field can be an indicator of reservoir flow capacity, storage capacity, and potential for water- and/or CO_2-flooding. Diagenetic histories of the various Desert Creek reservoirs were determined from more than 50 thin sections of representative samples selected from the conventional cores of each field for petrographic description and to grade each for suitability of enhanced recovery projects.

After the Anasazi field study, Runway field was selected for the second geostatistical modeling and reservoir simulation to allow comparison of the two models, and because Runway was a more promising candidate for a Phase II pilot demonstration due to its closer proximity to potential sources of CO_2. The key to increasing ultimate recovery from the Runway field (and similar fields in the basin) is to design a CO_2-miscible flood project capable of forcing oil from high-storage-capacity but low-recovery supra-mound units into the high-recovery mound-core units. As at Anasazi field, significant heterogeneity in the Runway lithotypes and the reservoir properties required development of a multi-stage procedure for incorporating the variations measured in conventional cores into the reservoir geostatistical model. Geostatistical modeling of the Runway reservoir incorporated unit thicknesses, flooding surfaces, and lithotypes observed in the core. Statistical modeling included architectural, porosity, and permeability for 15- and 17-layer models. The results were used in reservoir simulations to test and design a CO_2-miscible flood project.

The reservoir analysis for Runway field required a field-scale reservoir simulator. Enhanced recovery through CO_2 flooding was evaluated by varying the composition of the reservoir carbonate lithotypes, porosity, and permeability in order to accurately predict reservoir response. History matches were made by tying to recorded production and reservoir pressure history so that future reservoir performance could be confidently predicted. Economic assessments were conducted for CO_2 flooding in Runway field.

Simulation of Anasazi field has shown that a CO_2 flood is technically superior to a waterflood and economically feasible. For Anasazi field, an optimized CO_2 flood is predicted to recover a total 4.21 million stock tank barrels (0.67 million m^3) of oil representing in excess of 89 percent of the original oil in place. For Runway field, the best CO_2 flood is predicted to recover a

total of 2.4 million stock tank barrels (0.38 million m^3) of oil representing 71 percent of the original oil in place.

The Utah Geological Survey recommends continuation of the project into Phase II with a CO_2 pilot flood demonstration on either Anasazi or Runway fields. The field demonstration includes: conducting a CO_2 injection test(s), obtaining a CO_2 source and fuel gas (for the compressor), rerunning project economics, drilling a development well(s) (vertically or horizontally), purchasing and installing injection facilities, monitoring field performance, and validating and evaluating the techniques. The demonstration will prove (or disprove) CO_2-flood viability and thus help determine whether the technique can be applied to the other small carbonate buildup reservoirs in the Paradox basin. This will quantify the upside potential of CO_2 flooding for small fields in the entire basin from both a reserves and an economic standpoint.

Technology transfer during the fourth project year consisted of booth displays for various national and regional professional conventions, technical presentations, publications, newsletters, and a project home page on the Internet.

EXECUTIVE SUMMARY

The primary objective of this project is to enhance domestic petroleum production by field 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 (23,850,000-31,800,000 m^3) 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-(CO_2-) miscible flood project. The field demonstration, monitoring of field performance, and associated validation activities will take place within the Navajo Nation, San Juan County, Utah.

The Utah Geological Survey (UGS) leads a multidisciplinary team to determine the geological and reservoir characteristics of typical, small, shallow-shelf carbonate reservoirs in the Paradox basin. The Paradox basin project team consists of the UGS (prime contractor), Harken Southwest Corporation, and several subcontractors. This research is performed under the Class II Oil Program of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research and technology transfer activities for the fourth project year (February 9, 1998 through February 8, 1999). This work includes field data collection and compilation; determining diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each project field; reservoir geostatistical modeling, history matching, and reservoir CO_2-flood simulations of Runway field; determining reserves and secondary/tertiary recovery of each project field; economic assessments of CO_2 floods for Anasazi and Runway fields; and recommending plans for pilot flood implementation and production scenarios for Phase II, the field demonstration project. The results can be applied to similar reservoirs in many U.S. basins.

Reservoir data, cores and cuttings, geophysical logs, various reservoir maps, and other information from the project fields and regional exploratory wells were collected. Well locations, production reports, completion tests, core analysis, formation tops, and other data were compiled and entered in a database developed by the UGS.

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each field can be an indicator of reservoir flow capacity, storage capacity, and potential for water- and/or CO_2-flooding. In order to determine the diagenetic histories of the various Desert Creek reservoirs, 50 thin sections of representative samples were selected from the conventional cores of each field for petrographic description and to evaluate shallow-shelf/shelf-margin phylloid-algal, bryozoan, and calcarenite carbonate buildups. We analyzed the reservoir diagenetic fabrics and porosity types of these buildups to: (1) predict facies patterns, (2) determine the sequence of diagenetic events, and (3) provide data input for the reservoir modeling and simulation studies. The vertical releif of most carbonate buildups, or mounds, caused subaerial exposure when sea level fell. This setting produced four major, generally early, diagenetic environments: (1) meteoric vadose zone, (2) meteoric phreatic zone, (3) marine phreatic zone, and (4) mixing zone. Many reservoirs in the project fields have a mixing-zone as well as a fresh-water overprint. Within the vadose and meteoric phreatic zones, neomorphism, leaching/dissolution, and fresh-water cementation has taken place. Those fields that had a portion of the carbonate buildup facing the open marine environment, generally a steep-wall complex, developed early-marine cements. Many reservoirs contain two generations of dolomite from seepage reflux by brines from bordering hypersaline lagoons. Post-

burial diagenesis included syntaxial cementation, silicification, late calcite spar, saddle dolomite, stylolitization, bitumen plugging, and anhydrite replacement.

The carbonate buildup reservoir at Runway field was selected for a follow-up study after the Anasazi field reservoir assessment, both for comparison of results, and also as a more promising candidate for a Phase II pilot demonstration due to the closer proximity of Runway to potential sources of CO_2. The key to increasing ultimate recovery from the Runway field (and similar fields in the basin) is to design a CO_2-miscible flood project capable of forcing oil from high-storage-capacity but low-recovery supra-mound units into the high-recovery mound-core units. The significant heterogeneity in the Runway field lithotypes and the reservoir properties requires a multi-stage procedure for incorporating the variations measured in conventional cores from the field and outcrop analogues into the reservoir geostatistical model. Statistical modeling included architectural, porosity, and permeability of 15- and 17-layer models.

The internal architecture of the reservoir between the wells was modeled using a marked-point (Boolean) process for emplacement of ten constituent lithotypes. Emplacement sequences were established and the relative lithotype proportions varied stochastically. The pair-wise, block-exchange process for simulating Desert Creek reservoir porosity between the Runway wells was carried out using the well-known stochastic relaxation technique known as simulated annealing. Sensitivity studies were conducted which indicated that most of the variation in effective reservoir properties could be retained with careful scaling of porosity and permeability. Lithotypes were assigned to gridblocks in 15 layers. Porosity was volume-averaged for the 15-layer model, and effective permeability was computed by solution of the pressure equation using the field-scale reservoir simulator.

Compositional simulation was used to history match (model) predicted production to the recorded past production performance of Runway field, and to predict the performance of continued primary depletion and various CO_2 floods. The simulation study employed the stochastically generated reservoir description. The reservoir fluid was characterized via an equation-of-state calibrated using CO_2-swelling tests conducted on crude oil from Anasazi field and the original, black oil, pressure-volume-temperature data for Runway field. Gas-oil and water-oil relative permeabilities, capillary pressure, and rockpore volume compressibility data were generated for the principal productive facies.

Simulation of Anasazi field the previous year showed that a CO_2 flood is technically superior to a waterflood, and economically feasible. For Anasazi field, an optimized CO_2 flood is predicted to recover a total 4.21 million stock tank barrels (0.67 million m^3) of oil. This represents an increase of 1.65 million stock tank barrels (0.26 million m^3) of oil over predicted primary depletion recovery as of January 1, 2012. The projected 4.21 million stock tank barrels of oil production represents in excess of 89 percent of the original oil in place. For Runway field, the best CO_2 flood is predicted to recover a total of 2.4 million stock tank barrels (0.38 million m^3) of oil. This represents an increase of 1.58 million stock tank barrels (0.25 million m^3) of oil over predicted primary depletion recovery as of January 1, 2012. The projected 2.4 million stock tank barrels of oil production represents 71 percent of the original oil in place.

The UGS recommends continuation of the project into Phase II with a CO_2 pilot flood demonstration on Anasazi or Runway fields. The field demonstration includes: conducting a CO_2 injection test(s), obtaining a CO_2 source and fuel gas (for the compressor), rerunning project economics, drilling a development well(s) (vertically or horizontally), purchasing and installing injection facilities, monitoring field performance, and validating and evaluating the techniques.

The demonstration will prove (or disprove) CO_2-flood viability, and thus help determine whether the technique can be applied to the other small carbonate buildup reservoirs in the Paradox basin. The financial impact of simultaneous or sequential flooding of a series of reservoirs should also be assessed. This will quantify the upside potential of CO_2 flooding for the entire basin from both a reserves and an economic standpoint. The knowledge gained in modeling historical and future production performance of the Anasazi and Runway reservoirs indicates that the overall mound geometry and internal facies architecture are critical to matching and predicting performance. Thus, each mound will likely require an individual reservoir study to quantify its CO_2-flood potential and to identify the appropriate implementation strategy for maximum oil recovery.

Technology transfer during the fourth project year consisted of displaying project materials at: the UGS booth during the national convention of the American Association of Petroleum Geologists; the new Utah Geological Survey Sample Library open house; a Rocky Mountain Region of the Petroleum Technology Transfer Council symposium; and the Interstate Oil and Gas Compact Commission annual meeting. In addition, two technical presentations were made to geological associations. Project team members published abstracts, quarterly and annual reports, newsletters, and technical journal papers detailing project progress and results. The UGS maintained a home page for the Paradox basin project on the Internet.

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1. INTRODUCTION

Thomas C. Chidsey, Jr.; Utah Geological Survey

Over 400 million barrels (63,600,000 m^3) of oil have been produced from shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation in the Paradox basin of Utah, Colorado, and Arizona. With the exception of the giant Greater Aneth field, 100-plus oil fields in the basin typically contain 2 to 10 million barrels (318,000-1,590,000 m^3) of original oil in place per field. To date, none of these small fields have been the site of secondary/tertiary recovery techniques used in large carbonate reservoirs. Most of these fields are characterized by extremely high initial production rates followed by a very short production life (primary), and hence early abandonment. At least 200 million barrels (31,800,000 m^3) of oil is at risk of being left behind in these small fields because of inefficient recovery practices and undrained heterogeneous reservoirs. The purpose of this multi-year project is to enhance domestic petroleum production by field demonstration and technology transfer of an advanced-oil-recovery technology in the Paradox basin.

The benefits expected from the project are: (1) increasing recoverable reserves by identifying untapped compartments created by reservoir heterogeneity, (2) increasing deliverability through a carbon-dioxide- (CO_2-) miscible flood which exploits the reservoir along optimal fluid-flow paths, (3) identifying reservoir trends for field extension drilling and stimulating exploration in Paradox basin fairways, (4) preventing premature abandonment of numerous small fields, (5) reducing development costs by more closely delineating minimum field size and other parameters necessary to a successful flood, (6) allowing limited energy investment dollars to be used more productively, and (7) increasing royalty income to the Navajo Nation; Federal, State, and local governments; and fee owners. These benefits also apply to other areas in the Rocky Mountain region, the Michigan and Illinois basins, and the Midcontinent.

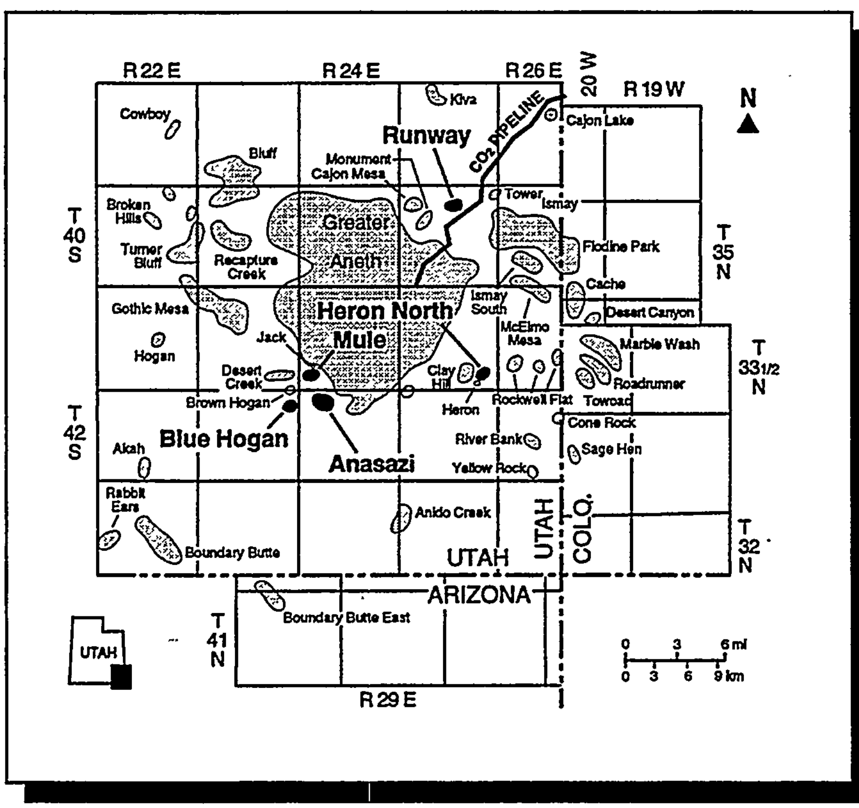

Figure 1.1. Location of project fields (dark shaded areas with names in bold type) in the southwestern Paradox basin on the Navajo Nation, San Juan County, Utah.

The geological and reservoir characteristics of five fields (figure 1.1) that produce oil and gas from the Desert Creek zone of the Paradox Formation were quantitatively determined by a multidisciplinary team.

Anasazi field was chosen as the best candidate for a pilot CO_2-flood demonstration project after reservoir simulations were completed on both the Anasazi and Runway fields. To evaluate these fields as models for other shallow-shelf carbonate reservoirs, the Utah Geological Survey (UGS), Harken Southwest Corporation, Eby Petrography & Consulting Inc., and REGA Inc. entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Class II Oil program.

A two-phase approach is being used to increase production and reserves from the shallow-shelf carbonate reservoirs in the Paradox basin. Phase I is the geological and reservoir characterization of the five small fields. Work done during the fourth year and continuing into the fifth year of this phase includes:

(a) field data collection and compilation,

(b) determining diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each field,

(c) field-scale geologic analysis to focus on the reservoir heterogeneity, quality, and lateral continuity versus compartmentalization,

(d) reservoir geostatistical modeling of Runway field,

(e) history matching and reservoir CO_2-flood simulations of Runway field,

(f) determining field reserves and secondary/tertiary recovery,

(g) economic assessments of CO_2 floods for Anasazi and Runway fields, and

(h) recommending plans for pilot flood implementation and production scenarios for Phase II, the field demonstration project.

Phase II will be a demonstration project on Anasazi field, which was selected from the characterization study, using a CO_2-miscible flood. This technique was identified as having the greatest potential for increased well productivity and ultimate recovery. The demonstration project will include:

(a) conducting a CO_2 injection test(s),

(b) acquiring a CO_2 source for the flood project,

(c) acquiring a fuel gas source for the compressor,

(d) rerunning project economics,

(e) drilling a development well(s), vertically or horizontally, to facilitate sweep during the pilot flood,

(f) purchasing and installing injection facilities,

(g) flood management, monitoring field performance, and evaluation of results, and

(h) determining the application of the project to similar fields in the Paradox basin and throughout the U.S.

The results of this project are being 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, maintaining a project home page on the Internet, and publication in newsletters and various technical or trade journals.

This report is organized into five sections: (1) Introduction, (2) Geological Characterization of Project Fields, Navajo Nation, San Juan County, Utah, (3) Geostatistical Modeling and Reservoir Engineering Analysis, Runway Field, (4) Economic Assessments of Reservoir CO_2 Floods and Recommendations, and (5) Technology Transfer. This report presents the progress of ongoing research and is not intended as a final report. Whenever possible, preliminary conclusions have been drawn based on available data.

2. GEOLOGICAL CHARACTERIZATION OF PROJECT FIELDS, NAVAJO NATION, SAN JUAN COUNTY, UTAH

Thomas C. Chidsey, Jr.; Utah Geological Survey.
and
David E. Eby; Eby Petrography & Consulting, Inc.

The five Paradox basin fields evaluated in Phase I of the project were Anasazi, Blue Hogan, Heron North, Mule, and Runway located within the Navajo Nation of southeastern Utah (figure 1.1); they are five of several satellite carbonate mounds around the giant Greater Aneth field. This evaluation included data collection and reservoir diagenetic analysis which was used in the statistical models and flow simulations. The geological and reservoir characterization of these fields and resulting models can be applied to similar fields in the basin (and other basins as well) where data might be limited. The following presents the preliminary results of the efforts during the fourth year of the project. Completed final reports on the various work tasks will be released by the UGS during Phase II of the project.

2.1 Field Data Collection and Compilation

Reservoir data, cores and cuttings, geophysical logs, various reservoir maps, and other information from the project fields and regional exploratory wells were collected by the UGS. Well locations, production reports, completion tests, core analysis, formation tops, and other data were compiled and entered in a database developed by the UGS. This database, *INTEGRAL*gim*, is a geologic-information database that links a diverse set of geologic data to records using PARADOX™ for DOS software. The database is designed so that geological information, such as lithology, petrophysical analyses, or depositional environment can be exported to software programs to produce strip logs, lithofacies maps, various graphs, statistical models, and other types of presentations. Production data, basic core analyses, geophysical log types, and well cutting information for these project wells have been entered into the UGS INTEGRAL*gim database. In addition, completion test data and formation tops have also been entered into the database for these wells. The database containing information from the project will be available as a UGS open-file (digital format) report at the conclusion of Phase II.

2.2 Reservoir Diagenetic Analysis

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each field can be an indicator of reservoir flow capacity, storage capacity, and potential for water- and/or CO_2-flooding. In order to determine the diagenetic histories of the various Desert Creek reservoirs, 50 thin sections of representative samples were selected from the conventional cores of each field for petrographic description and to evaluate shallow-shelf/shelf-margin phylloid-algal, bryozoan, and calcarenite carbonate buildups. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. We analyzed the reservoir diagenetic fabrics and porosity types of these buildups to: (1) predict facies patterns, (2) determine the sequence of diagenetic events, and (3) provide data input for the reservoir modeling and simulation studies.

Diagenetic characterization focused on reservoir heterogeneity, quality, and compartmentalization within each of the five project fields. All depositional, diagenetic, and porosity information was placed into the context of the production history to date of each field in order to construct a detailed overview for each enhanced recovery candidate. Of special interest is the determination of the most effective pore systems for oil drainage versus storage.

2.2.1 Diagenetic Environments

The vertical relief of most shallow-shelf/shelf margin carbonate buildups, or mounds, caused subaerial with exposure when sea level fell. This setting produced four major, generally early, diagenetic environments (figures 2.1 and 2.2): (1) fresh water (meteoric) vadose zone (above the water table, generally at or near sea level), (2) meteoric phreatic zone (below the water table), (3) marine phreatic zone, and (4) mixing zone (Longman, 1980). The "iceberg" principle (the Ghyben-Herzberg theory), which states that for every foot the water table rises above sea level there may be 20 feet (6.1 m) of fresh water below the water table, implies that a 1:20 ratio of mound height above the water table to fresh-water phreatic zone thickness can generally be applied to both carbonate mound and island buildups (Friedman and Sanders, 1978). Neomorphism, leaching/dissolution, and fresh-water cementation (dog-tooth, stubby, and small equant calcite) took place within the vadose and meteoric phreatic zones.

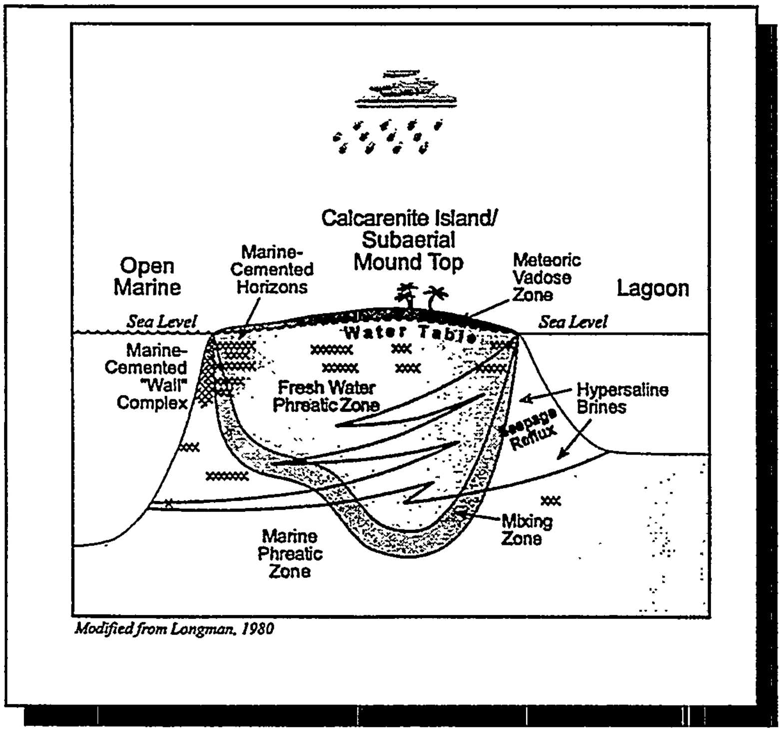

Figure 2.1. Model of early diagenetic environments found in the Desert Creek zone of the Paradox Formation, southern Paradox basin (modified from Longman, 1980).

The meteoric and marine phreatic zones were separated by a mixing zone of fresh and sea water, all of which dynamically fluctuated with sea level. Early dolomitization took place in the mixing zone. Most carbonate buildups (fields) have a mixing-zone as well as a fresh-water overprint.

That portion of the carbonate buildup facing the open-marine environment was generally a steep-wall complex where early-marine cements (such as fibrous isopachous, botryoidal, and radiaxial cements) were deposited by invading sea water flowing through the system. The opposite side of the mound typically bordered a hypersaline lagoon filled with dense brine that seeped into

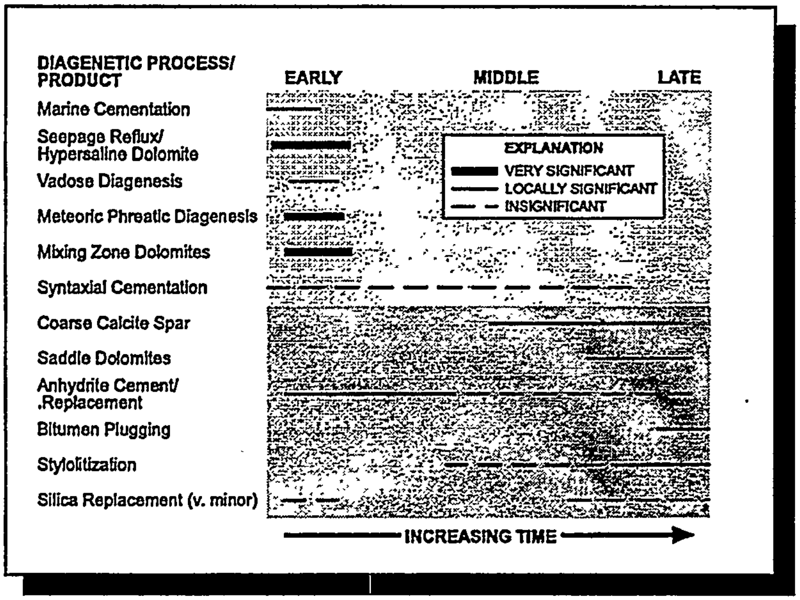

Figure 2.2. Ideal diagenetic sequence through time, including processes and products.

the phreatic zone (seepage reflux) to form a wedge-shaped zone of low-temperature dolomite, both early replacement dolomite and dolomite cement.

Post-burial diagenesis included the development of syntaxial cementation, silicification, late calcite spar, saddle dolomite, stylolitization, bitumen plugging, and anhydrite replacement (figure 2.2). There is an observed progression of post-burial diagenetic features from least to most important in terms of degraded reservoir quality (syntaxial cementation to anhydrite replacement) which also relates to increased reservoir heterogeneity in the case-study fields. Some of these diagenetic products create barriers and baffles to fluid flow. They are not observed on seismic records, are difficult to predict, and locally influence reservoir performance, storage capacity, and drainage. Finally, these post-burial diagenetic processes are not as significant in the case-study fields as earlier diagenetic modifications.

Figure 2.3. Slabbed core segment from 5,415.5 to 5,415.8 feet (1,650.6-1,650.7 m) of the Blue Hogan No. 1-J-1 well showing the typical pattern of marine cementation within the well-lithified "wall" complex.

2.2.2 Characteristics of Marine Cementation

Early marine cementation occurs in two settings: (1) the "wall" complex on the windward side (botryoidal fans and radiaxial blade cements) of the buildup, and (2) scattered horizons across the interior of buildups (fibrous isopachous and micritic cements). Slabbed core segments from the Blue Hogan No. 1-J-1 show the typical pattern of marine cementation within the well-lithified "wall" complex at the higher energy margin of a small phylloid-algal mound (figure 2.3). Isopachous bands of cements and small Neptunian dikes (see arrows, figure 2.3) are characteristic of the "wall." Figure 2.4 shows two generations of probable marine cements. The earlier generation was a brown micritic to microfibrous cement (between

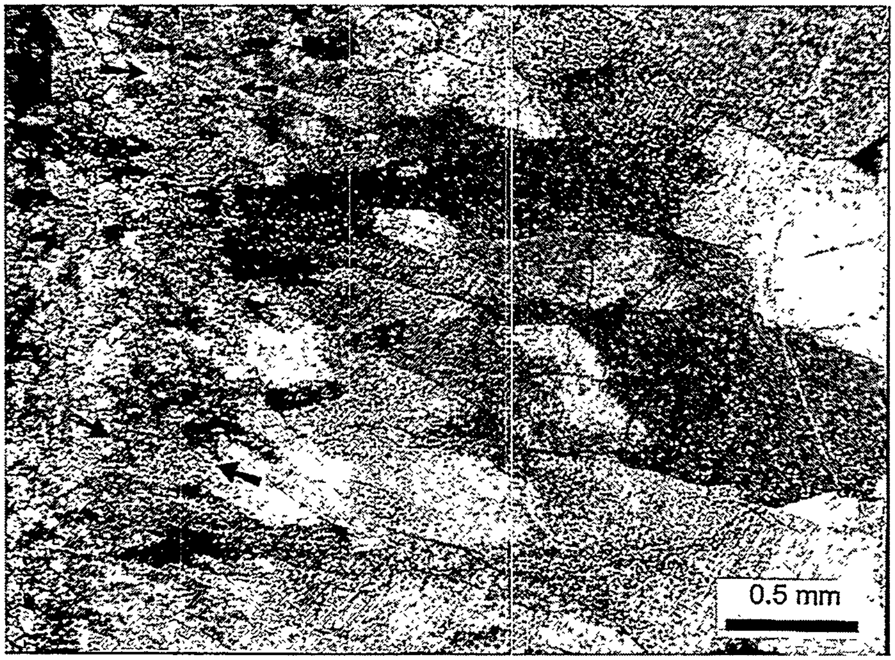

Figure 2.4. Photomicrograph (crossed nicols) of two generations of probable marine cements. Blue Hogan No. 1-J-1 well, 5,420.3 feet (1,652 m), Blue Hogan field.

arrows, figure 2.4) which was followed by a bladed radiaxial generation. Filling of most original pore space was by the radiaxial cements.

Locally, cemented zones can have a major impact on reservoir flow and storage capacity. Pervasive marine cement within a "wall" complex may be indicative of a nearby buildup/mound.

2.2.3 Characteristics of Meteoric Diagenesis (in Limestone Facies)

Dissolution is the dominant porosity-enhancing process of meteoric diagenesis which creates molds, vugs, and channels (figure 2.5). Much of the original fabric remains or can be determined. Early dissolution of lime muds creates microporosity. Indicative cements include stubby to equant

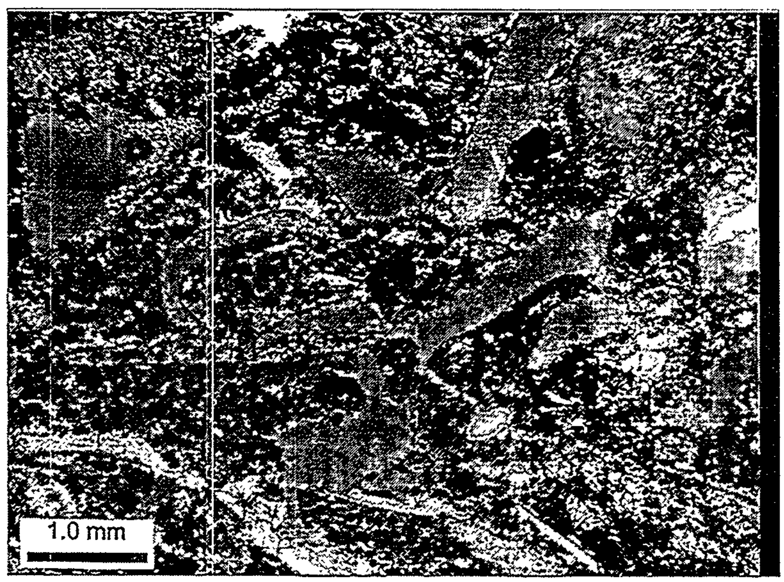

Figure 2.5. Photomicrograph (plane light) of interconnected solution-channel and moldic porosity with very little visible meteoric cements; porosity = 13.2 percent, permeablility = 20.4 millidarcies (md) by core-plug analysis. Mule No. 31-M well, 5,729.8 feet (1,746.4 m), Mule field.

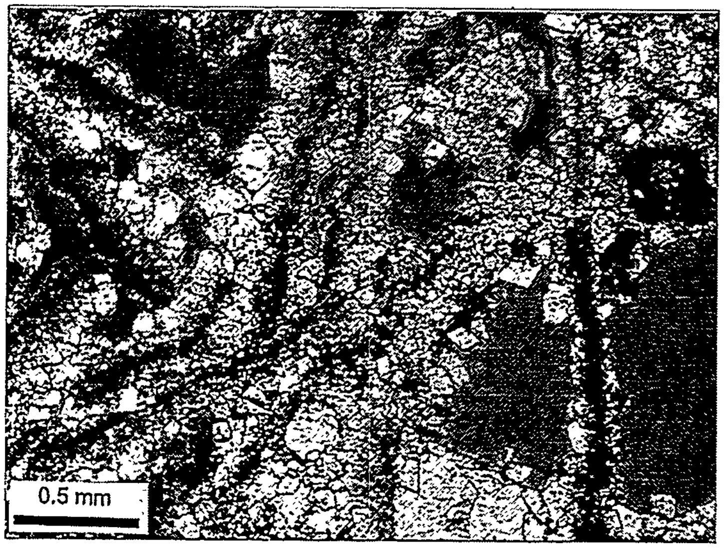

Figure 2.6. Photomicrograph (plane light) of early solution porosity within a phylloid-algal facies partially occluded by stubby to equant to "dogtooth" spar cements of probably meteoric phreatic origin; porosity = 12.5 percent, permeability 53.8 md by core-plug analysis. These types of cements have degraded the permeability of these solution-enhanced pore systems. Runway No. 10-C-5A well, 6,127.4 feet (1,867.5 m), Runway field.

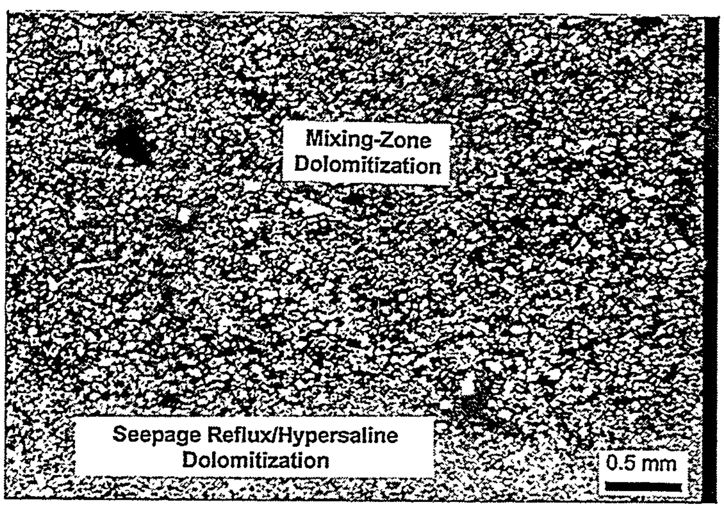

Figure 2.7. Photomicrograph (plane light) of a dolomitized wackestone/packstone showing the contrast between probable seepage reflux/hypersaline dolomitization toward the base and more porous mixing zone dolomitization above; porosity = 20.3 percent, permeability = 39.8 md by core-plug analysis. Note with ghosts of probable ostracods and crinoids. Runway No. 10-C-5A well, 6,120.2 feet (1,865.3 m), Runway field.

calcite and "dogtooth" calcite spars which sporadically line pores (figure 2.6). Vadose zones generally have less cement than the fresh-water phreatic zones. The depth/thickness of the meteoric vadose and fresh-water phreatic zones is dependent on the extent and duration of subaerial exposure as well as the amount of meteoric water influx.

Locally, meteoric diagenesis enhances reservoir performance. Extensively leached intervals may have both excellent storage and flow capacity, and should be considered candidates for CO_2 flooding projects. Microporosity increases storage capacity but limits fluid recovery.

2.2.4 Characteristics of Dolomitization

Dolomitization can be divided into two types, mixing zone and seepage reflux, each with different characteristics (figure 2.7). Mixing-zone dolomitization is usually incomplete dolomitization (fine-grained crystals). Some of the original fabric, micritization, and/or evidence of fresh-water dissolution often still remains. There are variable percentages of micro-intercrystalline and intercrystalline porosity. Mixing-zone dolomitization intervals are generally thinner than intervals affected by other diagenetic processes. The depth of the mixing zone is dependent on the thickness of the fresh-water phreatic zone, the volume of fresh water available, and/or the amount of subaerial exposure. Locally, mixing-zone dolomitization may reduce or enhance reservoir performance. Affected intervals may have modest to good storage capacity, while flow capacity can be highly variable.

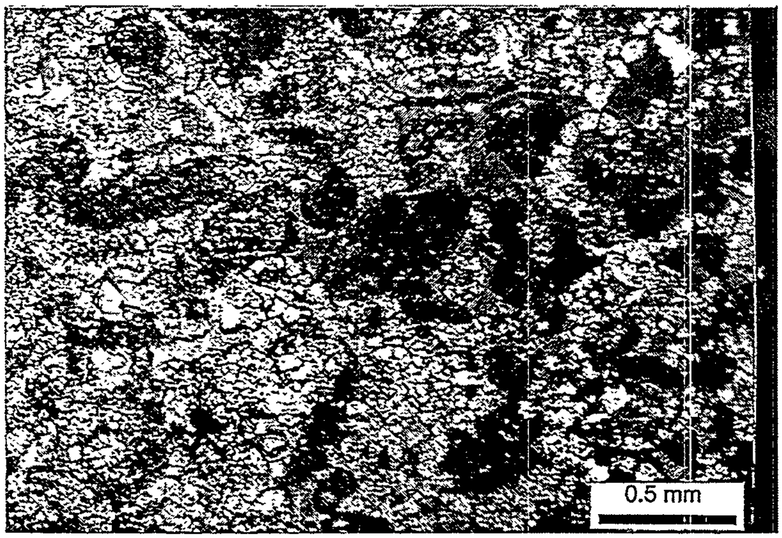

Figure 2.8. Photomicrograph (plane light) of dolomitized, well sorted, pelloidal/oolitic/bioclastic grainstone; porosity = 13.4 percent, permeability = 33.9 md by core-plug analysis. Note the very fine crystalline dolomite formed by seepage reflux processes followed by partial dissolution and other meteoric overprints. The combination of both processes have led to good storage potential and excellent flow capacity. North Heron No. 35-C well, 5,569.2 feet (1,697.4 m), Heron North field.

Seepage-reflux dolomitization usually involves complete dolomitization to destroy most of the original fabric/matrix. Dolomite crystals are fine to medium grained, often sucrosic; intercrystalline porosity dominates (figure 2.8). Seepage-reflux dolomitization occurs in mounds associated with lagoons where hypersaline brines are concentrated. It overprints the fresh-water phreatic, marine phreatic, and mixing zones across the entire extent of the mound buildup. Thick seepage-reflux dolomites are often proximal to evaporite-plugged lagoonal sediments. Locally, seepage-reflux dolomitization can enhance both reservoir flow and storage capacity. Those reservoirs with excellent storage capacity may be considered candidates for CO_2 flooding projects.

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3. GEOSTATISTICAL MODELING AND RESERVOIR ENGINEERING ANALYSIS: RUNWAY FIELD

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and
Thomas C. Chidsey, Jr.; Utah Geological Survey

The Desert Creek carbonate-mound/buildup reservoir at Runway field (figure 1.1) was selected for a follow-up study to the initial Anasazi field reservoir assessment (Chidsey and Allison, 1998) both for comparison with the earlier assessment, and also as a more promising candidate for a Phase II pilot demonstration due to its proximity to potential sources of CO_2. The pipeline that provides CO_2 for the Greater Aneth field CO_2 flooding program is 0.5 miles (0.8 km) southeast of Runway field. The Runway mound complex also has a long production history (more than seven years) and a large amount of hard data for reservoir characterization (three logged wells, two of which are also cored through the Desert Creek zone), and has considerable seismic coverage. The reservoir also is more gas rich than the other project fields and consists of both phylloid-algal and bryozoan buildup facies (Chidsey, Eby, and Lorenz, 1996).

3.1 Runway Field Overview - Location, Geometry, and General Stratigraphy

The discovery well for the Runway field, the Runway No. 10-G-1 (SW1/4NE1/4 section 10, T. 40 S., R. 25 E., Salt Lake Base Line), was completed in 1990 at an initial potential flow of 825 barrels (bbls) of oil per day (BOPD [131 m^3/d]) and 895 thousand cubic feet of gas per day (MCFGPD [25,346 m^3/d]) from commingled Desert Creek and upper Ismay zones. The Runway prospect was identified as a seismic anomaly located on the up-thrown edge of a basement-involved, Mississippian-age normal fault that was a topographic high during Paradox Formation time. Cumulative production from Runway field is 801,889 bbls of oil (BO [127,500 m^3]) and 2.68 billion cubic feet of gas (BCFG [0.08 billion m^3]) as of January 1, 1999 (Utah Division of Oil, Gas and Mining, 1999). Estimated primary recovery from the field was 720,000 BO (114,480 m^3) and 2.83 BCFG (0.08 billion m^3) (Chidsey and others, 1996a).

The detailed, combined structure/isopach map of the Desert Creek zone in the Runway area (figure 3.1) shows a Desert Creek mound buildup more than 50 feet (15 m) thick, based on well log and seismic information. Runway field is a lenticular, west- to east-northeast-trending lobate mound, 0.9 miles (1.5 km) long and 0.5 miles (0.8 km) wide (Chidsey and others, 1996a). The Runway field is somewhat larger (193 acres [78 ha]) than Anasazi (165 acres [67 ha]) with a thicker average net pay (72 feet [22 m] and 57 feet [17 m], respectively) but lower average net pay porosity (11.9 percent and 14.1 percent, respectively) (Chidsey and others, 1996a, b). Three additional dry holes drilled nearby provide off-mound thickness, lithology, and porosity data.

The Runway reservoir consists of a combination of bryozoan-buildup and phylloid-algal-buildup intervals. The presence of two buildup types at the Runway field suggests that the water depth changed as the carbonate deposits built up over the fault-controlled paleohigh. Various carbonate facies are encountered in all three Runway wells, which causes a high degree of spatial heterogeneity in reservoir properties.

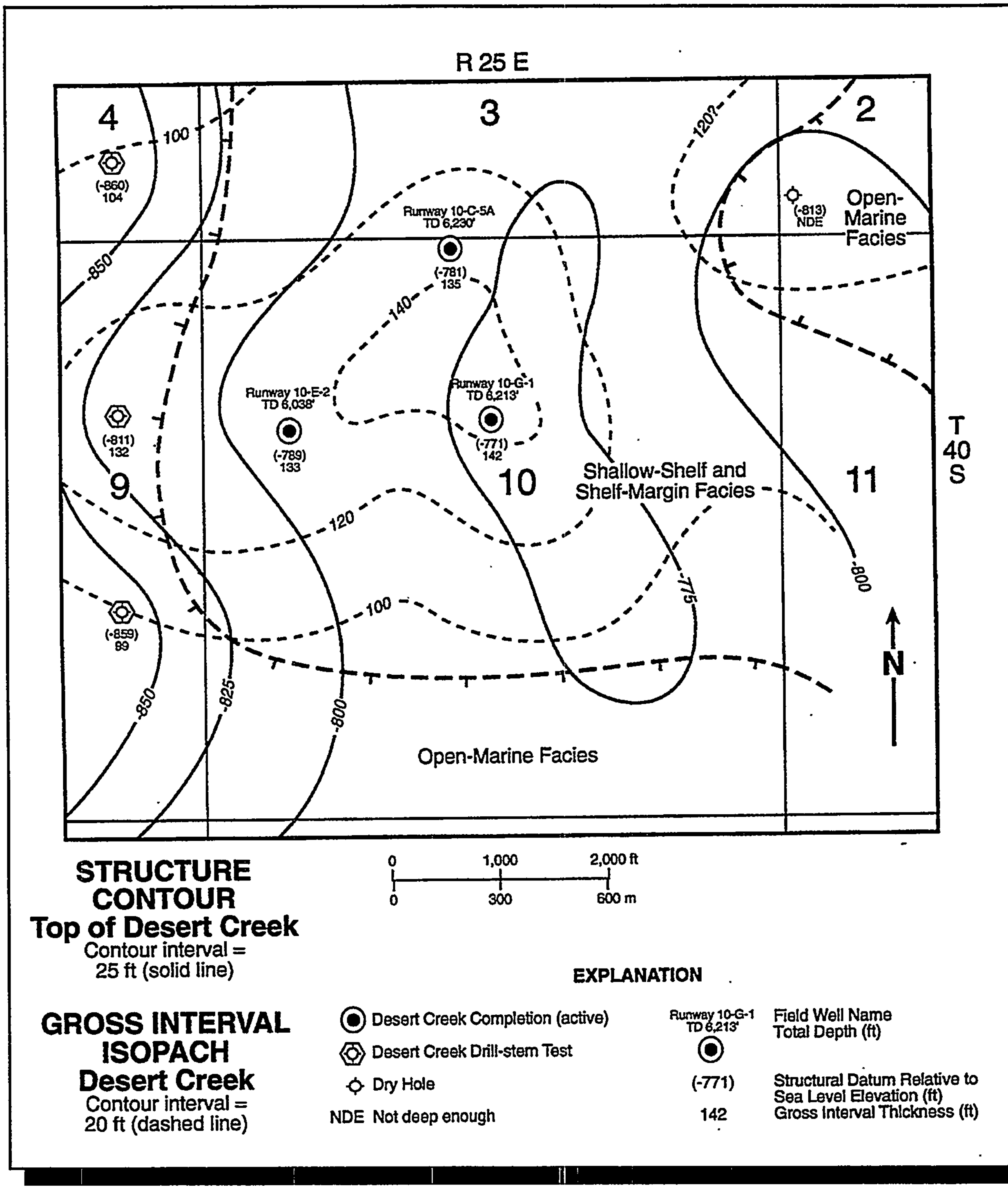

Figure 3.1. Combined Desert Creek zone structure contour and gross interval isopach map, Runway field, San Juan Co. Utah (Chidsey and others, 1996a).

Conventional cores from Runway field contain 15 to 19 lithologic units. Some units exhibit partial to complete dolomitization; late anhydrite plugging is also present. Pore types in these rocks include moldic, intercrystalline, and vuggy. At least three flooding surfaces are present and are likely barriers or baffles to fluid flow. Extensive karstification and solution-collapse brecciation has occurred in some of the middle to upper units.

The principal Desert Creek reservoir lithotypes in the bryozoan-dominated interval are bindstones and framestones. The principal reservoir lithotypes in the phylloid-algal-mound interval are porous lime bafflestones with some grainstones. Both carbonate buildups are interbedded with low-permeability wackestones and mudstones. Dolomitization has enhanced the reservoir potential of several lithotypes.

3.2 Reservoir Geostatistical Modeling

As at Anasazi field, significant spatial heterogeneity in the Runway field lithotypes and the reservoir properties field required a multi-stage procedure for incorporating the variation measured in conventional cores and outcrops into the Runway reservoir geostatistical model. Geostatistical modeling of the Runway reservoir incorporates unit thicknesses, flooding surfaces, and lithotypes observed in the core. Based on detailed examination of the cores and log data, and field observations from the Lower Ismay outcrop analogues, it was determined that a 50-layer geostatistical model would adequately capture the lithologic variability in the platform, mound-core, and supra-mound intervals (Chidsey, Brinton, Eby, and Hartmann, 1996; Chidsey, Eby, and Lorenz, 1996; Chidsey and others, 1996a; Culham and Lorenz, 1998). Observed lithologic, porosity, and permeability data from the three Runway wells were incorporated into the layering at the well locations. These model "conditioning" data were fixed throughout the subsequent modeling process.

Although the mound-core interval of the Runway Desert Creek reservoir is predominantly phylloid algal and bryozoan limestones, the overlying supra-mound dolomites and limestones exhibit a variety of lithotypes. A series of ten distinct lithotypes was identified within the Desert Creek reservoir. These lithotypes include carbonate mudstones, packstones/wackestones, grainstones, mound-building algal and bryozoan limestones, and solution collapse breccias. Several lithotypes are characterized by enhanced porosity and/or dolomitization.

The size and shape of the mound build-up area, the estimated areal extent of lithotype architectural bodies known to be present in the reservoir, and the constraints imposed by numerical modeling provided the framework used to define the areal grid for the Runway reservoir characterization and simulation model (figure 3.2). This model consists of 36 rows and 42 columns of grid cells, each measuring 180 feet square (54.9 m^2) (figure 3.2). The 42 by 36 areal-grid just spans the reservoir build-up, and encompasses an area of 1,125 acres (455 ha).

The internal architecture of the Desert Creek reservoir was modeled between the wells using a marked-point (Boolean) process for emplacement of the ten constituent lithotypes (figure 3.3). In the mound-core interval, the phylloid algal and bryozoan limestones were emplaced deterministically, corresponding to the seismic buildup isolith. A total of 20 preliminary geostatistical models were generated using this procedure for later sensitivity studies of the impact of reservoir continuity on production performance.

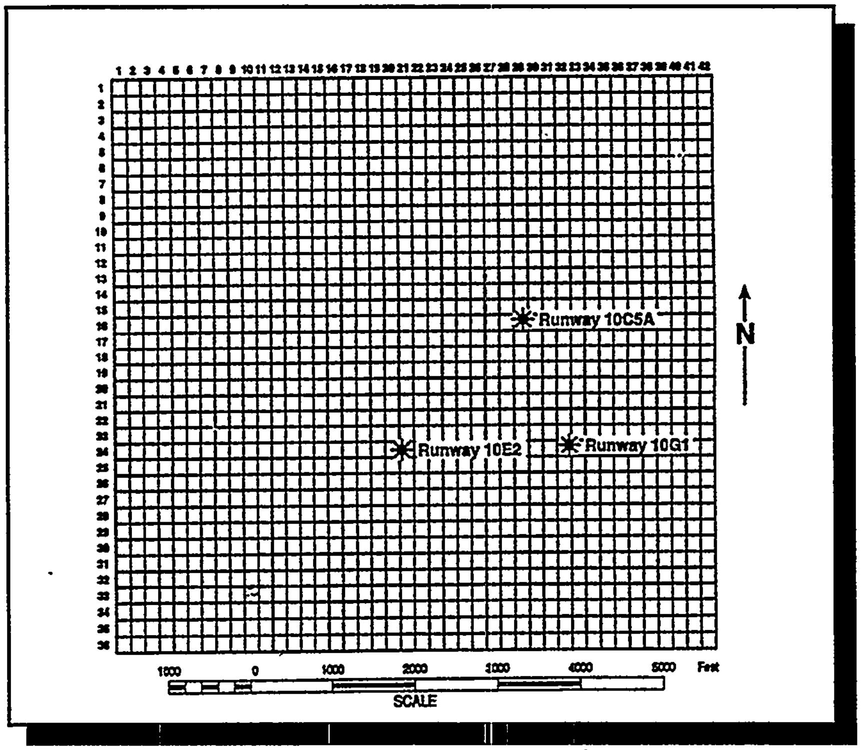

Figure 3.2. Runway field simulation grid and well locations.

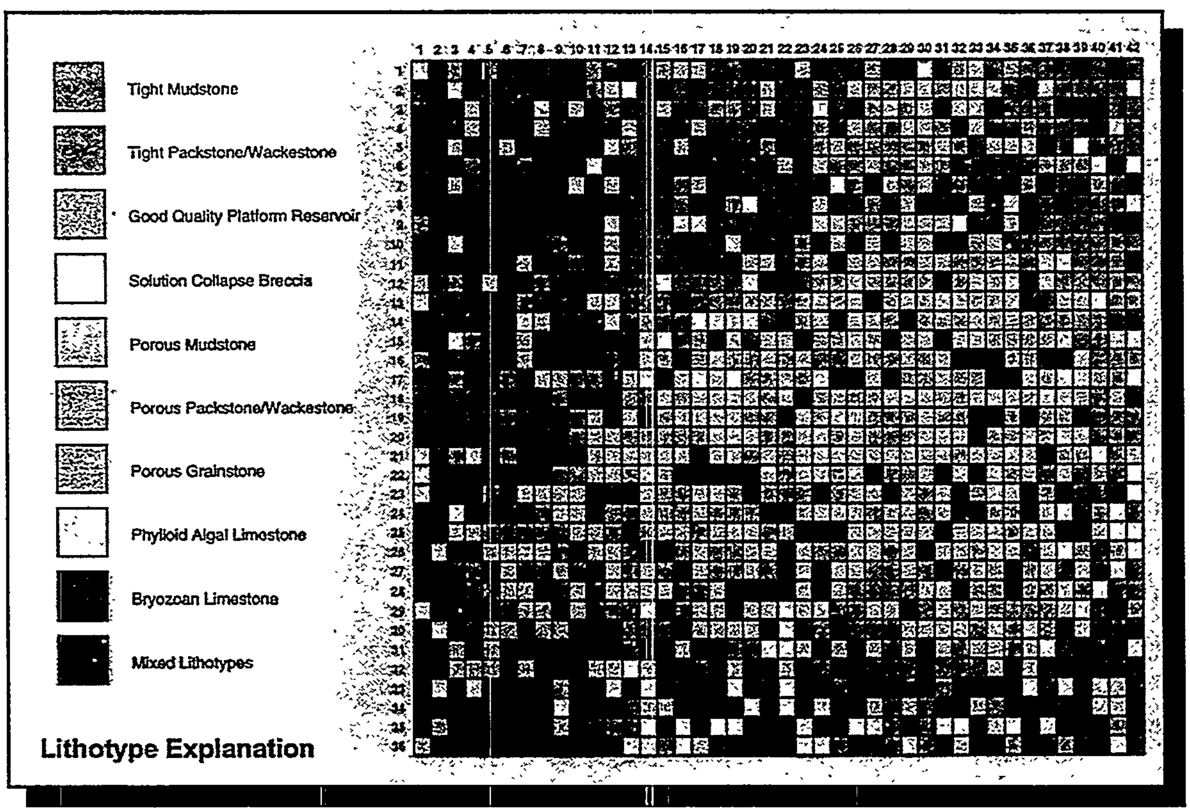

Figure 3.3. Spatial distribution of lithotypes at Layer 4 (supra-mound interval) from the 17-layer geostatistical Runway reservoir simulation model.

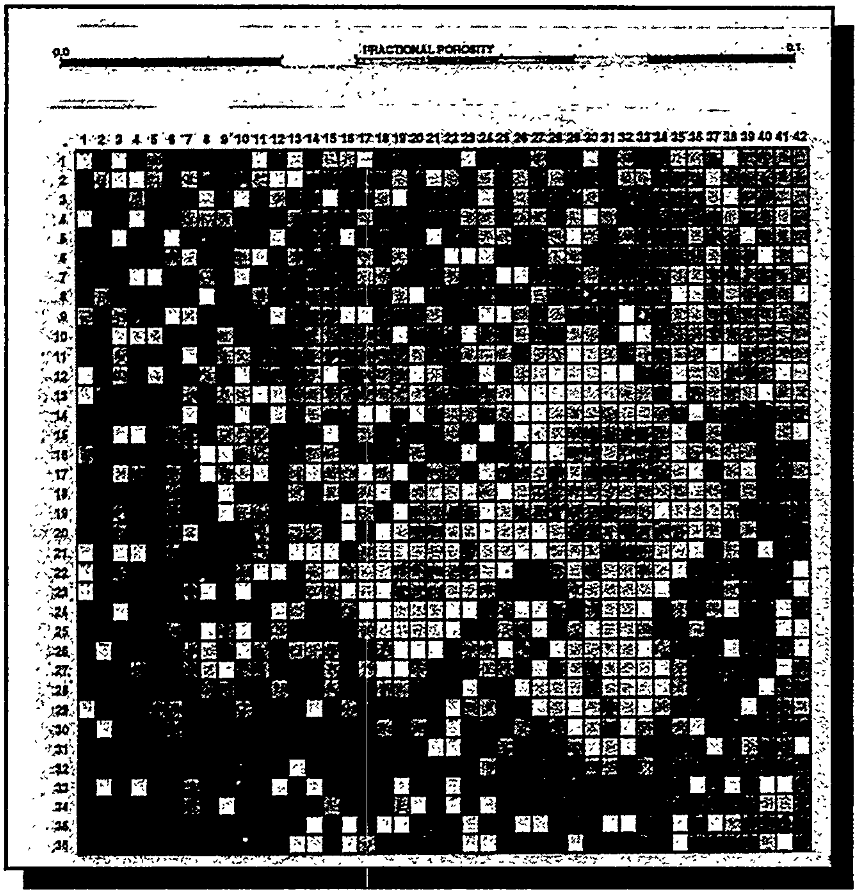

Figure 3.4. Spatial distribution of porosity (fractional) at Layer 4 from the 17-layer geostatistical Runway reservoir simulation model.

The initial architectural model was modified by pair-wise exchange of gridblocks to fit porosity constraints of both the local spatial variation and the overall (global) average porosity distribution grid derived from seismic amplitudes (figure 3.4). The pair-wise, block-exchange process for simulating Desert Creek reservoir porosity between the Runway wells was carried out using the well-known stochastic relaxation technique, "simulated annealing."

Several features of the 50-layer geostatistical models are noteworthy. First, the platform, mound-core, and supra-mound intervals are clearly distinguished by the continuous development of the highly permeable phylloid algal and bryozoan limestones in the mound core, contrasted with the heterogeneous, less permeable, but more porous, mixed lithotypes in the underlying platform interval, and in the overlying supra-mound interval (figure 3.5). Second, much of the off-mound area is occupied by carbonate mudstone, while most of the supra-mound interval directly above the mound core consists of non-mud lithotypes. This is in keeping with lithotype distributions in the Runway wells and in the Lower Ismay outcrops. In contrast to the previously studied Desert Creek carbonate mound reservoir at Anasazi field (figure 1.1), the best quality supra-mound lithotype (porous grainstone) bodies are largely restricted to the mound area, and do not extend far out into the adjacent off-mound areas as detrital "aprons," as seen at Anasazi. This is consistent with the generally deeper water environment inferred from the presence of bryozoan limestones at Runway field (Chidsey, Eby, and Lorenz, 1996).

Finally, because of computer flow-simulation runtime limitations, the number of layers in the Desert Creek reservoir model needed to be simplified from 50 to 15. Sensitivity studies indicated that most of the variation in effective properties are retained with careful scaling of porosity and permeability. Lithotypes were assigned to each of the 15-layer gridblocks according to the dominant lithotype in the corresponding 3.5 layers of the parent 50-layer geostatistical model. Porosity was volume-averaged for the 15-layer model, and effective permeability was computed by solution of the pressure equation using the field-scale reservoir simulator.

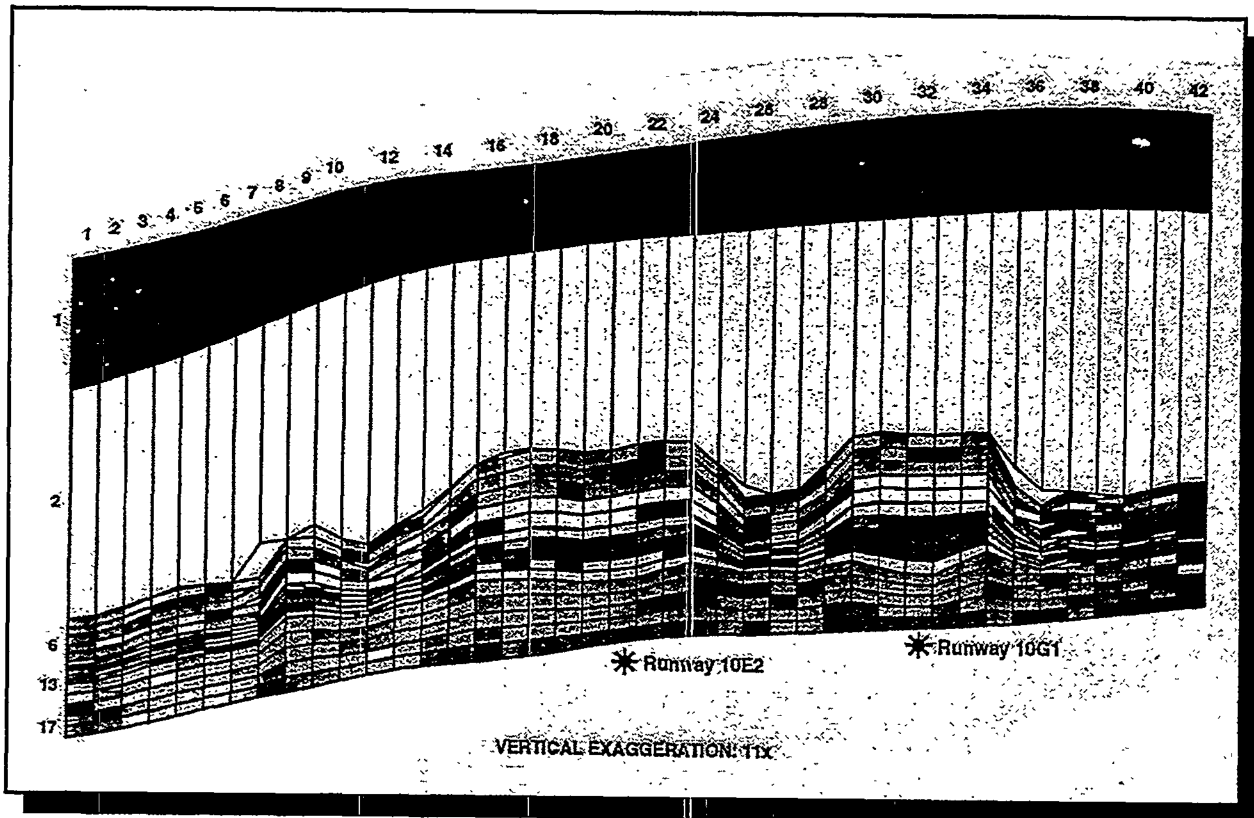

Figure 3.5. East-west cross section, through the Runway Nos. 10E-2 and 10G-1 wells, of the 17-layer geostatistical Runway reservoir simulation model displaying the spatial distribution of lithotypes in the Desert Creek and Ismay zones. See figure 3.3 for explanation of lithotypes.

The Runway reservoir model was further modified because the lower dolomite of the Upper Ismay is perforated and under production in the Runway No. 10G-1 well in addition to the Desert Creek carbonate mound reservoir. This separate Upper Ismay reservoir is isolated from the Desert Creek reservoir by as much as 115 feet (35.1 m) of non-producing section comprised of the Desert Creek anhydrite, Gothic Shale, Lower Ismay carbonates, and Hovenweep Shale. In the final Runway reservoir model, the Upper Ismay reservoir is designated as Layer 1, and the intervening interval isolating the Desert Creek and Upper Ismay reservoirs is Layer 2; thus, the final model consists of a total of 17 layers.

3.3 Carbon Dioxide Flood Performance Prediction

3.3.1 General Description

Compositional simulation was used to history match (model) predicted production to actual past production performance of the Runway field and to predict the performance of continued primary depletion and various CO_2 floods (Culham and Lorenz, 1998). The simulation study employed a stochastically generated reservoir description with 12 different facies. The reservoir fluid was characterized via an 11-pseudo-component equation-of-state which was calibrated using

CO_2-swelling tests conducted on crude oil from Anasazi field and the original, black oil, pressure-volume-temperature (PVT) data for Runway field (Chidsey, 1997a, 1997b; Lorenz and others, 1997, 1998). Gas-oil and water-oil relative permeabilities, capillary pressure, and rock pore-volume-compressibility data were generated for the three principal productive facies: phylloid algal limestone, enhanced porosity packstones/wackestones, and bryozoan limestone.

3.3.2 Simulation History Match and CO_2 Flood Prediction

The compositional study consists of production history matching and prediction phases. Key history match variables included individual well and field gas production rates, and periodically measured reservoir pressure values. Once the simulator was calibrated by generating a suitable match with actual production data it was used to predict the performance of the reservoir under continued primary production and CO_2-flood operations.

Carbon-dioxide flood performance predictions for several different operating conditions and well configurations have been completed. Figure 3.6 compares primary depletion performance versus CO_2 flooding using two horizontal injection wells. For this example the incremental oil recovery over primary as of January 1, 2012 is approximately 1.34 million stock tank bbls (MMSTB [0.21 million m^3]).

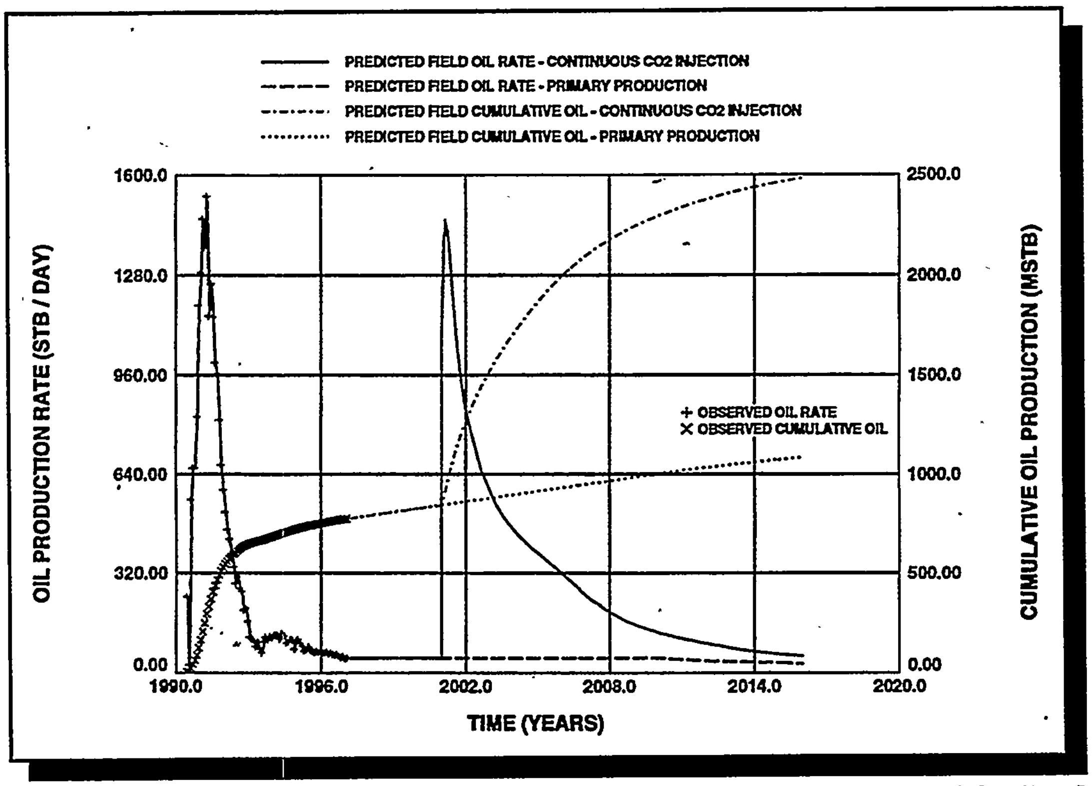

Figure 3.6. Oil recovery - primary depletion versus continuous CO_2 flood injection/flood recovery, Runway field.

Oil and gas saturations were modeled for the start of CO_2 injection. Ten years of primary production have generated a variable free gas saturation (0 to 40 percent) as well as producing 825,000 stock tank bbls (STB [131,175 m^3]) of oil. The simulator model also shows extensive gas segregation into the supra-mound interval.

Figure 3.7 illustrates the oil saturation distribution in the Ismay (upper layer) and Desert Creek (lower layer) zones at the start of CO_2 injection, based on a "cut away" through the Runway Nos. 10G-1 and 10E-2 production wells. The two injectors (shown in figure 3.7 as three-dimensional arrows pointing downward) are horizontal wells but the horizontal leg of each well is hidden from view. The uppermost injector is placed along the northwestern flank of the mound and the lowermost injector is placed along the southeastern flank of the mound. Both injectors were completed in the supra-mound interval.

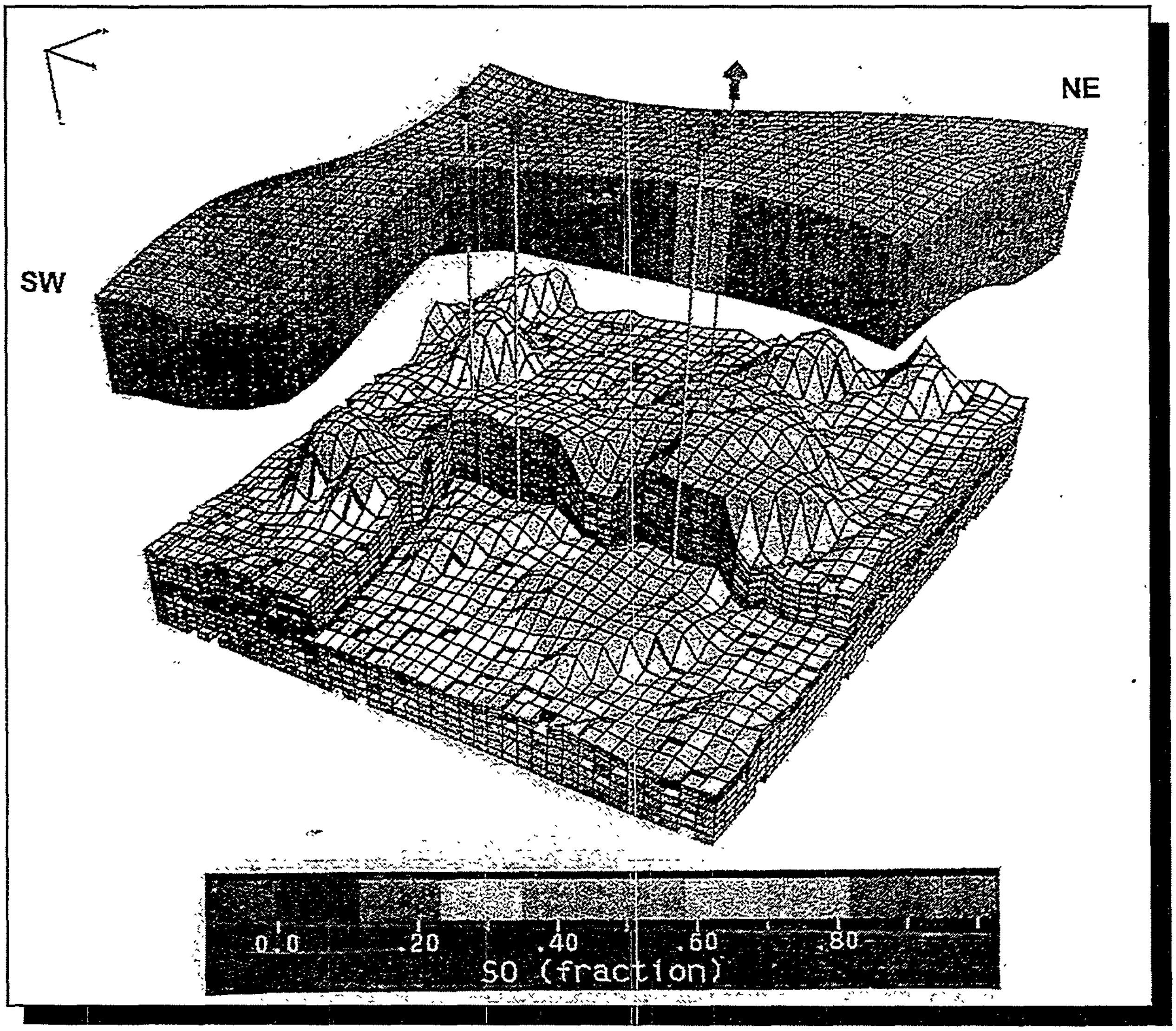

Figure 3.7. Block diagram displaying reservoir oil saturation distribution at the start of CO_2 injection. Shown is a "cut away" through one of the proposed horizontal injector wells and the Runway Nos. 10G-1 and 10E-2 production well locations. SO (fraction) is the oil saturation.

Figure 3.8 illustrates the oil saturation distribution after 4.5 years of CO_2 injection using two injectors. The figure shows two important points. First, reservoir pressurization redissolves all free hydrocarbon gas present at the start of injection, returning the majority of the reservoir to initial oil saturation values. Second, the volume of the reservoir contacted by the injected CO_2 shows a near zero residual oil saturation. This displaced oil is produced via the existing field production wells. Both the supra-mound and mound-core intervals have been swept by CO_2, but there is an uncontacted portion of the reservoir between the Runway Nos. 10G-1 and 10C-5A wells. This will be swept after additional CO_2 injection based on the simulation. The study also shows the extensive contact of reservoir volume by CO_2 (liquid phase mole fraction of CO_2) after 4.5 years of CO_2 injection. At the operating pressure level of 3,000 pounds per square inch (psi [20,790 kpa]), CO_2 and hydrocarbons are at or near miscible conditions. Thus, the oil displacement will be essentially complete (low residual oil saturation values).

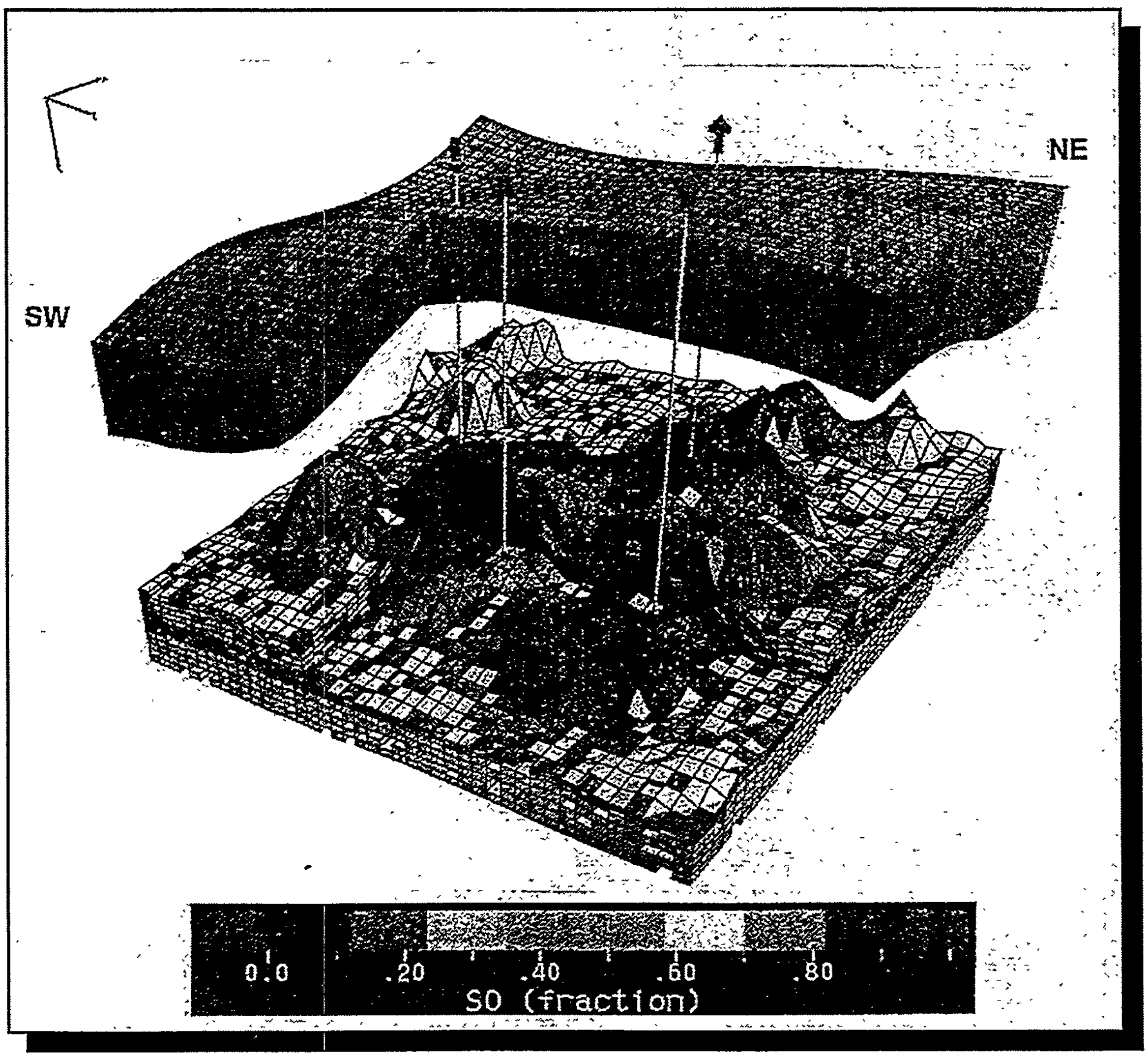

Figure 3.8. Block diagram displaying reservoir oil saturation distribution after 4.5 years of CO_2 injection, Runway field.

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4. ECONOMIC ASSESSMENTS OF RESERVOIR CO_2 FLOODS AND RECOMMENDATIONS

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and
Thomas C. Chidsey, Jr.; Utah Geological Survey

4.1 Overview

The principal objectives of Phase I of the project study were to develop detailed quantitative descriptions of shallow-shelf carbonate buildups (algal mounds) and use these descriptions coupled with composition simulation to predict the performance of the reservoirs in the mound complexes under three different reservoir recovery processes. The three processes are: primary depletion, CO_2 flooding, and waterflooding (Chidsey and Allison, 1998). The economic feasibility of implementing one or more recovery processes was also investigated.

The results of the compositional studies conducted for Anasazi and Runway fields indicate that CO_2 flooding is the only technically feasible recovery process suitable for these reservoirs. Based on this conclusion, CO_2-flood implementation costs were developed. Implementation costs, in conjunction with reservoir performance, production, and injection predictions, were used to complete a suite of economic assessment studies. One of the various CO_2-implementation options studied provided the best economic return; this option involved a continuous CO_2-injection case utilizing re-injection of unprocessed produced gas, a leased main injection compressor, and DOE cost share. This option provided a before-tax, net present value (NPV), discounted at 10 percent per year, of more than $5.9 million, and a before-tax rate of return (ROR) of 32 percent on a total investment of $2.7 million for Anasazi field. The profitability index (PI) of this particular implementation was determined to be 10.4 to 1.0. For Runway field, before-tax NPV, discounted at 10 percent per year, would be more than $3.1 million, and the before-tax ROR would be 30 percent on a total investment of $2.79 million. The PI of this particular implementation was determined to be 5.0 to 1.0.

The study results on predicted CO_2 flood responses and the associated economics, support the extension of the overall shallow-shelf carbonate evaluation program to Phase II. Phase II involves the implementation and completion of a CO_2 flood in the Anasazi or Runway reservoirs.

4.2 Anasazi Field

4.2.1 Economic Assessment of CO_2 Flood

Using reservoir simulation-based performance predictions and current CO_2-flood implementation costs, detailed economic assessments were conducted for a number of different CO_2-flood options. These sets of studies indicated that:

1. A CO_2 flood of the Anasazi reservoir has robust economics. With DOE participation, the project would have a ROR of 62 percent, a payout of 35 months, a PI of 15 to 1, and a discounted (10 percent) NPV in excess of $12.5 million. Even without DOE participation the economics remain robust with a ROR of 48 percent, a payout of 39 months, a PI of 8 to 1, and a discounted NPV of over $11.0 million. The capital requirements would be $3.146 million.

2. Leasing the compressor on a five-year contract basis is better economically than purchasing the compressor. Leasing improves the ROR by approximately $1.0 million.

3. The benefit from separating CO_2 from hydrocarbons in produced gas and using the hydrocarbons for fuel and sales are offset by the large capital investment required for a membrane separation facility. Thus, re-injection of all produced gas without processing is economically more attractive than implementing a CO_2 flood with gas processing.

4. The difference between minimum and maximum cost options for installation of flow/injection lines and the CO_2 supply is approximately $1.0 million; however, the economics are still robust. With DOE cost sharing, the ROR is 56 percent with a PI of 11.5 to 1.

5. The ROR and PI are not significantly different for a process using blowdown after six years of CO_2 injection versus the continuous CO_2 injection case. However, the NPV is substantially less with blowdown (approximately $1.4 million). The lower NPV is a result of lower oil recovery for the blowdown case (800,000 STB [127,000 m^3] less than the continuous injection case).

Production data and injection gas requirements, including CO_2 make-up purchases, were used to assess, from an economic standpoint, the financial merits of CO_2 flood with an 8.0 million cubic feet of gas per day (MMCFGPD [230,000 m^3/d]) total injection rate commencing January 1, 2000. The economic assessment, using two compressor options, was conducted assuming the following conditions: (1) leased compressor (option 1 - $19,500/option 2 - $23,500 [same compressor with a different engine]), (2) CO_2 supply line construction using the minimum costs option ($825,000), (3) no gas processing, and (4) cost sharing by DOE. This assessment demonstrates that CO_2 flooding provides both an adequate flood response with either of the compressor options, an acceptable economic ROR of 32 percent, and a payout of 36 months. A discounted (10 percent) NPV of $5.9 million could be realized by implementing a CO_2 flood under the proposed conditions.

In summary, if the CO_2 flood performs as predicted, it is a financially robust process for increasing the reserves of the Anasazi reservoir; however, the ROR and NPV are very sensitive to oil prices (figures 4.1 and 4.2). Therefore, economics should be re-run before installation of injection facilities.

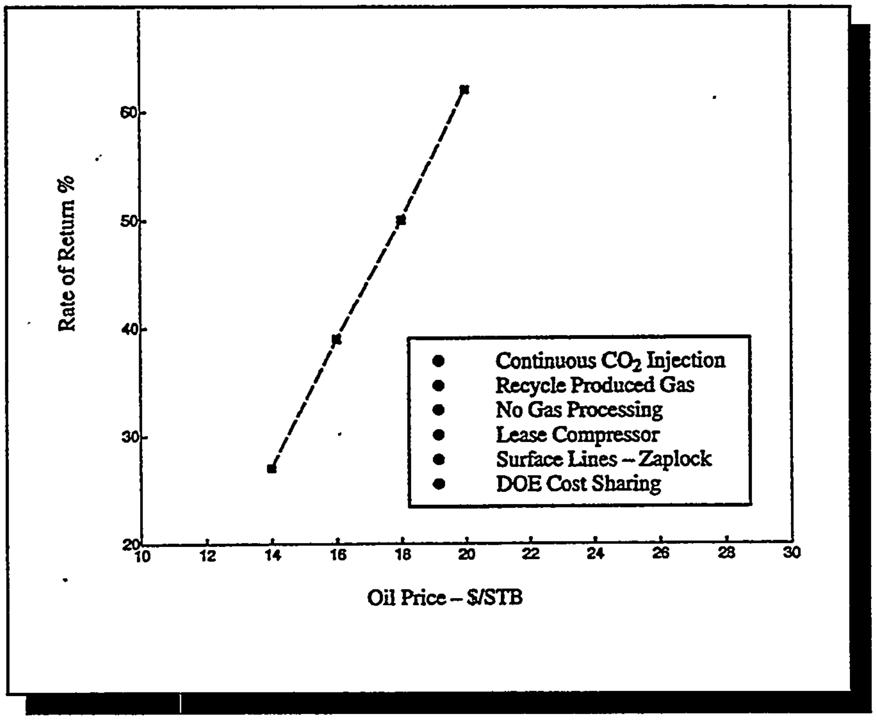


Figure 4.1. Rate of return versus price of oil, Anasazi field CO_2 flood at high rate.

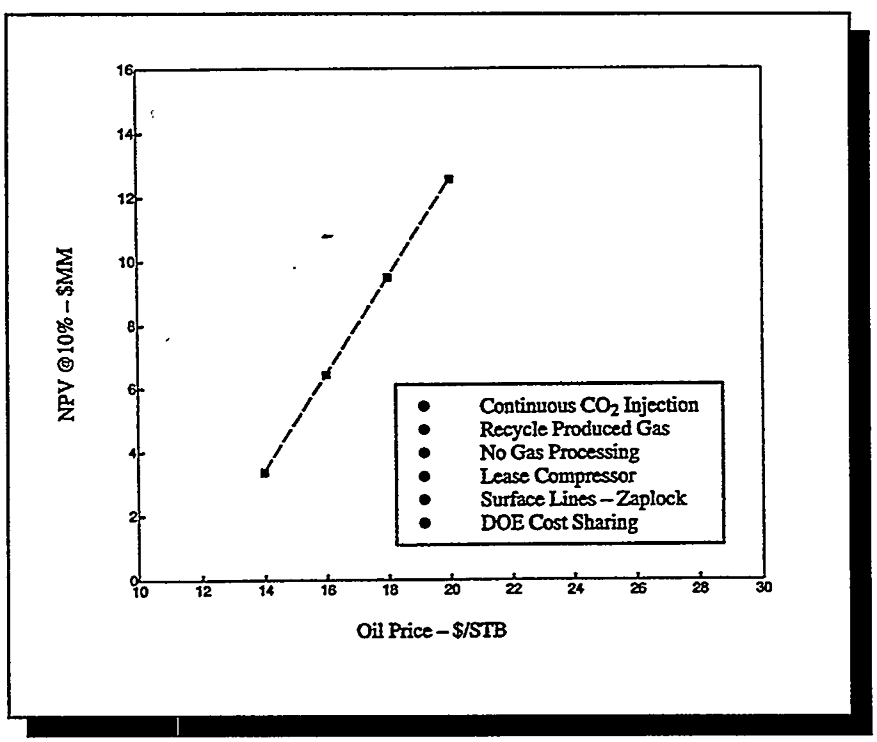


Figure 4.2. Net present value versus price of oil, Anasazi field CO_2 flood at high rate.

4.2.2 Recommendations

Based on the results of the completed geologic study, reservoir performance predictions, and the associated economic assessment of implementing a CO_2 flood in the Anasazi reservoir, the following production scenario is recommended:

1. A CO_2-injection project should be implemented in the Anasazi reservoir.

2. A field injectivity test using CO_2 should be conducted on the Anasazi No. 6H-1 well, a project well in the western part of the field, to establish long-term injection rate data before committing to further Phase II work.

3. After the CO_2 source is obtained for Anasazi field, economics should be re-run to see if the project is still economically feasible at current prices.

4. The main injection compressor should be leased rather than purchased to provide the most operating flexibility and least financial risk.

5. Produced gas processing is not required for a single field CO_2-flood implementation case. It is not required from a reservoir processing standpoint nor is it justified economically.

6. Horizontal well injectivity should be predicted from the appropriate well-test models after calibration with vertical well-test data.

4.3 Runway Field

4.3.1 Economic Assessment of CO_2 Flood

Using reservoir simulation-based performance predictions and current CO_2-flood implementation costs, detailed economic assessments were conducted for five different CO_2-flood options. This set of studies indicated that:

1. A CO_2 flood of the Runway reservoir has acceptable economics. With DOE participation the project would have a ROR of 30 percent, a payout of 32 months, a PI of 5 to 1, and a discounted (10 percent) NPV in excess of \$3.1 million. Even without DOE participation the economics remain acceptable with a ROR of 21 percent, a payout of 39 months, a PI of 2.8 to 1, and a discounted NPV of almost \$2.0 million. The capital requirements would be \$2.789 million.

2. Based on the Anasazi study, leasing rather than purchasing a compressor was adopted for the Runway evaluation.

3. The difference between a minimum and maximum cost option for installation of flow/injection lines and the CO_2 supply is approximately $233,000; however, the economics are still acceptable. With DOE cost sharing, the ROR is 29 percent with a PI of 4.8 to 1, and a discounted NPV of $2.9 million.

4. Most economic evaluations exhibited negative cash flows in the year 2008, when operating costs exceed revenues. At this point the projects were terminated. However, the reservoir process should have been changed from continuous CO_2 injection to blowdown and the economics re-run. The additional recovery from blowdown, without the operating costs associated with CO_2 injection, would improve economic returns. Thus, additional prediction runs should be completed to assess the economic effect of conversion to blowdown.

In summary, if the CO_2 flood performs as predicted, it is a financially acceptable process for increasing the reserves of the Runway reservoir. As in Anasazi field, the ROR and NPV are very sensitive to oil prices (figures 4.3 and 4.4). Therefore, economics should also be re-run before installation of injection facilities.

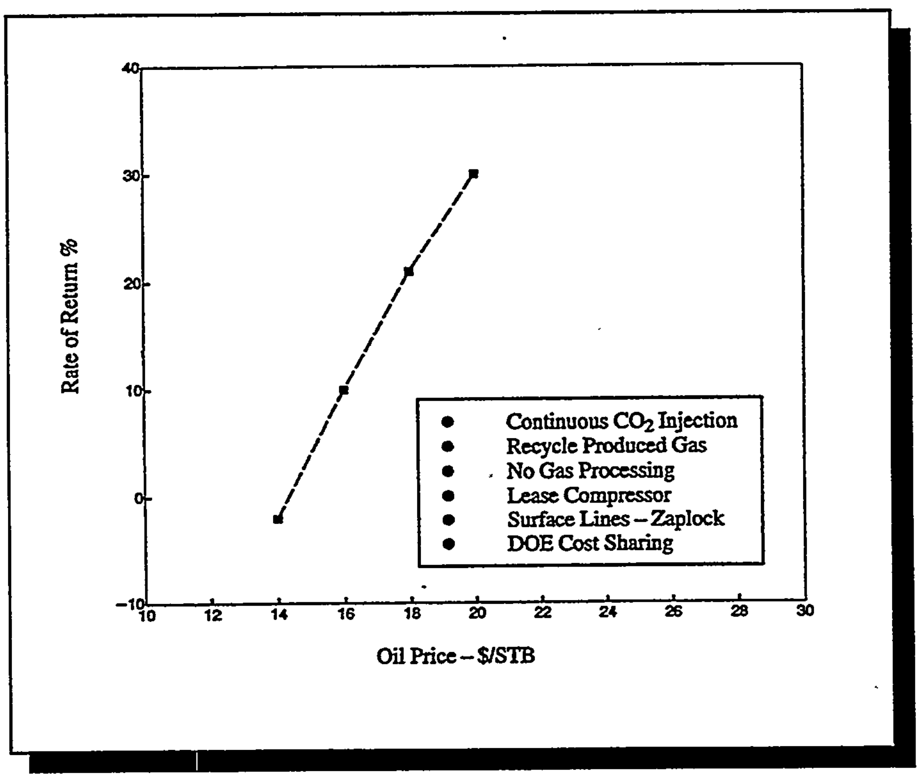


Figure 4.3. Rate of return versus price of oil, Runway field CO_2 flood at high rate.

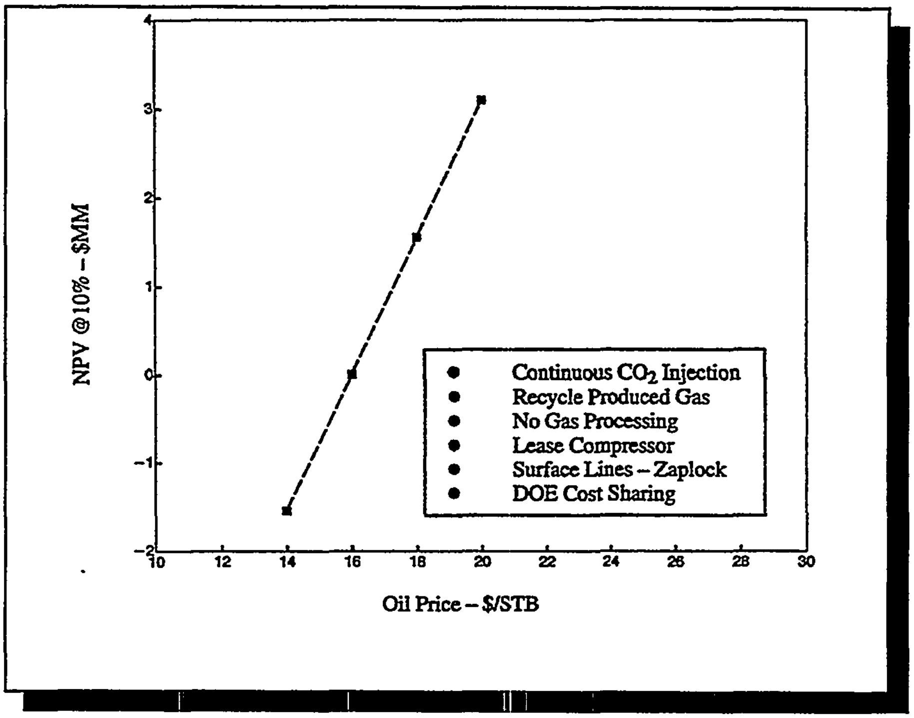


Figure 4.4. Net present value versus price of oil, Runway field CO_2 flood at high rate.

4.3.2 Recommendations

Based on the results of the completed geologic study, reservoir performance predictions, and economic evaluations using a \$20/bbl oil price of a CO_2 flood in Runway field, the following production scenario is recommended.

1. A CO_2-injection project could be implemented in the Runway reservoir.

2. A field injectivity test using CO_2 should be conducted on a Runway well to establish long-term injection rate data before committing to further Phase II work.

3. After the CO_2 source is obtained for Runway field, economics should be re-run to see if the project is still economically feasible at current prices.

4. The main injection compressor should be leased rather than purchased to provide the most operating flexibility and least financial risk.

5. The economic trade-off of shutting in producers during reservoir fill-up versus continued production during fill-up should be assessed.

6. Horizontal well injectivity should be predicted from the appropriate well-test models after calibration with vertical well-test data.

4.4 Reserve and Recovery Determinations for Project Fields

The cumulative production for the five project fields as of January 1, 1999, is summarized in table 4.1. Heron North field is currently shut-in (Utah Division of Oil, Gas and Mining, 1999). Primary recovery and original oil in place (OOIP) (table 4.2) were determined from volumetric reserve calculations, material balance calculations, and decline curve extrapolations as well as refined geologic characterization. These volumetric calculations were made by evaluating well logs and reservoir aerial extent (as defined by seismic reflection data) coupled with reservoir geometry. Material balance and decline curve calculations utilized the production and pressure history. Knowing the OOIP and the primary recovery, the amount of oil left behind was calculated. Finally, utilizing the results from the simulation studies of Anasazi and Runway fields, estimates were made of the sweep efficiencies for CO_2 flooding and the ultimate enhanced recovery for all project fields (table 4.2). Using an average predicted oil recovery of 71.8 percent (percent recovery of remaining oil in place after primary recovery) as derived for the Runway and Anasazi reservoirs, allows reserve additions to be estimated if CO_2 is also applied to all project fields. The reserve additions for all five fields totals over 8.2 million STB (1.3 million m^3) of oil.

Table 4.1. Cumulative production from project fields (Utah Division of Oil, Gas and Mining, 1999).

Project Field	Cumulative Production*		
	Oil (bbl)	Gas (MCF)	Water (bbl)
Anasazi	1,883,393	1,625,892	29,942
Blue Hogan	311,842	303,938	1,903
Heron North	206,446	328,713	34,820
Mule	410,792	273,247	31,710
Runway	801,889	2,675,307	5,987

* As of January 1, 1999

Table 4.2. Reserve and recovery determinations.

Project Field	OOIP* (MSTB)	Primary Recovery		ROIP** (MSTB)	CO_2 Flood Projected Recovery (MSTB)	CO_2 Flood Recovery % ROIP
		Oil (MSTB)	Gas (MCF)			
Anasazi†	4,706	2,000	1,890,000	2,706	2,208	81.6
Blue Hogan	2,530‡	321	968,000	2,209	1,586	71.8
Heron North	2,640‡	216	2,650,000	2,424	1,740	71.8
Mule	2,000‡	454	288,000	1,546	1,110	71.8
Runway	3,372	825	2,830,000	2,547	1,577	61.9

* Original oil in place (thousand stock tank barrels [MSTB]), mound-core and supra-mound intervals (includes platform interval in Runway)

** Remaining oil in place

† High-rate case starting CO_2 flood January 1, 2000

‡ Estimate based on approximate volumetric data

4.5 Conclusions

Phase I of the project showed that a CO_2 flood was technically superior to a waterflood and was economically feasible. For Anasazi field, an optimized CO_2 flood is predicted to recover a total 4.21 million STB (0.67 million m^3) of oil. This represents an increase of 1.65 million STB (0.26 million m^3) of oil over predicted primary depletion recovery as of January 1, 2012. The projected 4.21 million STB of oil production represents in excess of 89 percent of the OOIP in the mound complex and 36.8 percent of the OOIP of the total system modeled. For Runway field, the best CO_2 flood is predicted to recover a total of 2.4 million STB (0.38 million m^3) of oil. This represents an increase of 1.58 million STB (0.25 million m^3) of oil over predicted primary depletion recovery as of January 1, 2012. The projected 2.4 million STB of oil production represents 71 percent of the OOIP in the mound complex and 48 percent of the OOIP of the total system modeled, excluding the Ismay zone above the Desert Creek zone.

The UGS recommends continuation of the project into Phase II (Budget Period II) with a field demonstration of the technique on Anasazi or Runway fields. The field demonstration includes: conducting a CO_2 injection test(s), obtaining a CO_2 source and fuel gas for the compressor, rerunning project economics, drilling a development well(s) (vertically or horizontally), purchasing and installing injection facilities, monitoring field performance, and validating and evaluating the techniques.

The demonstration will prove (or disprove) CO_2-flood viability and thus help determine whether the technique can be applied to the other small carbonate buildup reservoirs in the Paradox basin. The financial impact of simultaneous or sequential flooding of a series of reservoirs should also be assessed. This will quantify the upside potential of CO_2 flooding for the entire basin from both a reserves and an economic standpoint. The knowledge gained in matching historical production and predicting the future performance of the Anasazi and Runway reservoirs indicates that the overall mound geometry and internal facies architecture are critical to matching and predicting production performance. Thus, each mound will likely require an individual reservoir study to quantify its CO_2-flood potential and identify the appropriate implementation strategy to maximize oil recovery.

4.6 References

Chidsey, T.C., Jr., and Allison, M.L., compilers, 1998, Increased oil production and reserves utilizing secondary/tertiary recovery techniques on small reservoirs in the Paradox basin, Utah - annual report: U.S. Department of Energy, DOE/BC/14988-10, 66 p.

Utah Division of Oil, Gas and Mining, 1999, December oil and gas production report: Utah Department of Natural Resources Division of Oil, Gas and Mining, non-paginated.

5. TECHNOLOGY TRANSFER

Thomas C. Chidsey, Jr.; Utah Geological Survey

The UGS is the Principal Investigator and prime contractor for four government-industry cooperative petroleum-research projects, including the Paradox basin project. These projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better, more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. The Class II Paradox basin and the Class I Bluebell field (Uinta Basin) projects include practical oil-field demonstrations of selected technologies. The third project involves geological characterization and reservoir simulation of the Ferron Sandstone on the west flank of the San Rafael uplift as a surface analogue of a fluvial-dominated, deltaic reservoir. The fourth project involves establishing a log-based correlation scheme for the Tertiary Green River Formation in the southwestern Uinta Basin to help identify new plays and improve the understanding of producing intervals. The DOE and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and state agencies are co-funding the four projects.

The UGS will release all products of the Paradox basin project in a series of formal publications. These will include all the data as well as the results and interpretations. Syntheses and highlights will be submitted to refereed journals as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodicals *Petroleum News* and *Survey Notes*, and on the project Internet home page.

Project publications, materials, plans, and objectives were displayed at the UGS booth during the 1998 annual national convention of the AAPG, May 17-20, in Salt Lake City, Utah. Project materials were also displayed at the UGS booth during the UGS-hosted Petroleum Technology Transfer Council (PTTC) symposium entitled *Fractured Reservoirs: A Symposium on Current Research, Modeling, and Enhanced Recovery Techniques*, October 23, 1998, and at the 1998 annual meeting of the Interstate Oil and Gas Compact Commission (IOGCC), December 6-8, 1998, both in Salt Lake City, Utah. The PTTC symposium was attended by 50 petroleum geologists and engineers. The IOGCC represents 36 oil- and gas-producing states. Attendees included government officials and regulators, industry representatives, state geologists, and politicians. The IOGCC assists states in maximizing domestic oil and gas production while protecting the environment. Three to four UGS scientists staffed the display booth at these events. Project displays will be included as part of the UGS booth at meetings throughout the duration of the project.

Construction of the new UGS Geological Sample Library, which now houses over 3,200 feet (975 m) of core from project wells, was completed in September 1998. During the Geological Sample Library open house, held on October 6, 1998, the public was invited to interact with project team members by examining Runway field core and reviewing poster displays of reservoir modeling, simulation results, and project objectives (figure 5.1).

Abstracts were submitted, and accepted, on the results of diagenetic analysis and an overview of Mule field for technical presentations at the 1999 AAPG national and Rocky Mountain Section meetings.

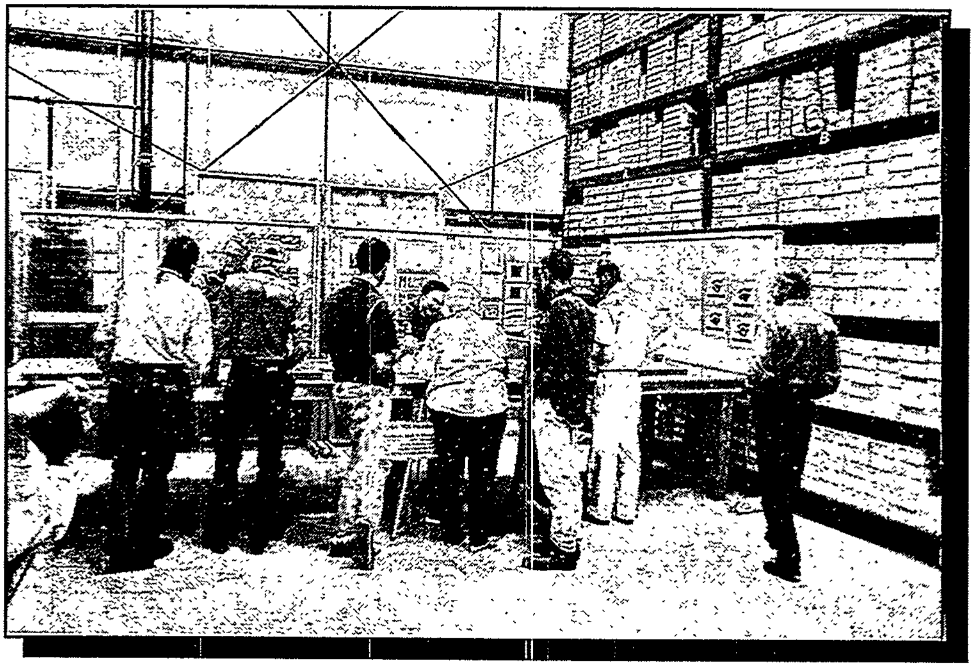


Figure 5.1. Attendees at the new UGS Sample Library open house examine core from the Runway project field, San Juan County, Utah. Photo by Tim Madden, Utah Geological Survey.

5.1 Utah Geological Survey *Petroleum News*, *Survey Notes*, and Internet Web Site

The purpose of the UGS *Petroleum News* newsletter is to keep petroleum companies, researchers, and other parties involved in exploring and developing Utah energy resources, informed of the progress on various energy-related UGS projects. *Petroleum News* contains articles on: (1) DOE-funded and other UGS petroleum project activities, progress, and results, (2) current drilling activity in Utah including coalbed methane development, (3) new acquisitions of well cuttings, core, and crude oil at the UGS Geological Sample Library, and (4) new UGS petroleum publications. The purpose of *Survey Notes* is to provide nontechnical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision makers, and the public. *Survey Notes* is published three times yearly and *Petroleum News* is published semi-annually. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Paradox basin project (more than 300 as of February 1999) or other DOE-sponsored projects.

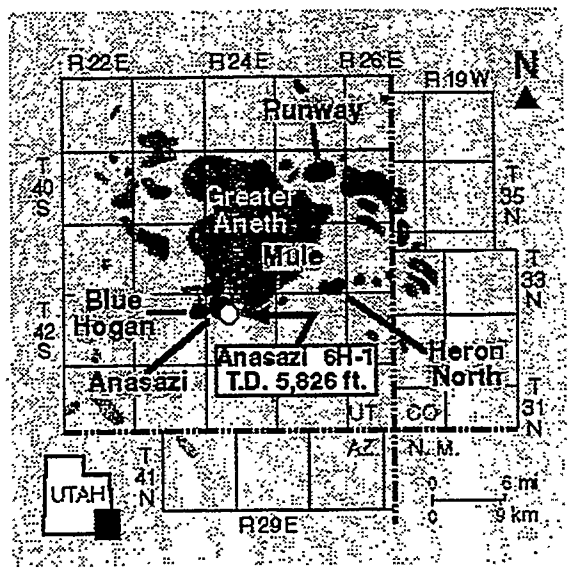
The UGS established a web site on the Internet, http://www.ugs.state.ut.us/. This site includes a page under the heading *Economic Geology Program*, that describes the UGS/DOE cooperative studies (Paradox basin, Ferron Sandstone, Bluebell field, Green River Formation), contains the latest issue of *Petroleum News*, and has a link to the U.S. Department of Energy web site. Each UGS/DOE cooperative study also has its own separate page on the UGS web site. The Paradox basin project page (http://www.ugs.state.ut.us/paradox.htm) contains: (1) a project location map, (2) a description of the project, (3) a list of project participants and their postal addresses and phone numbers, (4) executive summaries from the first, second, and third annual reports, (5) each of the project Quarterly Technical Progress reports, and (6) a reference list of all publications that are a direct result of the project (figure 5.2).

Utah Geological Survey

Paradox Basin - DOE Class II Study

Reports

- **Project description**
- **Project participants**
- **First Annual Technical Report**
- **Second Annual Technical Report**
- **Quarterly Technical Progress Reports:**
  - 1995 1st Quarterly Report
  - 1995 2nd Quarterly Report
  - 1995 3rd Quarterly Report
  - 1995 4th Quarterly Report
  - 1996 1st Quarterly Report
  - 1996 2nd Quarterly Report
  - 1996 3rd Quarterly Report
  - 1996 4th Quarterly Report
  - 1997 1st Quarterly Report
  - 1997 2nd Quarterly Report
  - 1997 3rd Quarterly Report



References

- **Publications resulting from the study**

For more information on the Paradox Basin Project, contact Tom Chidsey, (801) 537-3364, email: nrugs.tchidsey@state.ut.us. For copies of reports with tables and figures, contact Roger L. Bon, (801) 537-3363, email: nrugs.rbon@state.ut.us.

Bluebell Field Project / Ferron Sandstone Project
Petroleum News / Economic Geology Program

UGS Home

Figure 5.2. The Paradox basin project page, http://www.ugs.state.ut.us/paradox.htm, from the UGS Internet web site.

5.2 Presentations

The following technical and nontechnical presentations were made during the year as part of the Paradox basin project technology transfer activities. These presentations described the project in general and gave detailed information on the reservoir characterization, exploration trends, geostatistics, reservoir models, and simulations.

"Reservoir Characterization of a Heterolithic Carbonate Mound, Runway Field, Paradox Basin, Utah" by D.M. Lorenz, W.E. Culham, T.C. Chidsey, Jr., and Kris Hartmann; American Association of Petroleum Geologists Annual Convention, Salt Lake City, Utah, May 1998.

"Upper Devonian Carbonate Buildups Impersonating Paradox Basin Phylloid Algal Mounds" by David E. Eby; Utah Geological Association monthly meeting, Salt Lake City, Utah, January 1999.

5.3 Project Publications

Chidsey, T.C., Jr., 1998, Paradox basin project yields successful horizontal well: Utah Geological Survey, Survey Notes v. 31, no. 1, p. 3-4.

Chidsey, T.C., Jr., and Allison, M.L, 1998, compilers, Increased oil production and reserves utilizing secondary/tertiary recovery techniques on small reservoirs in the Paradox basin, Utah - annual report: U.S. Department of Energy, DOE/BC/14988-10, 66 p.

Lorenz, D.M., Culham, W.E., Chidsey, T.C., Jr., and Hartmann, Kris, 1998, Reservoir characterization of a heterolithic carbonate mound, Runway field, Paradox basin, Utah [abs.]: American Association of Petroleum Geologists Annual Convention, Extended Abstracts II, p. A415.

Montgomery, S.L., 1998, Pennsylvanian carbonate buildups, southern Paradox basin - new opportunities for increased reserves: Petroleum Frontiers, v. 15, no. 4, 76 p.

Montgomery, S.L., Chidsey, T.C., Jr., Eby, D.E., Lorenz, D.M., and Culham, W.E., 1999, Pennsylvanian reserves in heterogeneous, shallow-shelf reservoirs: American Association of Petroleum Geologists Bulletin, v. 83, no. 2, p. 193-210.