FOSSIL ENERGY

DOE/BC/14988-9
(DE96001301)

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

Annual Report
February 9, 1996 to February 8, 1997

By
Thomas C. Chidsey, Jr.

MASTER

August 1997

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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DOE/BC/14988-9
Distribution Category UC-122

Increased Oil Production And Reserves Utilizing Secondary/Tertiary Recovery Techniques On Small Reservoirs In The Paradox Basin, Utah

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Prepared for
BDM-Oklahoma/
U.S. Department of Energy
Assistant Secretary for Fossil Energy

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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 are being evaluated for waterflood or carbon-dioxide-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.

Outcrops of the Paradox Formation Ismay zone along the San Juan River of southeastern Utah, provided a small-scale analogue of the reservoir heterogeneity, flow barriers and baffles, and lithofacies geometry observed in the fields. This analogue included: (1) a phylloid algal mound, (2) a "reef wall", and (3) a carbonate detrital wedge and fan. These characteristics are being incorporated in the reservoir simulation model.

Three generalized facies belts are present in the Desert Creek zone of the Paradox Formation: (1) open-marine, (2) shallow-shelf and shelf-margin, and (3) intra-shelf, salinity-restricted facies. The shallow-shelf and shelf-margin facies belt, where all five project fields are located, includes shallow-shelf carbonate buildups, platform-margin calcarenites, and platform-interior carbonate muds and sands. Productive carbonate buildups can be divided into three types: (1) phylloid algal (further subdivided into shelter, mud-rich, and solution-breccia facies), (2) coralline algal, and (3) bryozoan. Hydrocarbons are stratigraphically trapped in porous and permeable lithotypes within the mound-core intervals, particularly phylloid-algal buildup facies, and the heterogeneous supra-mound intervals of the Desert Creek carbonate buildups.

Structure contour maps on the top of the Desert Creek zone of the Paradox Formation and gross Desert Creek interval isopach maps were constructed for the project fields. These maps were combined to show carbonate buildup trends, define limits of field potential, and indicate possible combination structural and stratigraphic traps. Basic reservoir parameters and production histories for each field were also compiled and summarized.

A new seismic program was permitted and conducted in the Mule field. The additional seismic data were used to determine the extent of the algal-mound buildup in the field and the orientations and lengths of any horizontal development drilling.

The Anasazi field was selected for the initial geostatistical modeling and reservoir simulation. The key to increasing ultimate recovery from the Anasazi field (and similar fields in the basin), is to design either waterflood or carbon-dioxide-miscible flood projects capable of forcing oil from high-storage-capacity but low-recovery supra-mound units into the high-recovery mound-core units. The results of statistical modeling are being used in reservoir simulations to test and design those types of projects. One of ten geostatistical realizations representing the full range of possible configurations of internal architecture and distribution of reservoir properties was selected for conducting the history matching and reservoir performance phase of the reservoir simulation.

A compositional simulation approach is being used to model primary depletion, waterflood, and CO_2-flood processes. During this second year of the project, team members performed the

following reservoir-engineering analysis of Anasazi field: (1) relative permeability measurements of the supra-mound and mound-core intervals, (2) completion of geologic model development of the Anasazi reservoir units for use in reservoir simulation studies including completion of a series of one-dimensional, carbon dioxide-displacement simulations to analyze the carbon dioxide-displacement mechanism that could operate in the Paradox basin system of reservoirs, and (3) completion of the first phase of the full-field, three-dimensional Anasazi reservoir simulation model, and the start of the history matching and reservoir performance prediction phase of the simulation study.

Technology transfer during the second project year consisted of booth displays for various national and regional professional conventions, technical presentations, publications, a project workshop and field trip to outcrop analogues and field facilities, newsletters, and establishment of a project home page on the Internet.

EXECUTIVE SUMMARY

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 (23,850,000-31,800,000 m^3) 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-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 in Bartlesville, Oklahoma. This report covers research and technology transfer activities for the second project year (February 9, 1996 through February 8, 1997). This work includes evaluation of outcrop analogues, reservoir facies characterization, reservoir mapping, seismic acquisition, geostatistical modeling, production history matching, and reservoir performance prediction. The results can be applied to similar reservoirs in many U.S. basins.

Outcrops of the Paradox Formation Ismay zone along, the San Juan River of southeastern Utah, provided small-scale analogues of reservoir heterogeneity, flow barriers and baffles, and lithofacies geometry. Cyclic sedimentation is recorded by four dominant facies recognized in a single, shoaling-upward sequence: (1) substrate carbonate, (2) phylloid algal, (3) intermound, and (4) skeletal capping. The study site, located in Wild Horse Canyon, is interpreted as consisting of three principal features: (1) a phylloid algal mound with grainstone buildups deposited at or near sea level, (2) a "reef wall" that formed in a higher energy, more marginal setting than the mound, and (3) a carbonate detrital wedge and fan consisting of shelf debris. These characteristics are being incorporated in the reservoir simulation model.

Reservoir data, cores and cuttings, geophysical logs, various reservoir maps, and other information from the project fields and regional exploratory wells are being 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. Cores were described from selected project wells with special emphasis on bounding surfaces of possible flow units.

Regionally three generalized facies belts were identified: (1) open-marine, (2) shallow-shelf and shelf-margin, and (3) intra-shelf, salinity-restricted facies. 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. Productive carbonate buildups can be divided into three types: (1) phylloid algal, (2) coralline algal, and (3) bryozoan. The controls on the development of each buildup type were water depth, prevailing wave energy, and paleostructural position. The best stratigraphic hydrocarbon traps in the region are associated with phylloid-algal buildup facies. Phylloid-algal buildup facies can be subdivided into shelter, mud-rich, and solution-breccia facies.

The principal buildup process for phylloid-algal growth occurred during high stands of sea level. During low stands of sea level, these buildups experienced considerable porosity modification.

Hydrocarbons are stratigraphically trapped in porous and permeable lithotypes within the mound-core and supra-mound intervals of the Desert Creek carbonate buildups. Three factors create reservoir heterogeneity within productive mound-core and supra-mound intervals: (1) variations in ten distinct lithotypes, (2) diagenesis, and (3) mound relief and flooding surfaces. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Structure contour maps on the top of the Desert Creek zone of the Paradox Formation and gross Desert Creek interval isopach maps were constructed for the Anasazi, Blue Hogan, Heron North, Mule, and Runway project fields, San Juan County, Utah. These maps were combined to show carbonate buildup trends, define limits of field potential, and indicate possible combination structural and stratigraphic traps. A new seismic program was permitted by government and tribal regulatory agenies and conducted in the Mule field. The seismic data collected were used to determine the extent of the algal-mound buildup in the field and the orientations and lengths of any horizontal development drilling. These seismic data were interpreted, new isochron maps were constructed, and the results were incorporated into the overall interpretation of the southwest Aneth region.

Of the five carbonate buildup fields in the Desert Creek zone originally identified as candidates for detailed study, the Anasazi field was selected for the initial geostatistical modeling and reservoir simulation. The key to increasing ultimate recovery from the Anasazi field (and similar fields in the basin), is to design either waterflood or carbon-dioxide-miscible flood projects capable of forcing oil from high-storage-capacity but low-recovery supra-mound units into the high-recovery mound-core units. The results of statistical modeling are being used in reservoir simulations to test and design those types of projects. An initial set of ten geostatistical, equally probable representations of lithologic and reservoir properties in the Anasazi reservoir complex has been generated using a five-stage procedure. One geostatistical realization representing the full range of possible configurations of internal architecture and distribution of reservoir properties was selected for conducting the history matching and reservoir performance phase of the reservoir simulation.

Basic reservoir parameters for the Anasazi, Blue Hogan, Heron North, Mule, and Runway fields were compiled and summarized. Production history curves were also plotted for each field. These plots include monthly oil, gas, and water production, and number of producing wells

A compositional simulation approach is being used to model primary depletion, waterflood, and carbon-dioxide-flood processes. During this second year of the project, team members performed the following reservoir engineering analysis of Anasazi field: (1) relative permeability measurements of the supra-mound interval (dolomite) and mound-core interval (limestone) facies, (2) completion of geologic model development of the Anasazi reservoir units for use in reservoir simulation studies including completion of a series of one-dimensional, carbon-dioxide-displacement simulations to analyze the carbon-dioxide-displacement mechanism that could operate in the Paradox basin system of reservoirs, and (3) completion of the initial full-field, three-dimensional Anasazi reservoir simulation model, and the initiation of the history matching and reservoir-performance prediction phase of the simulation study. Concurrently with the completion of the history match, some initial prediction runs were completed to assess the additional oil recovery that would be obtained by injecting carbon dioxide and repressuring the reservoir.

Technology transfer during the second project year consisted of displaying project materials at the UGS booth during the national and regional conventions of the American Association of Petroleum Geologists and at a UGS co-sponsored Paradox Basin Symposium. A project workshop and field trip to outcrop analogues and field facilities were included as part of the Paradox Basin Symposium. In addition, four technical and nontechnical presentations were made to geological societies, tribal leaders, and government officials. Project team members published abstracts, guidebook articles (seven), or newsletters detailing project progress and results. The UGS established a home page for the Paradox basin project on the Internet.

ACKNOWLEDGMENTS

This research is performed under the Class II Oil Program of the U.S. Department of Energy (DOE), National Petroleum Technology Office, contract number DE-FC22-95BC14988. The Contracting Officer's Representative is Rhonda P. Lindsey. Additional funding is being provided by the Utah Office of Energy and Resource Planning, Jeff Burks, Director.

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This report or portions of it were reviewed by Bryce Tripp, Utah Geological Survey and Rhonda P. Lindsey, National Petroleum Technology Office, U.S. Department of Energy.

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 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 waterflood or 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) causing technology to be used in other identified basins with similar types of reservoirs, (5) preventing premature abandonment of numerous small fields, (6) reducing development costs by more closely delineating minimum field size and other parameters necessary to a successful flood, (7) allowing limited energy investment dollars to be used more productively, and (8) 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.

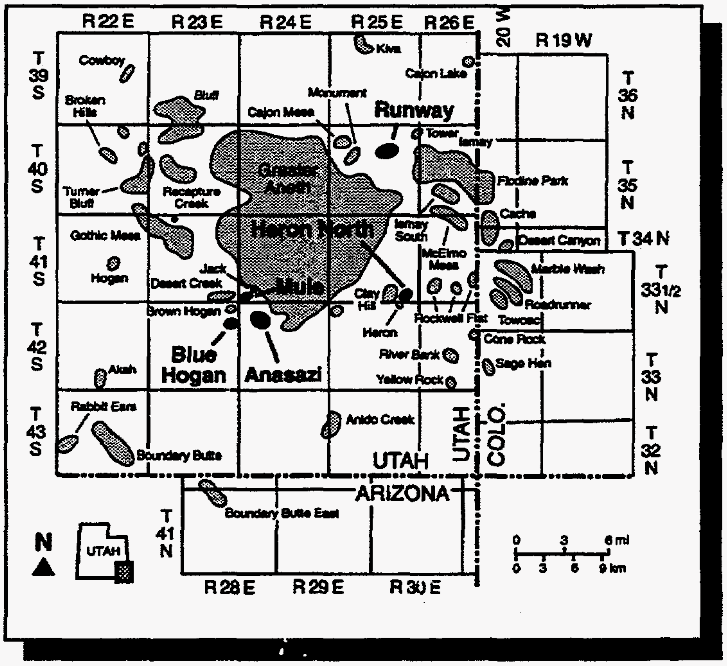

Figure 1.1. Shallow-shelf carbonate fields (the five project fields are indicated by dark shading with names in bold type) in the Paradox basin, Navajo Nation, San Juan County, Utah are targeted for geological and reservoir characterization.

The geological and reservoir characteristics of five fields (figure 1.1) which produce oil and gas from the Desert Creek zone of the Paradox Formation are being quantitatively determined by a multidisciplinary team. The best candidate for a pilot waterflood or CO_2-flood demonstration project will be chosen after a reservoir simulation has been completed. To evaluate these fields as models for other shallow-shelf carbonate reservoirs, the Utah Geological Survey (UGS), Harken

Southwest Corporation, Eby Petrography & Consulting Inc., LithoLogic Inc., and REGA Inc. entered into a cooperative agreement with the U.S. Department of Energy 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 during the second year and continuing into the third year of this phase includes:

(a) evaluating the results of outcrop data collected from the Paradox Formation along the San Juan River which provide production-scale analogues of reservoir-facies characteristics, geometry, and distribution,

(b) determining geological setting and facies characterization of carbonate buildups,

(c) analyzing the sequence stratigraphic framework to define and predict reservoir development and continuity,

(d) acquiring new seismic data and drilling both vertical and horizontal development wells,

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

(f) extensive reservoir mapping,

(g) determining field reserves and recovery,

(h) various laboratory tests and analogies to large scale waterfloods/CO_2 floods,

(I) reservoir simulation, and

(j) determining the economic viability of secondary/tertiary recovery options.

Phase II will be a demonstration project on the field selected from the characterization study using the secondary/tertiary recovery techniques identified as having the greatest potential for increased well productivity and ultimate recovery. The demonstration project will include:

(a) drilling a development well to facilitate sweep during the pilot flood,

(b) acquiring a CO_2 and/or water source for the flood project,

(c) installation of CO_2 and/or waterflood injection facilities,

(d) conversion of a producing well to injection,

(e) flood management, monitoring, and evaluation of results, and

(f) 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, and publication in newsletters and various technical or trade journals.

This report is organized into six sections: (1) Introduction, (2) Outcrop Reservoir Analogues, (3) Geological Characterization of Project Fields, Navajo Nation, San Juan County, Utah, (4) Geostatistical Modeling, (5) Engineering Reservoir Characterization of the Carbonate Reservoir in the Desert Creek Zone, and (6) 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. OUTCROP RESERVOIR ANALOGUES

Thomas C. Chidsey, Jr.; Utah Geological Survey
Lisë Brinton; LithoLogic, Inc.
David E. Eby; Eby Petrography & Consulting, Inc.
and
Kris Hartmann; Harken Southwest Corp.

Phylloid-algal buildups or mounds within the Paradox Formation are the major producers of oil and gas in the Paradox basin. With the exception of the Greater Aneth field in southeastern Utah, most fields are small, ranging in size from 0.5 to 1 mile (0.8-1.6 km) wide and 0.5 to 4.5 mile (0.8-7 km) long. They consist of 1 to 8 wells at 20-, 40-, and 80-acre (8-, 16-, and 32-ha) spacing. The principal producing intervals are the Desert Creek and Ismay zones of the Paradox Formation with pay thickness ranging from 18 to 100 feet (6-30 m). At the reservoir production scale (less than 0.5 miles [0.8 km]), reservoir heterogeneity is the major cause of low recovery rates, particularly in the upper parts of the buildups.

Carbonate buildups exposed in outcrops of the Paradox Formation along the San Juan River of southeastern Utah provide production-scale analogues of reservoir-facies characteristics, geometry, distribution, and the nature of boundaries contributing to the overall heterogeneity of these rocks. Algal buildups in the Ismay zone are exposed at river level 17 miles (27 km) west of Bluff, Utah and continue up a northeast-trending tributary canyon on the south side of the river, informally named Wild Horse Canyon (figure 2.1). High-resolution, outcrop-based sequence-stratigraphic analysis has been conducted on these rocks by Goldhammer and others (1991, 1994), Simo and others (1994), Best and others (1995), Weber, Sarg, and Wright (1995), Weber, Wright, and others (1995), Gianniny and Simo (1996), and Grammar and others (1996).

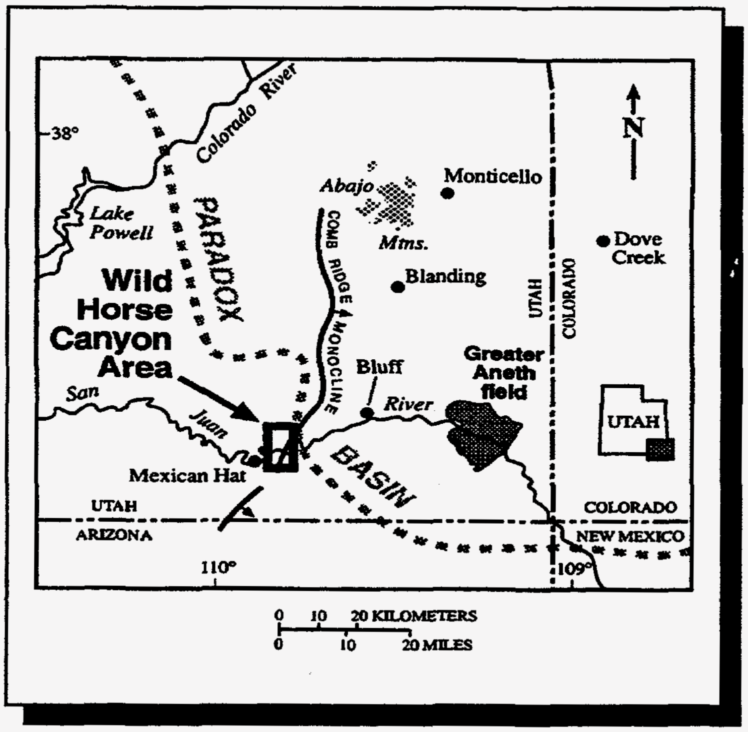

Figure 2.1. Location of Paradox Formation outcrops in the Wild Horse Canyon area along the San Juan River, southeastern Utah.

The goal of this project task was to examine a single, small but representative mound complex within a 5th-order sequence-stratigraphic cycle as an analogue for Ismay and Desert Creek reservoirs in the eastern part of the Paradox basin. The specific objectives were to: (1) increase understanding, at a reservoir production scale, of vertical and lateral facies variations and relationships within phylloid-algal buildups; (2) describe the lithologic characteristics associated with each buildup facies; (3) determine buildup morphology, internal geometries, and possible permeability and porosity distributions; and (4) identify potential impediments and barriers to fluid flow within the mound complex.

An outcrop-analogue model, combined with the details of internal lithofacies characteristics, can be used as a "template" for evaluation of data from conventional core, geophysical and petrophysical logs, and seismic surveys. When combined with subsurface geological and production data, the analogue model will improve development drilling and production strategies, reservoir-simulation models, reserve calculations, and design and implementation of secondary/tertiary oil recovery programs in the small fields of the Paradox basin and elsewhere.

2.1 Methods

Quantitative data gathered during the 1995 field season from several selected outcrops was evaluated. These data included: (1) the sizes, shapes, orientations, and stratigraphic positions of units within the mounds, (2) facies relationships, and (3) gross reservoir properties of the key mound storage units, flow units, and permeability barriers. The work involved interpretation and analyses of: (1) numerous outcrop photomosaics, (2) stratigraphic sections, (3) the areal extent of the mounds and associated facies, and (4) representative petrographic thin sections. Photomosaics were generated from digitized oblique outcrop photographs using image-editing software. The photomosaics consist of joined, distortion-corrected images. Scale of the photos was determined in the field by measuring locatable horizontal and vertical points on the photograph. The photomosaics were then annotated with distinct unit, facies, and flooding surface boundaries (figure 2.2). Major elements of reservoir architecture, lateral variations in reservoir properties, and definition of an internal "representative elementary volume" for modeling fluid storage and flow in each key facies were particularly emphasized.

2.2 Interpretation

Morphologically, algal buildups within the Ismay zone of the Paradox Formation consist of large, northwest-trending algal banks separated by interbank troughs or channels. Smaller, secondary algal mounds and intermounds define the upper surfaces of the algal banks. Cyclic sedimentation is recorded by four dominant facies recognized in a single, shoaling-upward sequence: (1) substrate carbonate, (2) phylloid algal, (3) intermound, and (4) skeletal capping (Brinton, 1986; Grammar and others, 1996). An outcrop in the Wild Horse Canyon area displaying these and additional facies was selected for detailed study (Chidsey, Brinton, and Eby, 1996).

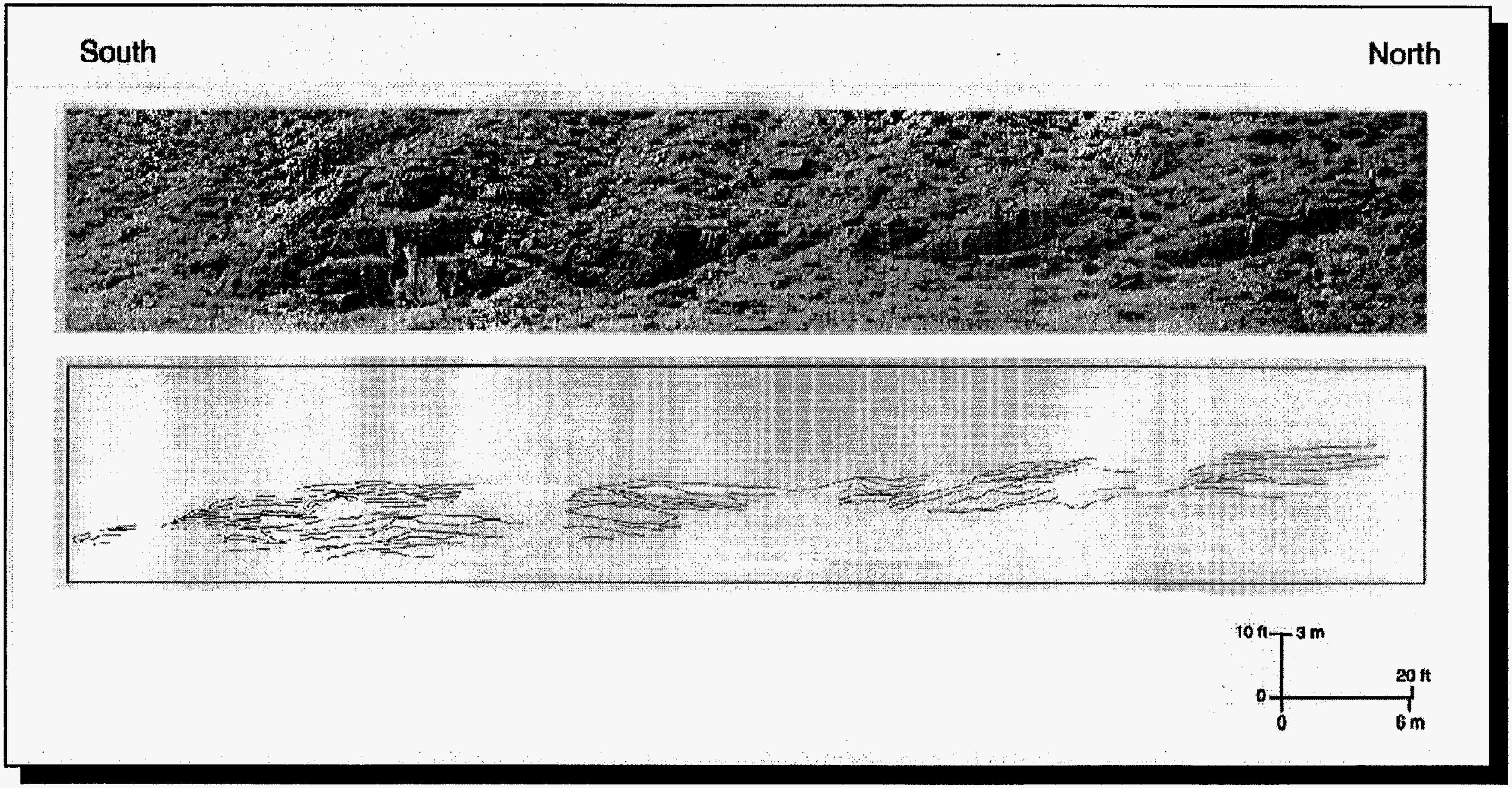

Figure 2.2. Photomosaic, view to the west, and interpretation below showing bedding planes of the phylloid-algal mound complex of the lower Ismay zone in Wild Horse Canyon, near the San Juan River, Utah (from Chidsey, Brinton, and Eby, 1996). Note the large trough right of center in the mosaic.

The Wild Horse Canyon study site is interpreted as consisting of three principal features: (1) a phylloid-algal mound with grainstone buildups deposited at or near sea level, (2) a "reef wall" that formed in a higher energy, more marginal setting than the mound, and (3) a carbonate detrital wedge and fan consisting of shelf debris (figure 2.3). This interpretation is not only based on observations made at the outcrop, but also incorporates subsurface core data which are documented and discussed in Chidsey, Eby, and Lorenz (1996).

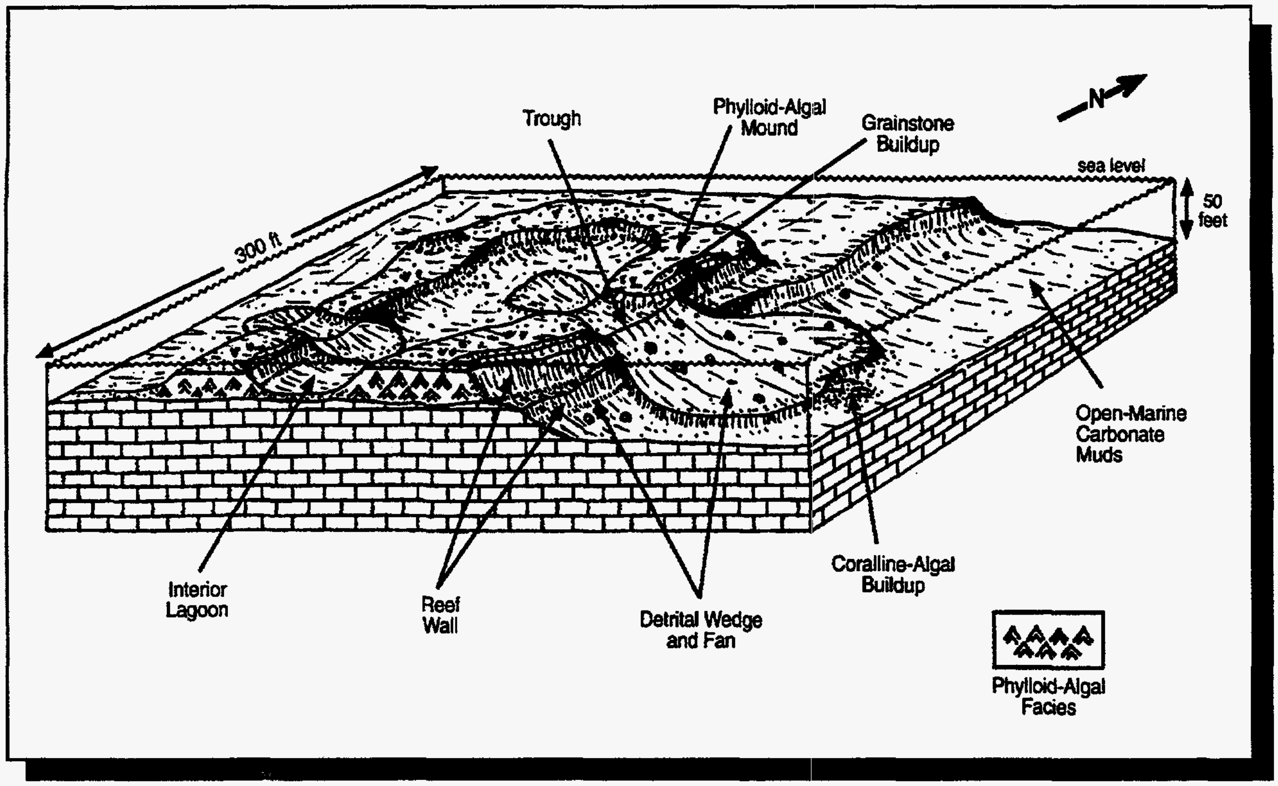

Figure 2.3. Block diagram displaying depositional interpretation of Wild Horse Canyon mound complex and associated features (from Chidsey, Brinton, and Eby, 1996). This interpretation is a composite of inferences made from outcrop and subsurface data.

Bafflestone and *Chaetetes*- and rugose-coral-bearing grainstone and packstone textures observed in the northern part of the Wild Horse Canyon complex comprise the main phylloid-algal mound. A texturally and compositionally similar algal buildup constitutes the primary reservoir facies in oil and gas fields to the east of the study site. A flooding surface recognized on top of the buildup in outcrop and probable low-permeability lithotypes (packstone and cementstone) within the buildup might act as barriers or baffles to fluid flow in the subsurface. The Wild Horse Canyon outcrop appears to be only a portion of a larger algal-bank complex, or one of a series observed in the San Juan Canyon. Although not documented at this outcrop locality, observations from core in similar areas in the subsurface suggest an interior-lagoon and other associated facies likely formed west of the study area as part of this complex (Chidsey, Eby, and Lorenz, 1996). Hypothetical facies relationships are illustrated in the schematic block diagram (figure 2.3).

The rudstone, cementstone, and lumpstone depositional textures represent deposits which were part of, or near, what might be interpreted as a "reef wall" (figure 2.3). The presence of internal sediments in these rocks indicates an influx of mud during storms or mud routinely distributed by stronger currents. The reef wall records deposition and intense sea-floor cementation as a result of reflux of large pore volumes of water through sediments occupying a high-energy marginal setting between shallow-shelf and deeper, open-marine conditions. The reef wall may have served as a barrier behind which algal buildups could develop and thrive in a more protected setting that facilitated preservation of primary shelter porosity. The presence of reef-wall facies in a well core might serve as a proximity indicator for a more prospective drilling target. Examples of this relationship have been observed in the Blue Hogan and Brown Hogan fields, southwest of the Greater Aneth field (Chidsey, Eby, and Lorenz, 1996).

An intermound trough in the center of the mound could represent a tidal channel flowing across the reef wall (figure 2.3). Material shed from the mound and reef wall and subsequently carried through the tidal channel might have been deposited as a detrital wedge or fan on open-marine carbonate muds. These features are recorded by the grainstone and transported material observed in outcrop on the east side of the complex. Coralline-algal buildups may have also developed near the carbonate detrital fan but were not observed at this locality in the canyon. Reservoir-quality porosity may have developed in troughs, detrital wedges, and fans identified from core and facies mapping. If these types of deposits are in communication with mound-reservoir facies in the subsurface, they could serve as conduits facilitating sweep efficiency in secondary/tertiary recovery projects. However, the relatively small sizes and the abundance of intermound troughs over short distances, as observed along the river, suggests caution should be used when correlating these facies between development wells. Facies that appear correlative and connected from one well to another may actually be separated by low-permeability facies which inhibit flow and decrease production potential.

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

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The five Paradox basin fields being evaluated in Phase I of the project are Runway, Heron North, Anasazi, Mule, and Blue Hogan located within the Navajo Nation of southeast Utah (figure 1.1); they are five of several satellite carbonate mounds around the giant Greater Aneth field. This evaluation included data collection, core analysis and description, reservoir mapping, and drilling the first of possibly three development wells. 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 results of these efforts during the second year of the project.

3.1 Data Collection

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. The UGS acquired information for 52 project wells. Production data, basic core analyses, geophysical log types, and well cutting information for these project wells were entered into the UGS INTEGRAL*gim database. In addition, completion test data and formation tops were also 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 I (the geological and reservoir characterization study).

Cores were described from selected project wells with special emphasis on bounding surfaces of possible flow units. The core descriptions follow the guidelines of Bebout and Loucks (1984) which include: (1) basic porosity types, (2) mineral composition in percentage, (3) nature of contacts, (4) carbonate structures, (5) carbonate textures in percentage, (6) carbonate fabrics, (7) grain size (dolomite), (8) fractures, (9) color, (10) fossils, (11) cement, and (12) depositional environment. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes.

3.2 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 (figure 3.1): (1) open-marine, (2) shallow-shelf and shelf-margin, and (3) intra-shelf, salinity-restricted facies belts (Chidsey, Eby, and Lorenz, 1996; Chidsey, 1997). 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.

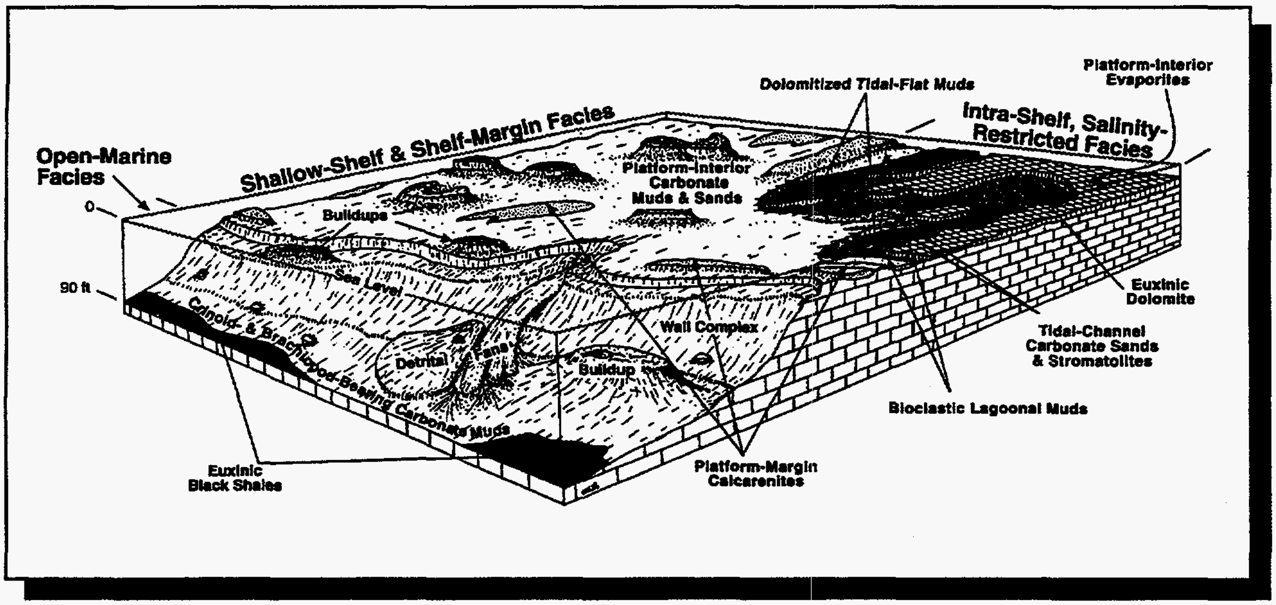

Figure 3.1. Block diagram displaying major facies within regional facies belts for the Desert Creek zone, Pennsylvanian Paradox Formation, southeastern San Juan County, Utah (from Chidsey, Eby, and Lorenz, 1996).

3.2.1 Carbonate Buildups

Productive carbonate buildups are located in the shallow-shelf and shelf-margin areas. These buildups can be divided into three types: (1) phylloid algal, (2) coralline algal, and (3) bryozoan (Eby and others, 1993; Chidsey, Eby, and Lorenz, 1996). The controls on the development of each buildup type were water depth, prevailing wave energy, and paleostructural position. Mapping of seismic anomalies and reservoir thicknesses indicates that carbonate phylloid algal buildups or mounds were doughnut or horseshoe shaped or a composite of the two shapes. Many of the phylloid algal buildups were large enough to enclose interior lagoons.

3.2.1.1 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 feet (0.3-12 m). 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 feet (1-12 m). 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 feet (1 m) above sea level to 30 feet (9 m) 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 buildup 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 (figure 1.1). 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 buildup facies. Bafflestone within these facies have excellent reservoir properties where primary shelter porosity is well-developed. However, anhydrite and early marine, botryoidal to fibrous cements occasionally plug pores.

The principal buildup process for phylloid-algal growth occurred during high stands of sea level (figure 3.2A) (Chidsey, Eby, and Lorenz, 1996). Phylloid algal mounds generally developed on the platform-interior carbonate muds and sands. The mound substrate of platform-interior carbonates is referred to as the platform interval. Calcified phylloid-algal plates sheltered abundant primary "vugs," with mounds of phylloid algae building upward within the available accommodation space. As mounds grew, detrital skeletal material was shed and deposited as dipping beds along the exterior flanks and interior lagoons. The floors of the interior lagoons consisted of muddy marine limestone with fossils. Early marine cementation commonly occurred along mound walls facing open-marine environments. Bryozoan-dominated buildups developed in deeper water along the flanks of the phylloid-algal mounds. Coralline-algal buildups developed in association with marine-cemented walls and detrital-fan complexes. These skeletal bafflestone and cementstone portions of the buildups are referred to as mound-core intervals and are easily identified in core.

During low stands of sea level, these buildups experienced considerable porosity modification (figure 3.2B). Leached cavities, vugs, and seepage-reflux dolomites developed in the mound core and flank sediments. Evaporitic dolomites and anhydrite filled the interior lagoons. Islands consisting of high-depositional- energy calcarenites and low-depositional energy stromatolites, as well as troughs representing tidal channels, formed on the tops of buildups during times of subaerial exposure (figure 3.2B and C). These portions of the buildups are referred to as supra-mound intervals.

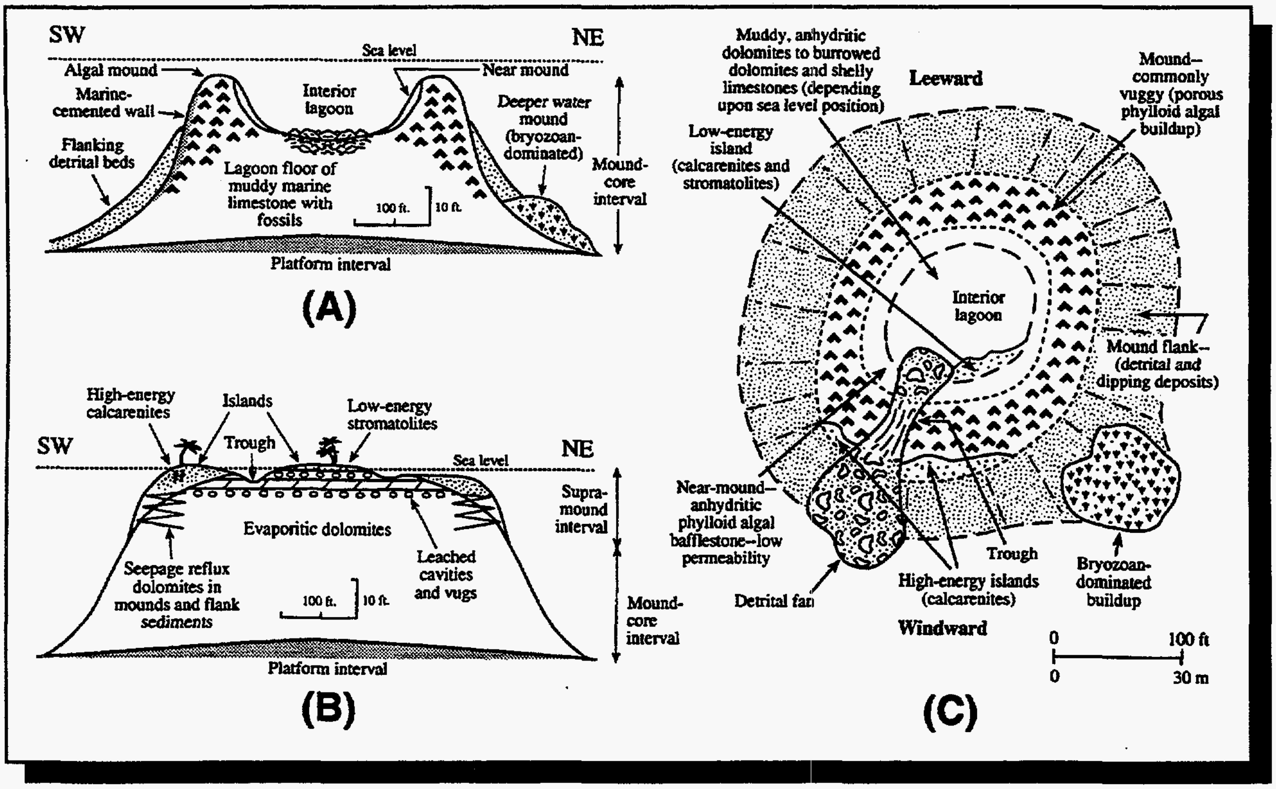

Figure 3.2. Detailed environmental setting of Desert Creek algal buildup features surrounding the Greater Aneth field. (A) Cross section during high stands of sea level when the mound was actively growing. (B) Cross section during low stands of sea level when the mound experienced porosity modification, erosion of the mound margins, evaporite dolomites filled in the lagoon, and troughs (tidal channels) and islands developed on the top. (C) Map view of idealized algal buildup (from Chidsey, Eby, and Lorenz, 1996).

__3.2.1.2 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 feet (8-14 m). These buildups are a component of the wall complex (figure 3.1) 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 selectively dolomitized bindstone, boundstone, and framestone. 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 (figure 1.1). 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.

3.2.1.3 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 feet (8-14 m). These facies were prevalent on the northeast part of the shallow shelf where winds from the east and paleotopography from Mississippian-aged normal faulting produced better marine conditions for bryozoan colony development.

The depositional fabrics are bindstone, bafflestone, and packestone 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 (figure 1.1). These traps are small and their geometry is difficult to determine. Porosity is good but pores (intraskeletal) are isolated unless connected by bryozoan sheets; permeability is variable. Minor to abundant amounts of early marine botryoidal to fibrous cement plugs pores.

3.2.2 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 feet (1.5 m) above sea level to 20 feet (6 m) 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 (figure 1.1). 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 only have moldic pores which result in classic "heart break" reservoirs. In addition, bitumen (or solid hydrocarbons) sometimes plug intercrystalline and interparticle pores.

3.2.3 Platform-Interior Carbonate Muds and Sands

The platform-interior carbonate mud and sand facies are wide-spread across the shallow shelf. This facies represents a low to moderate energy environment. Mud and sand 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 feet to 45 feet (1.5-14 m).

The depositional fabrics of the platform-interior carbonate mud and sand 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 mud and sand facies can contain reservoir-quality rocks if dolomitized. This facies is present in Anasazi, Heron, Heron North, and Runway fields (figure 1.1).

3.3 Trapping Mechanism and Reservoir Heterogeneity

Hydrocarbons are stratigraphically trapped in porous and permeable lithotypes within the mound-core and supra-mound intervals of the Desert Creek carbonate buildups. These intervals are effectively sealed by impermeable platform intervals at the base, marine muds on the flanks, and a 20-feet- (6-m-) thick layer of anhydrite, usually at the top of the Desert Creek zone. Primary oil recovery is about 40 percent in mound-core intervals but 15 percent or less in the supra-mound intervals (Chidsey, Eby, and Lorenz, 1996). In these traps, determining the nature, location, and extent of reservoir heterogeneity is the key to increasing oil recovery.

Three factors create reservoir heterogeneity within productive mound-core and supra-mound intervals: (1) variations in lithotypes, (2) diagenesis, and (3) mound relief and flooding surfaces. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

3.3.1 Lithotypes

Ten distinct lithotypes, each of which exhibits a characteristic set of reservoir properties, have been identified from conventional core in the mound-core and supra-mound intervals (Chidsey, Eby, and Lorenz, 1996; Chidsey, 1997). They include: tight mudstones, packstones, wackestones, and marine-cemented grainstones (also present on the buildup flanks of both intervals); similar carbonate fabrics (mudstones, packstones, wackestones, and grainstones) exhibiting enhanced porosity resulting from dolomitization and/or leaching found in the supra-mound interval (and also scattered throughout the buildup flank areas); and thick, porous, highly permeable phylloid-algal lime bafflestones; and associated mound-flank breccias (slumped and chaotic mixed carbonates) which are almost entirely restricted to the mound-core interval. Geometries and patterns of spatial arrangement of these lithotypes can be inferred from outcrop analogue studies and by comparison with previous work in the nearby Greater Aneth field (Brinton, 1986; Best and others, 1995; Weber, Sarg, and Wright, 1995; Weber, Wright, and others, 1995; Beall and others, 1996; Gianniny and Simo, 1996; and Grammer and others, 1996).

The mound-core intervals are the most homogenous part of these buildups and are dominated by bafflestones and a few thin dolomudstones, packstones, and wackestones. The overlying supra-mound intervals exhibit the greatest heterogeneity with multiple combinations of lithotypes and various lithofacies thicknesses. Overall, the supra-mound intervals have lower permeability but surprisingly, higher average porosity than the underlying mound-core intervals.

3.3.2 Diagenesis

The principal types of diagenesis which influence reservoir quality within these buildup fields are cementation, leaching, dolomitization, stylolitization, and anhydrite or bitumen plugging (Chidsey, Eby, and Lorenz, 1996). During early diagenesis, reservoir quality is often modified by leaching (dissolution) of framework grains and mixing-zone dolomitization. Early marine cementation can add rigidity to the buildup complex. Of course, extensive marine cementation results in diminished reservoir quality.

During late (burial) diagenesis, stylolite development is common and dissolution along some stylolites enhances reservoir quality. Extensive burial dolomitization, cementation along stylolites, plugging of pores and pore throats by bitumen (particularly in grainstones) and/or anhydrite are the major causes of reservoir quality reduction in the buildups. Within many mound-core intervals, the upper portions of the algal bafflestones are extensively plugged with anhydrite, forming barriers or baffles to fluid flow.

3.3.3 Mound Relief and Flooding Surfaces

The nature of the original surfaces of supra-mound intervals can add to the reservoir heterogeneity of these buildups. For example, multiple troughs formed by tidal currents may contain good quality grainstones. However, these grainstones are typically separated by poor quality lithotypes which were deposited adjacent to the troughs. In addition, these deposits may not be connected to one another in other parts of the buildup surfaces. Thus, what might appear as the same units in core or on geophysical logs from one well to another, may be time equivalent but separate in terms of fluid flow.

Subaerial exposure of the buildups may have produced karst zones (depending on prior mound relief) favorable to reservoir development. Relative sea level rise produced flooding surfaces or time lines, usually thin shales, which act as barriers or baffles to fluid flow (figure 3.3). As many as eight correlative flooding surfaces have been identified in some buildups. Lithotypes between these surfaces are genetically related in time and space, thus correlation of these sequences must not cross time lines (Weber, Wright, and others, 1995).

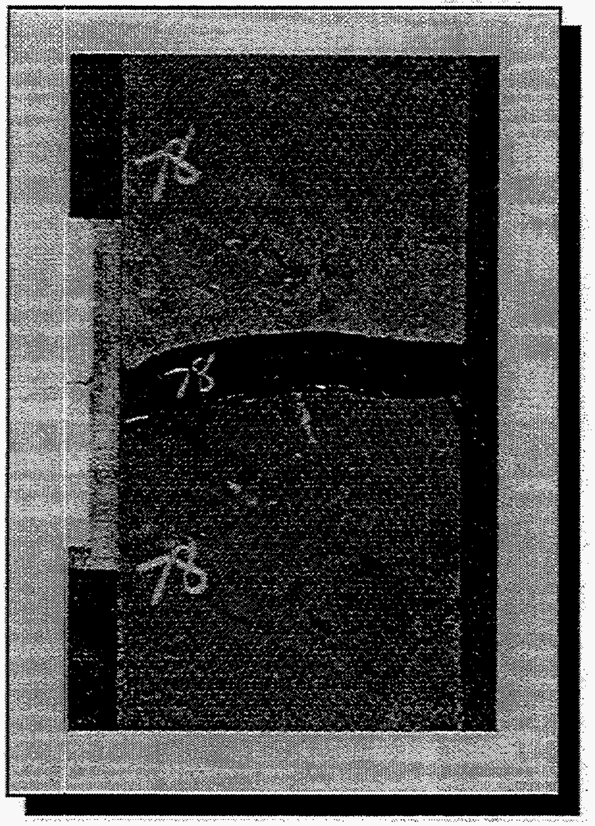

Figure 3.3. Shale break representing a probable flooding surface or 5th-order parasequence at 5,678 feet (1,730 m) in the Anasazi No. 5L-3 well, Anasazi field, San Juan County, Utah.

3.4 Reservoir Mapping and Interpretation of New Seismic Data

Structure contour maps on the top of the Desert Creek zone of the Paradox Formation and gross Desert Creek interval isopach maps were constructed for the Anasazi, Blue Hogan, Heron North, Mule, and Runway project fields, San Juan County, Utah (Chidsey, Eby, and others, 1996a-e). These maps were combined to show carbonate buildup trends, define limits of field potential, and indicate possible combination structural and stratigraphic traps (figures 3.4-3.8). Well names and total depths are given for project field wells. The maps indicate Desert Creek completions, completion attempts, and drill-stem tests and display the Desert Creek subsea top and gross thickness for each well. These maps incorporated correlations from all geophysical well logs in the areas, and regional Chimney Rock shale structure maps and gross Desert Creek isopach maps generated from closely spaced seismic lines.

The Mule field, near the southwestern edge of the Greater Aneth field (figure 1.1), was identified as a seismic anomaly expressed by isochron thickening of the Desert Creek zone of the Paradox Formation, amplitude dimming of the Desert Creek reflector, and a "doublet" development of the Desert Creek event (Johnson and Groen, 1993). The field consists of two wells, the Mule No. 31-K-1 (N) discovery well (SE1/4SW1/4 section 31, T. 41 S., R. 24 E., Salt Lake Base Line) and the Mule No. 31-M well (SW1/4SW1/4 section 31, T. 41 S., R. 24 E., Salt Lake Base Line), completed in 1991 and 1992, respectively. The Mule field is a lenticular mound consisting of a mud-free, phylloid algal buildup combined with mound-flank detrital deposits. The Mule No. 31-K-1 (N) well was deviated about 1,140 feet (347 m) south-southeast, avoiding topographic problems and a highway, to encounter what was thought to be the main part of the buildup. Several beds in the well core exhibit characteristics of mound-flank deposits such as down slope gravity transport and sharp erosional basal contacts. The Desert Creek zone tested approximately 10 barrels (bbls) (1.6 m^3) of oil per hour (based on several swab tests) with water cut increasing on each test, and produced only 283 bbls (50 m^3) of oil before the well was shut-in. The Mule No. 31-M offset well encountered a thick mound-core interval and had an initial potential flow (IPF) of 735 bbls of oil (117 m^3/d) and 97 thousand cubic feet (MCF) (2,747 m^3/d) of gas per day from the Desert Creek zone.

A new seismic program was permitted and conducted in the Mule field. The additional seismic data were used to determine the extent of the algal mound buildup in the field and the orientations and lengths of any horizontal development drilling. Five miles (8 km) of two-dimensional swath seismic data were generated along northeast-southwest lines across the Mule area (figure 3.9). These seismic data were interpreted and incorporated into the overall interpretation of the southwest Aneth region. The following isochron maps were constructed: Ismay zone to Desert Creek zone (figure 3.10), Desert Creek zone to Akah zone, and Ismay zone to Gothic shale. These maps indicate the Mule field is a lenticular, south- to northeast-trending, linear mound with additional reservoir potential on strike to the northeast of the Mule No. 31-M well. Harken Southwest Corporation, the field operator, plans to re-enter the Mule No. 31-K-1 (N) well in March 1997 and drill horizontally in a northwest direction to penetrate a significant portion of the mound buildup. This will be the first-ever horizontal well designed to extend the productive limits of a small algal buildup in the basin. If this well is successful, horizontal drilling may be used by other operators in similar small fields throughout the Paradox basin.

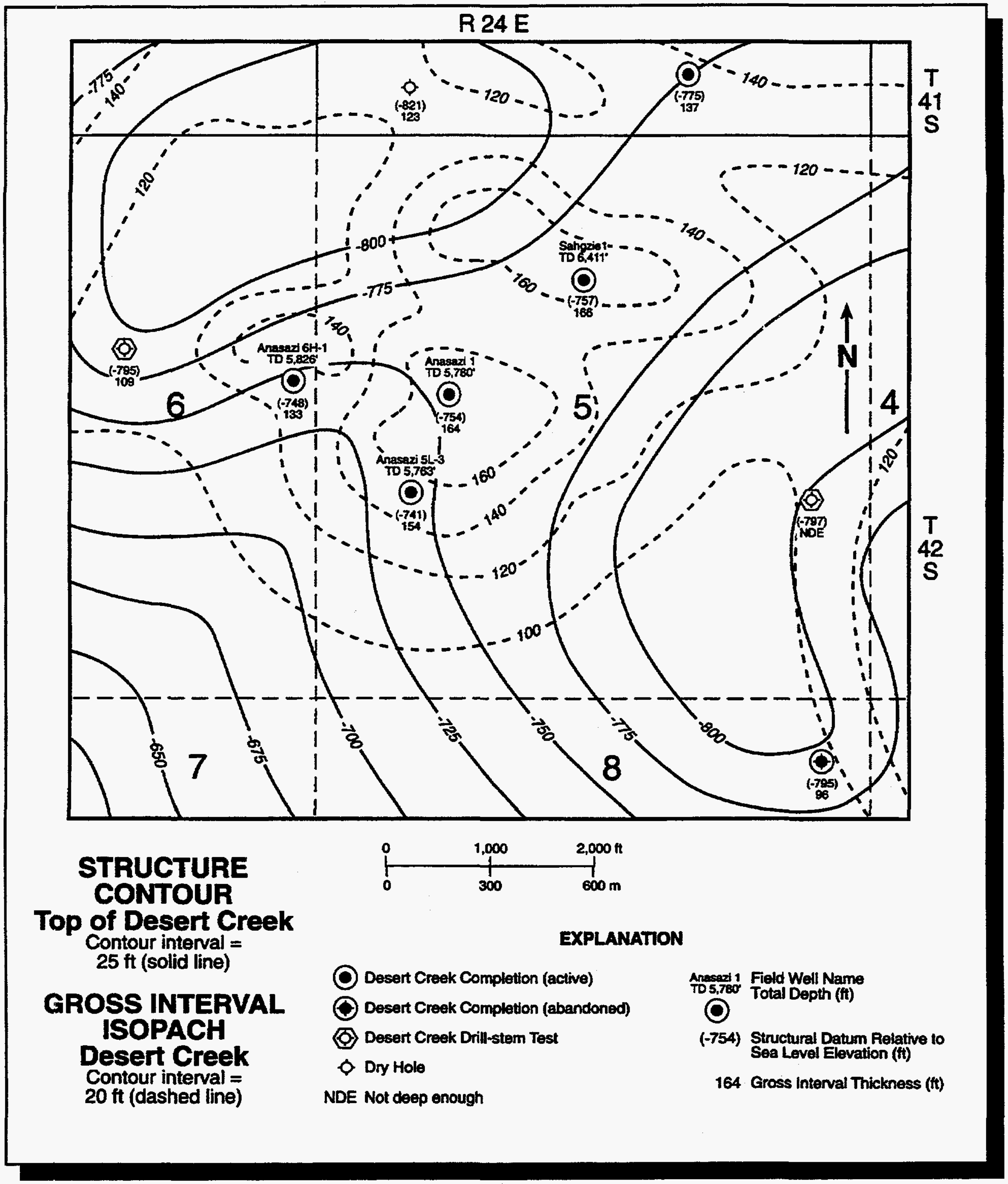

Figure 3.4. Combined Desert Creek zone structure contour and gross interval isopach map, Anasazi field, San Juan County, Utah, Navajo Nation (from Chidsey, Eby, and others, 1996a).

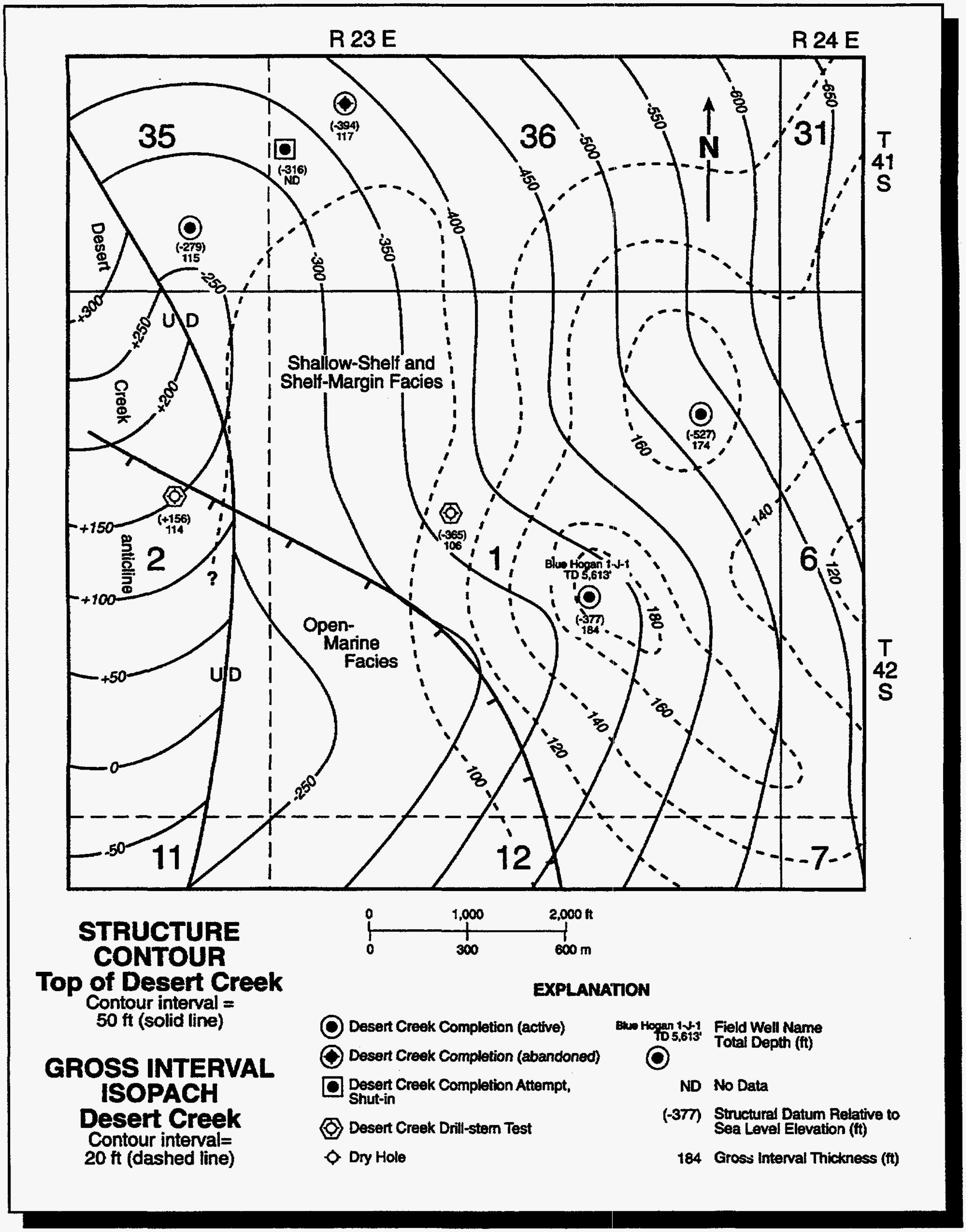

Figure 3.5. Combined Desert Creek zone structure contour and gross interval isopach map, Blue Hogan field, San Juan County, Utah, Navajo Nation (from Chidsey, Eby, and others, 1996b). Hachured lines separate carbonate depositional facies.

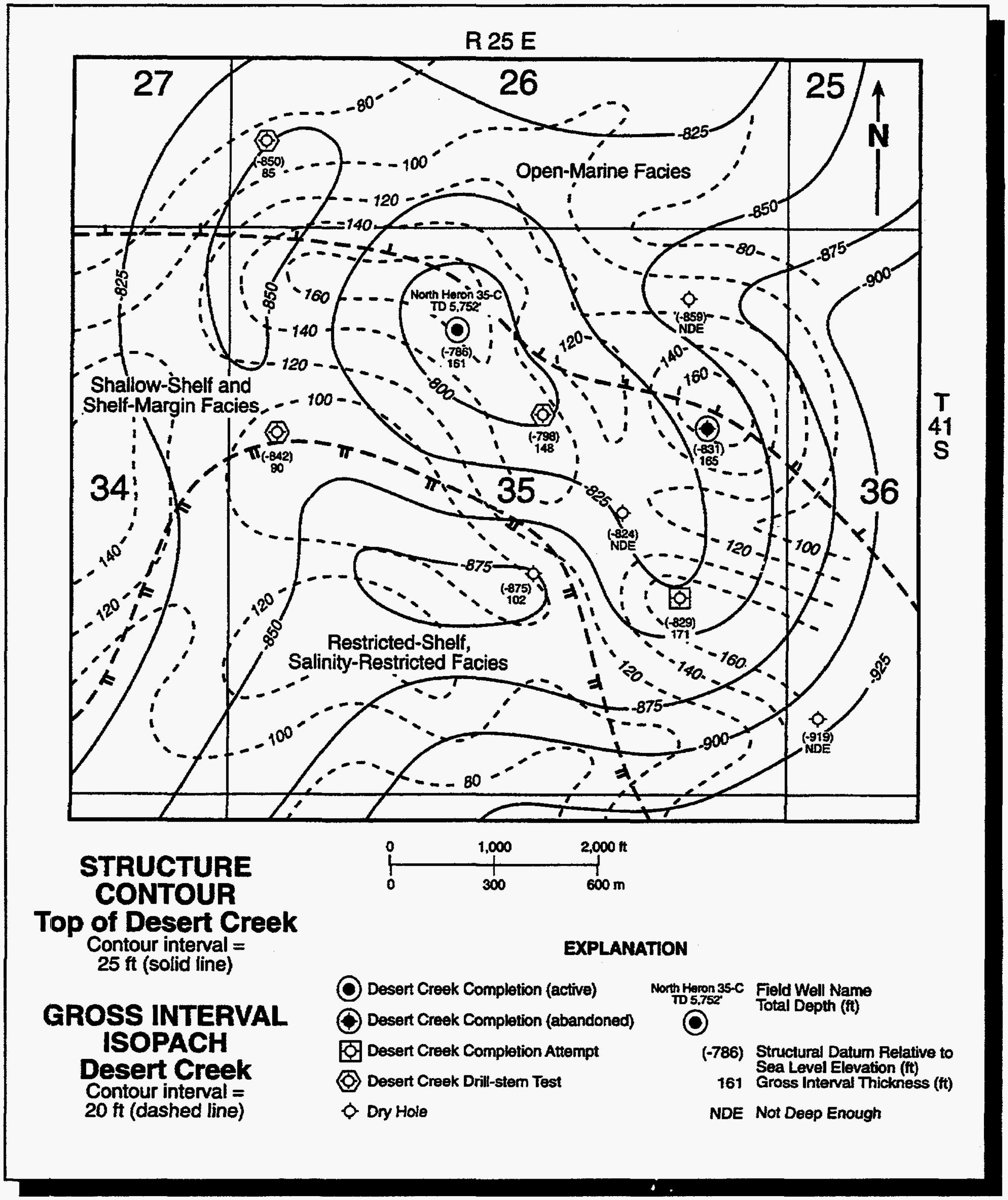

Figure 3.6. Combined Desert Creek zone structure contour and gross interval isopach map, Heron North field, San Juan County, Utah, Navajo Nation (from Chidsey, Eby, and others, 1996c). Hachured lines separate carbonate depositional facies.

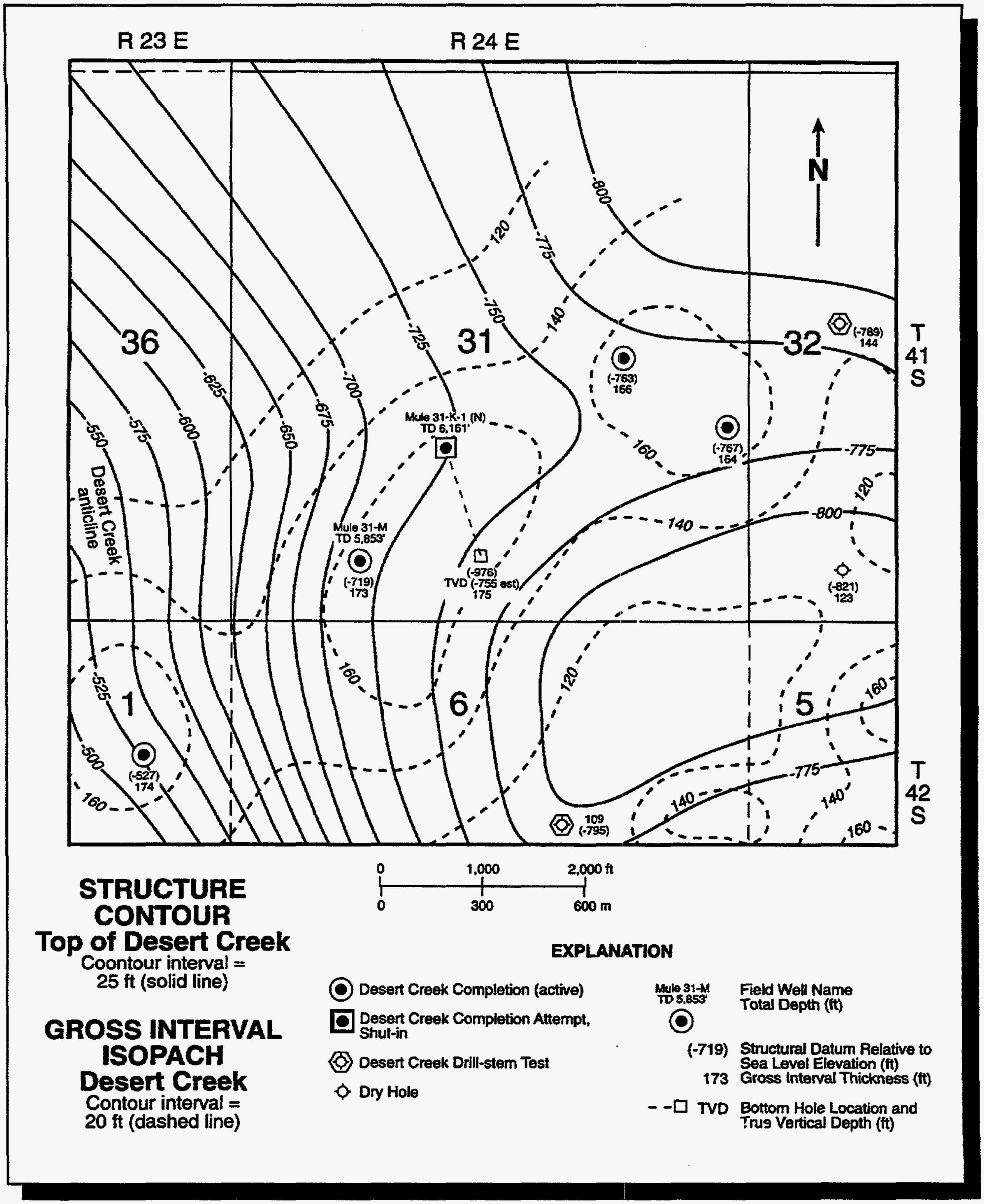

Figure 3.7. Combined Desert Creek zone structure contour and gross interval isopach map, Mule field, San Juan County, Utah, Navajo Nation (from Chidsey, Eby, and others, 1996d).

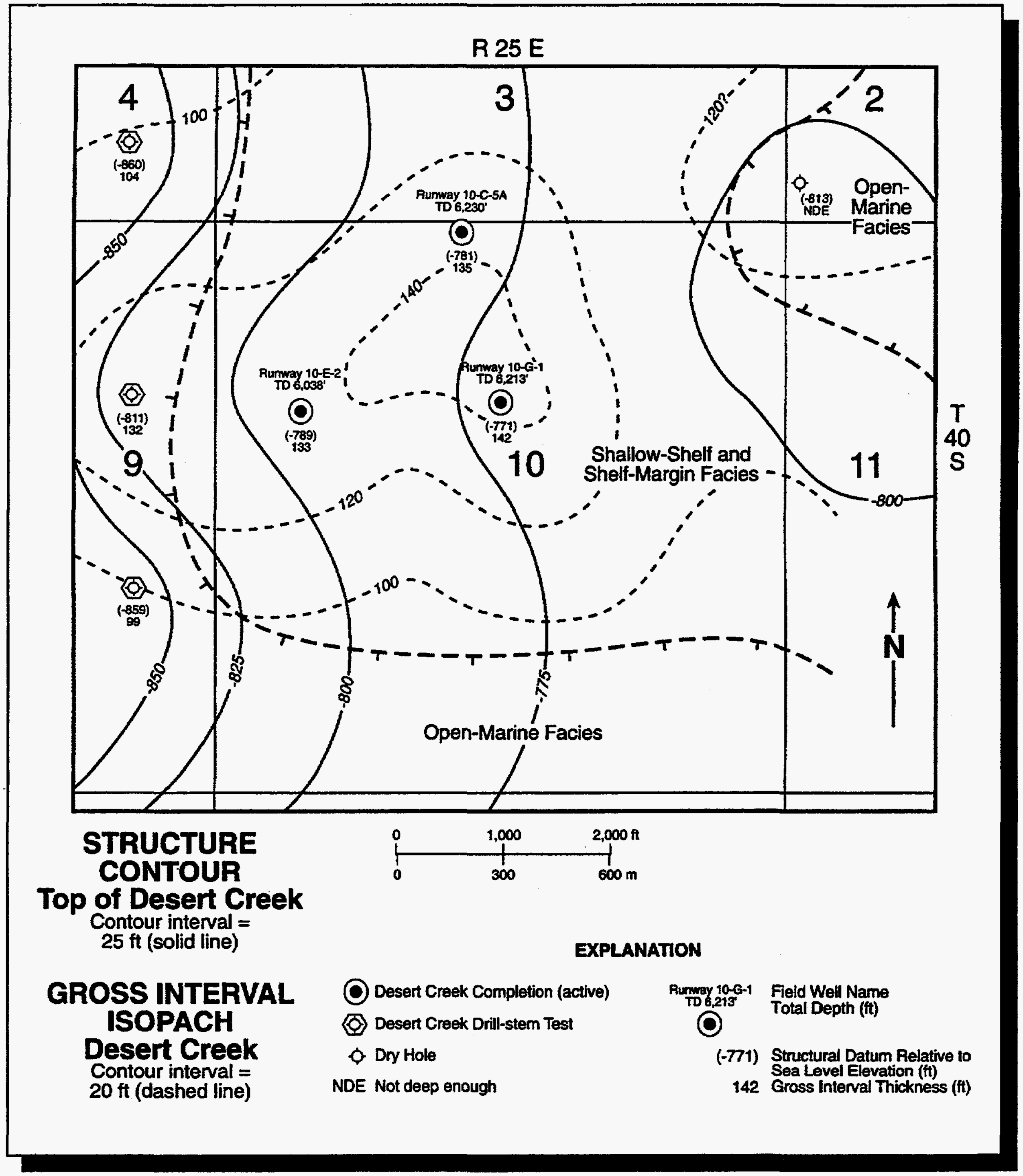

Figure 3.8. Combined Desert Creek zone structure contour and gross interval isopach map, Runway field, San Juan County, Utah, Navajo Nation (from Chidsey, Eby, and others, 1996e). Hachured lines separate carbonate depositional facies.

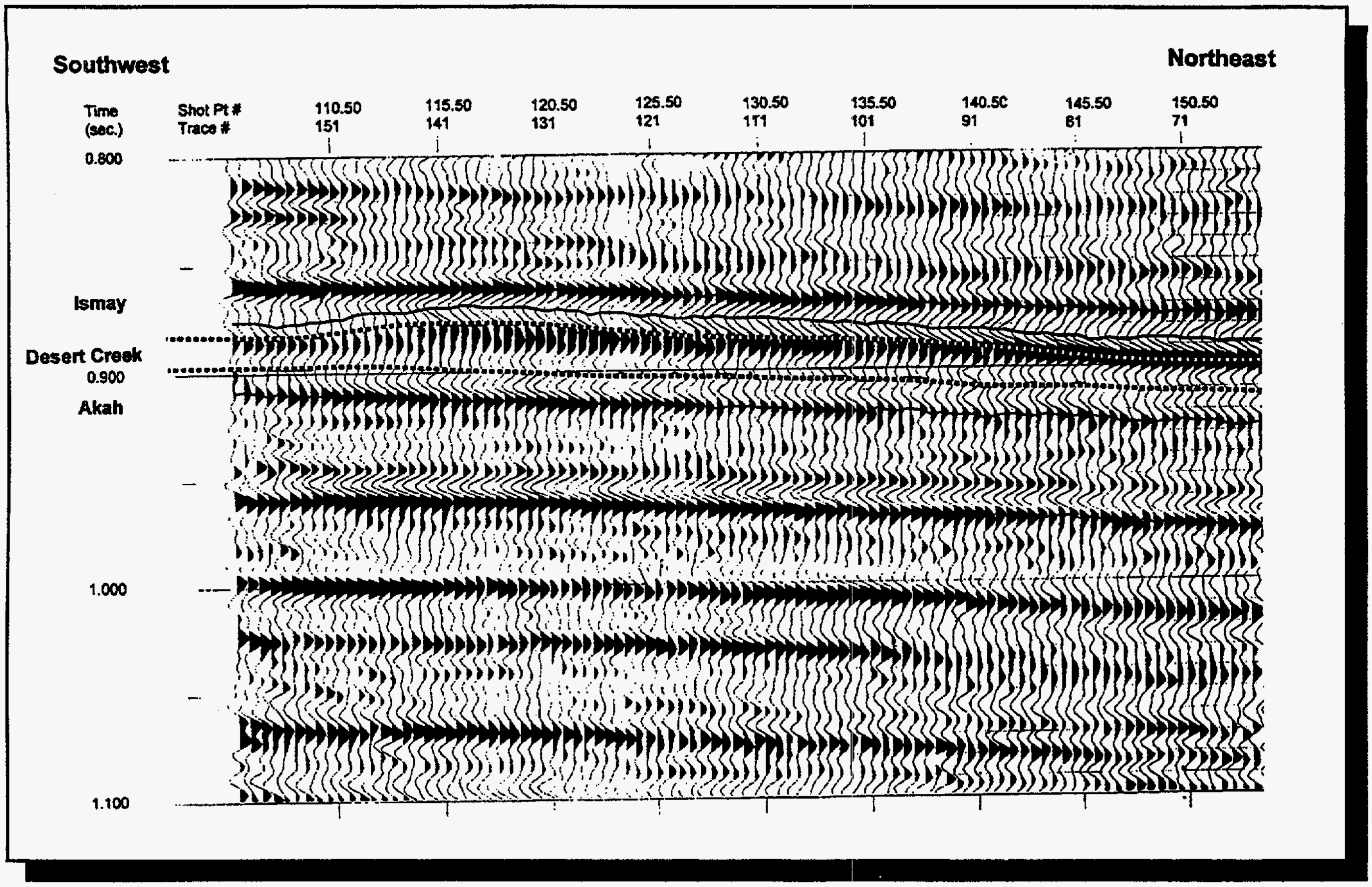

Figure 3.9. Southwest-northeast migrated seismic line (Mule 300) defining the Mule field algal mound buildup. Traces per inch = 20; inches per second = 10; 0.900 second is approximately 5,850 feet (1,783 m) (see figure 3.10 for seismic line and shot-point locations).

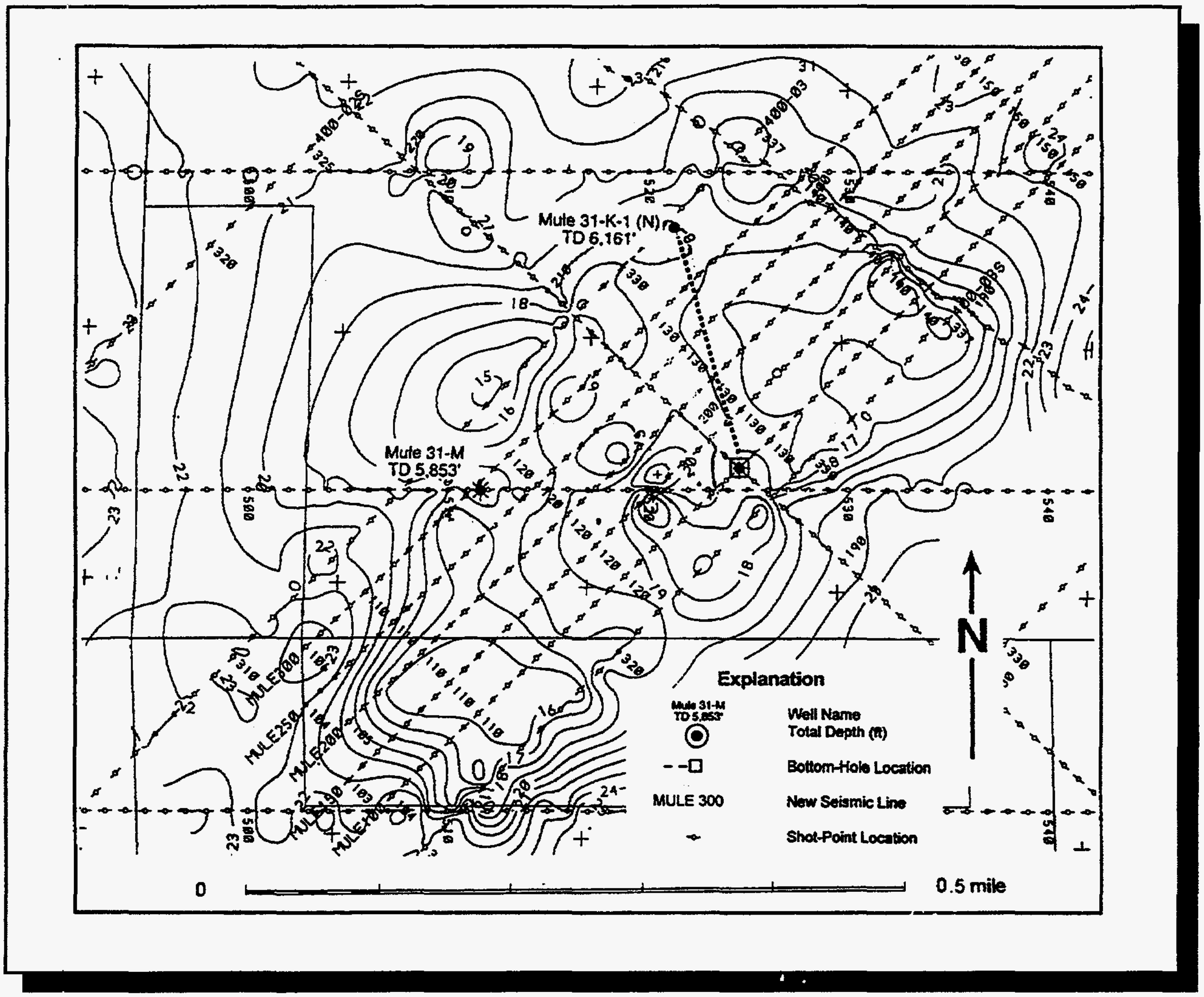

Figure 3.10. Ismay zone to Desert Creek zone (Pennsylvanian Paradox Formation) isochron map, Mule field area. Contour interval = 1 millisecond.

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4. GEOSTATISTICAL MODELING

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Of the five carbonate buildup fields in the Desert Creek zone originally identified as candidates for detailed study, the Anasazi field was selected for the initial geostatistical modeling and reservoir simulation (figure 1.1). This mound complex has the longest production history (more than seven years) and largest amount of hard data for reservoir characterization (four logged wells, three of which are also cored through the Desert Creek zone), has the most seismic coverage (six two-dimensional lines), and was considered the most promising candidate for enhanced recovery.

The key to increasing ultimate recovery from the Anasazi field (and similar fields in the basin), is to design either waterflood or CO_2-miscible flood projects capable of forcing oil from high-storage-capacity but low-recovery supra-mound units into the high-recovery mound-core units. The results of these statistical models are being used in reservoir simulations to test and design those types of projects.

4.1 Anasazi Field Overview - Location, Geometry, and General Stratigraphy

The discovery well for the Anasazi field, the Anasazi No. 1 (SW1/4NW1/4 section 5, T. 42 S., R. 24 E., Salt Lake Base Line), was completed in 1990 at an IPF of 1,705 bbls of oil per day (BOPD) (271 m^3/d) and 833 thousand cubic feet of gas per day (MCFGPD) (23,591 m^3/d) from the Desert Creek zone. The Anasazi prospect, located off the southwest edge of the Greater Aneth field, was identified as a seismic anomaly near the east flank of the Desert Creek anticline.

The detailed combined structure/isopach map of the Desert Creek zone in the Anasazi area (figure 3.4) shows two mound buildups more than 60 feet (18 m) thick, based on well log and seismic information. Three peripheral dry holes (Navajo No. 4-D [section 5, T. 42 S., R. 24 E., Salt Lake Base Line], Navajo No. D-1 [section 6, T. 42 S., R. 24 E., Salt Lake Base Line], and Navajo No. B-7 [section 32, T. 41 S., R. 24 E., Salt Lake Base Line]) do not penetrate any mound buildup facies in the Desert Creek zone, and serve to define the average non-mound Desert Creek thickness (110 feet [34 m]) in the vicinity of the Anasazi field.

The Anasazi field is a lenticular, west- to northeast-trending lobate mound, 0.9 miles (1.5 km) long and 2,000 to 3,000 feet (610-914 m) wide (Chidsey, Eby, Groen, Hartmann, and Watson, 1996). The reservoir consists of a mud-poor, phylloid-algal buildup. A variety of carbonate facies is encountered in all four Anasazi wells which causes a high degree of spatial heterogeneity in reservoir properties. To adequately represent the effects of this heterogeneity on reservoir behavior, detailed characterizations of these heterogeneous facies and their joint distributions within the reservoir volume must be developed.

In the mound buildup area, the Desert Creek zone is stratigraphically subdivided into three intervals. The lowest interval, averaging 25 feet (8 m) in thickness, consists largely of tight dolomudstones, with some slightly enhanced porosity (up to 10 percent) and interbedded dolomitized packstones and wackestones. A middle interval or mound core (30 to 50 feet [9-15 m] thick) is comprised almost entirely of phylloid-algal bafflestone. These mound-building limestones exhibit substantial porosity (up to 22 percent locally) and permeability (generally 150 to 300 millidarcies [md]; locally greater than 1,000 md). Thin dolomudstones, packstones, wackestones, and a few grainstones are found in flanking peripheral areas. The upper interval (55 to 65 feet [17-20 m] thick) contains largely dolomitized mudstones, packstones, wackestones, and grainstones in which each lithotype shows a wide range of secondary pore system alteration from slight (porosity less than 2 percent and permeability less than 0.1 md) to significant (porosity greater than 24 percent and permeability up to 50 md). Based on detailed core and log interpretations of the Anasazi wells and on geological studies of nearby analogous Pennsylvanian carbonate mound buildups (see Section 2, Outcrop Reservoir Analogues), these three successive stratigraphic intervals are identified as distinct time-equivalent sequences, termed the "platform interval", the "mound-core interval" and the "supra-mound interval", respectively. Detailed correlation of flooding surfaces demonstrates their lateral continuity within the Anasazi mound complex. The mound-core and supra-mound intervals together constitute the Anasazi reservoir; the platform interval is tight and does not yield commercial hydrocarbons.

To represent the vertical and lateral heterogeneity known to be present in the Anasazi reservoir, yet ensure that the well-documented lateral and vertical communication also is realistically modeled, a detailed facies interpretation of the conventional core from three Anasazi wells (Anasazi Nos. 1, 5L-3, and 6H-1) was undertaken during the first year of the project. From these results, together with the log interpretations, conventional core analysis, and geologically inferred lateral facies relationships based on the outcrop studies, a reservoir modeling procedure was designed to incorporate the major facies types as individual architectural entities, each exhibiting internal heterogeneities in reservoir properties but contrasting sharply between the individual lithotypes. All ten architecturally distinct lithotypes (see section 3.3.1 Lithotypes) were identified in the mound core interval, eight of which also comprise the supra-mound interval in the Anasazi reservoir (table 4.1) (Chidsey, Eby, and Lorenz, 1996). They include the tight mudstones, packstones, wackestones, and grainstones characteristic of the off-mound areas in both intervals; similar facies exhibiting enhanced porosity resulting from dolomitization and/or leaching found in the buildup areas of the supra-mound interval (and also scattered throughout off-mound areas; and the porous, highly permeable phylloid-algal bafflestones and associated mound-flank breccias which are almost entirely restricted to the buildup areas of the mound-core interval.

4.2 Anasazi Geostatistical Models

An initial set of ten geostatistical, equally probable representations of lithologic and reservoir properties in the Anasazi reservoir complex has been generated. Based on borehole data and production tests from four wells, interpretations of the six two-dimensional seismic sections, well and field production data, and studies of geologically similar outcrop analogues, an extensive array of both hard and soft data constraints was developed and applied throughout the modeling process.

Table 4.1. Average reservoir properties of architectural lithotypes, Anasazi field.

Lithotype	Average Bed Thickness (ft)	Average Porosity (%)	Average Permeability (md)	Volume Proportion
Tight Carbonate Mudstone	3.7	2	0.25	0.24
Dolomitized Mudstone	5.5	9	1.51	0.06
Enhanced Porosity Mudstone	2.9	11	2.00	0.05
Tight Packstone/Wackestone	2.4	2	0.02	0.14
Enhanced Porosity Packstone/Wackestone	3.8	10	1.80	0.05
Cemented Grainstone	2.2	2	0.15	0.07
Porous Grainstone	3.2	15	15.00	0.08
Tubular Tempestites in Mudstone/Wackestone/Packstone	6.7	9	8.00 (est)	0.07
Phylloid Algal Limestone (Bafflestone)	42.0	10	150.00	0.22
Mound-Front Bioclastic Breccia	13.0	8	30.00 (est)	0.02

Reservoir model generation followed a five-stage procedure specifically designed for this project:

1. Monte Carlo generation of a 5 million-point, joint-probability distribution function (pdf) of the ten carbonate lithotype volumes identified in the Anasazi reservoir.

2. Using a random sample from this volume distribution, an initial model of reservoir architecture was obtained by stochastic emplacement of the various lithotype bodies within the reservoir volume. The sizes, shapes, orientations, and spatial distributions of these simple geometric bodies were constrained by observed data from wells, outcrops, and field analogues of modern carbonate facies.

3. Porosity values were then randomly assigned to each of these 75,000 individual lithotype blocks, constrained by the porosity pdf's developed for each lithotype from log and conventional core data. These porosity blocks were stochastically rearranged within the reservoir by simple gridblock exchange, using simulated annealing procedures to fit the vertically averaged reservoir porosity to the constraining porosity map based on the seismic-derived "reservoir quality index" (RQI). A secondary objective function, based on the vertical and lateral spatial covariance

exhibited by porosity within the individual lithotypes in the Anasazi wells and in previous studies, also was fit to the model.

4. Horizontal and vertical permeability were estimated from the resulting porosities using randomized transfer functions developed from the Anasazi core data.

5. To accommodate typical computer workstation constraints, the 50-layer geostatistical reservoir models, (figures 4.1 and 4.2) were rescaled to 15 layers (figures 4.3 and 4.4). Although most major reservoir features are preserved (for example phylloid-algal limestones [bafflestones] in the mound-core interval [shown as uniformly dark gray bodies in the illustrations] and thin, continuous and porous grainstones of the supra-mound interval [shown as light-to-medium gray] draped across the top of the mound core), some spatial continuity is altered in the rescaling process.

Of the ten equally probable geostatistical realizations of the reservoir model thus generated, one has been selected for conducting the history matching phase of the reservoir simulation. Additional minor adjustments of the original model constraints are being made in response to differences between the simulated reservoir behavior and observed production performance. When this process is completed, additional realizations will be generated to represent the full range of possible configurations of internal architecture and distribution of reservoir properties, consistent with known reservoir production behavior. This final model will be implemented in the predictive phases in the Anasazi reservoir performance simulation studies.

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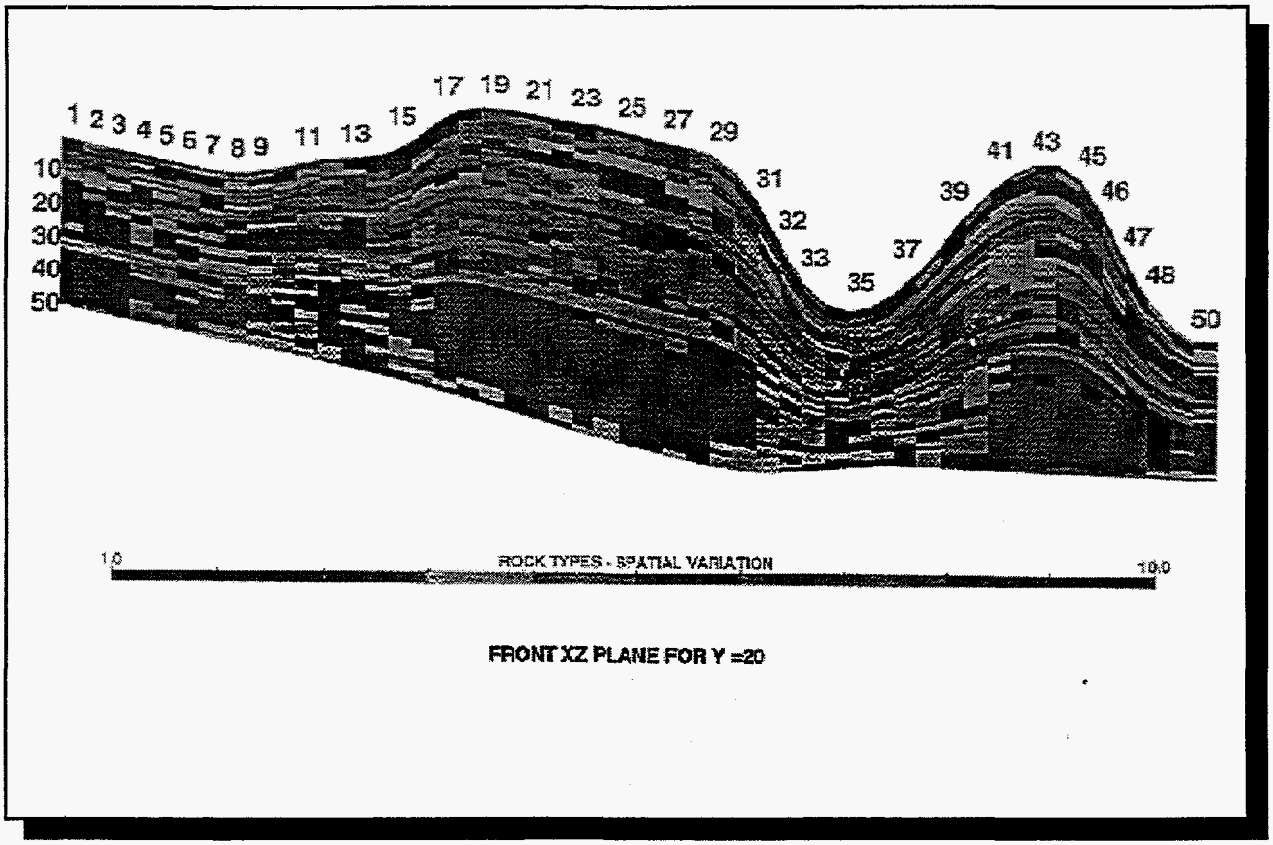

Figure 4.1. Cross section, through the Anasazi No. 1 well, of the 50-layer geostatistical Anasazi reservoir simulation model displaying the spatial distribution of lithotypes. Phylloid-algal limestones (bafflestones) in the mound-core interval are shown as uniformly dark gray bodies. Thin, porous grainstones of the supra-mound interval draped across the top of the mound core are shown as light-to-medium gray bodies.

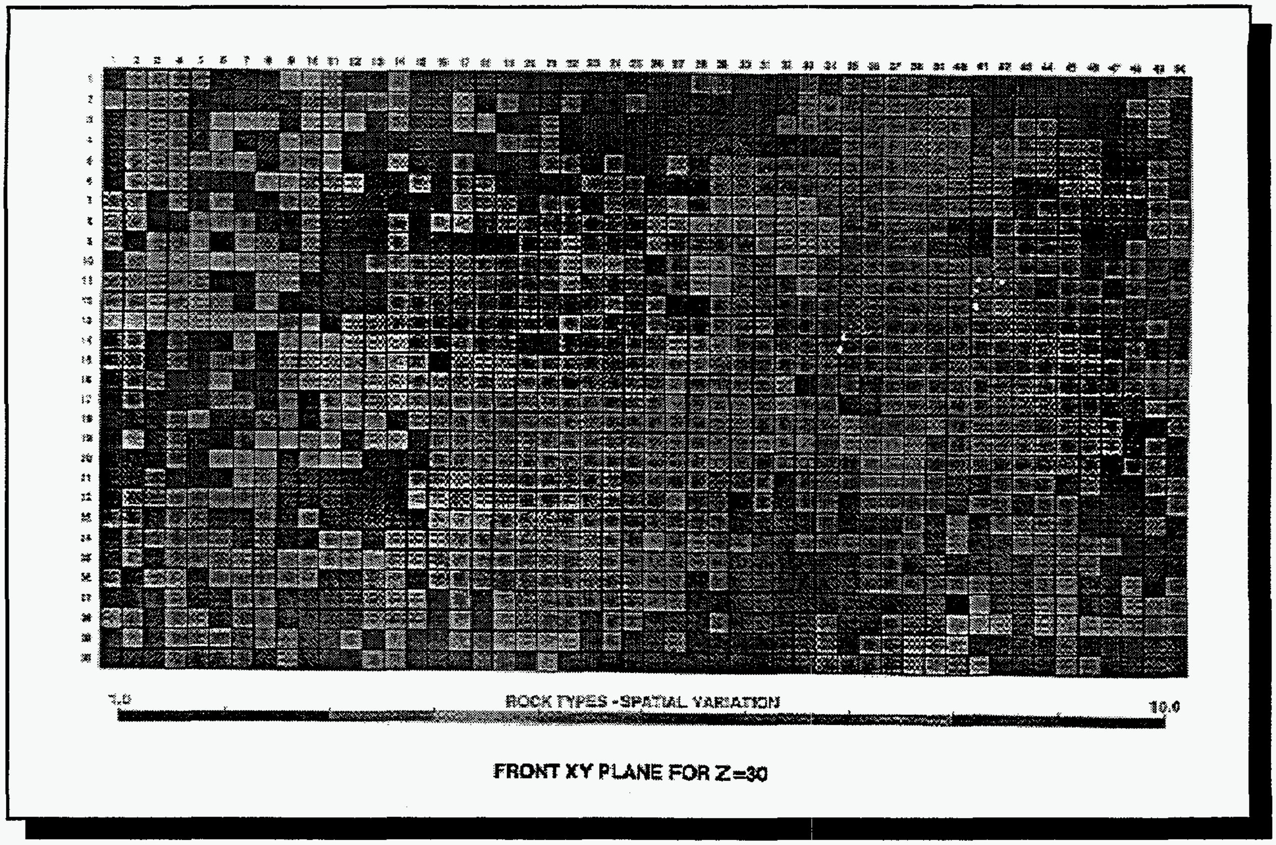

Figure 4.2. Spatial distribution of lithotypes at layer 30 from the 50-layer geostatistical Anasazi reservoir simulation model.

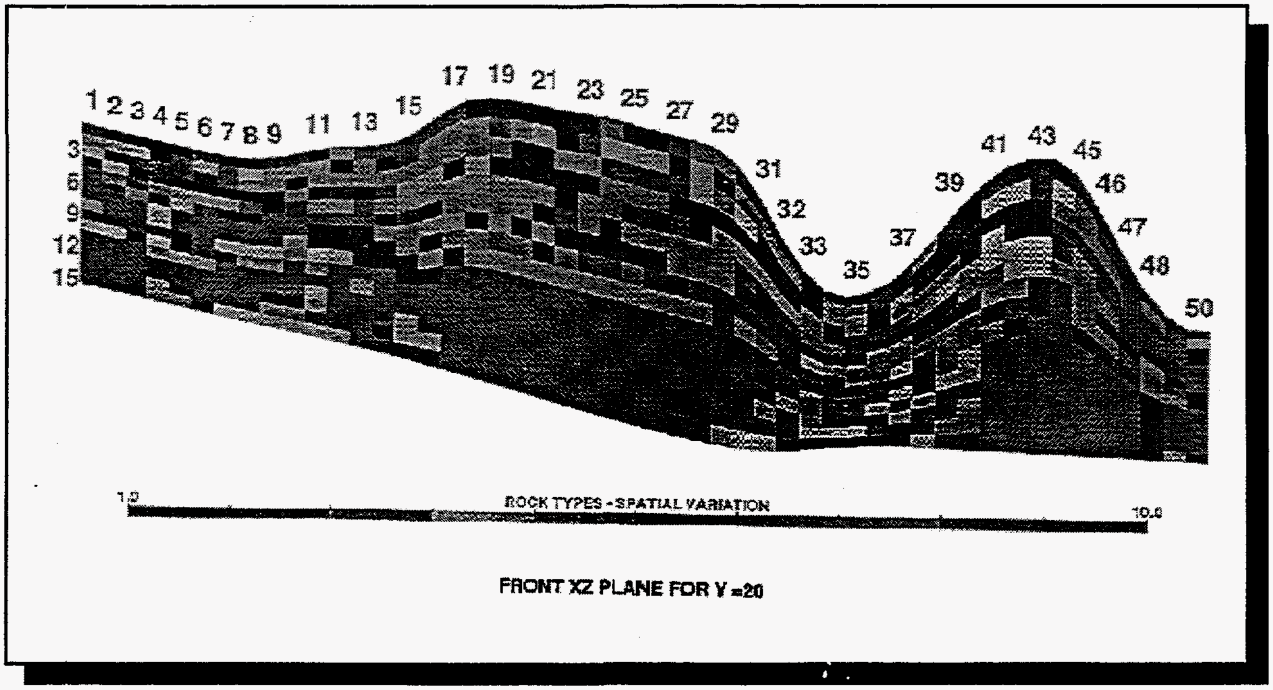

Figure 4.3. Cross section, through the Anasazi No. 1 well, of the 15-layer geostatistical Anasazi reservoir simulation model displaying the spatial distribution of lithotypes.

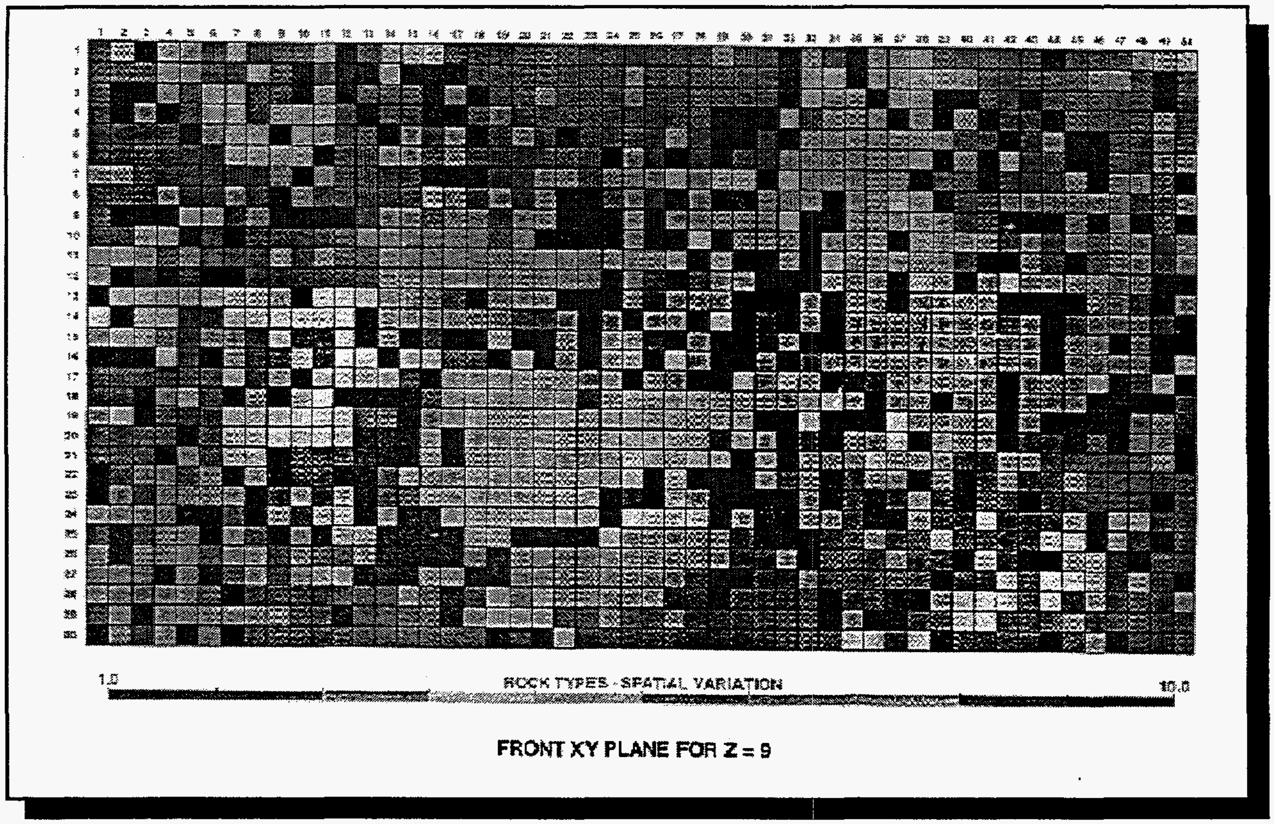

Figure 4.4. Spatial distribution of lithotypes at layer nine from the 15-layer geostatistical Anasazi reservoir simulation model.

5. ENGINEERING RESERVOIR CHARACTERIZATION OF THE CARBONATE RESERVOIR IN THE DESERT CREEK ZONE

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5.1 Basic Reservoir Engineering Analysis of the Five Project Fields

Basic reservoir parameters for the Anasazi, Blue Hogan, Heron North, Mule, and Runway fields were compiled from the following sources: (1) geophysical well logs, (2) core analyses, (3) compressibility tests on carbonates from the Anasazi Nos. 1 and 6H-1 wells, (4) pressure-volume-temperature (PVT) tests, (5) oil and gas analyses, (6) reservoir mapping, and (7) monthly production reports from the Utah Division of Oil, Gas and Mining. The results are summarized on tables 5.1-5.3. Production histories were also plotted for each field. These plots include monthly oil, gas, and water production, and number of producing wells (figure 5.1).

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

Table 5.1. Petrophysical properties and pressure data for project fields.

Field	Average Porosity (%)	Average Permeability (md)	Pore Volume Compressibility $(C_p \cdot 10^{-6}/\text{psi})$		Reservoir Pressure		Water Saturation (%)	Initial Gas-Oil Ratio (scf/STB)	Initial Formation Volume Factor (reservoir bbls/STB)	Bubble Point Pressure (psig)	Type of Drive
			Limestone	Dolomite	Initial (psig)	Present (psi)					
Anasazi	14.1	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	1,945	200-300	15	364:1	1.199	1,023	Gas Expansion
Blue Hogan	9.1	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	1,800	200-300	15	487:1	1.260	1,590	Gas Expansion
Heron North	15	17.7	ND	ND	1,934	200-300	15	644:1	1.328	1,922	Gas Expansion
Mule	13	≈ 190 for mound core ≈ 2 for supra-mound	2.3329	3.1849	2,050	200-300	15	478:1	1.240	1,478	Gas Expansion
Runway	11.9	17.3	ND	ND	2,162	200-300	15	967:1	1.511	2,141	Gas Expansion

ND = No data

Table 5.2. Cumulative production and estimated primary recovery for project fields.

Field	Carbonate-Buildup Facies Type	Spacing (acres)	Productive Area (acres)	Net Pay (ft)	Cumulative Production*			Approx. Recovery Factor (%)	Estimated Primary Recovery	
					Oil (bbls)	Gas (MCF)	Water (bbls)		Oil (bbls)	Gas (BCF)
Anasazi	Phylloid Algal	80	165	46	1,745,654	1,414,637	26,946	20	2,069,392	1.89
Blue Hogan	Phylloid Algal	80	89	82	292,376	272,900	1,843	20	645,000	0.968
Heron North	Platform-Margin Calcarenite	40	110	60	205,574	326,576	27,979	20	990,000	2.65
Mule	Phylloid Algal	80	48	47	365,428	225,069	21,988	20	430,603	0.288
Runway	Phylloid Algal/Bryozoan	40	193	50	772,508	2,440,394	3,907	20	720,000	2.83

*Utah Division of Oil, Gas and Mining Monthly Production Report, December 1996
Runway field includes commingled Desert Creek and Ismay zones
ND = No data

Table 5.3. Oil, gas, and water properties for project fields.

Field	Bottom-hole Temperature (°F)	Resistivity of Water (ohm-m @ BHT)	Oil Gravity (°API)	Oil Viscosity (cP @ initial reservoir conditions)	Gas Heating Value (BTU/ft^3)	Gas Specific Gravity (decimal fraction)
Anasazi	138° @ 5,777'	0.035	41	0.951	1,400.3	0.8080
Blue Hogan	128° @ 5,613'	0.035	40.6	0.811	1,497.0	0.8992
Heron North	126° @ 5,752'	0.035	44.0	0.475	1,321.0	0.8335
Mule	128° @ 5,804'	0.035	44.0	ND	1,539.0	0.8890
Runway	126° @ 6,203'	0.070	40.5	0.314	1,356.5	0.7790

ND = No Data

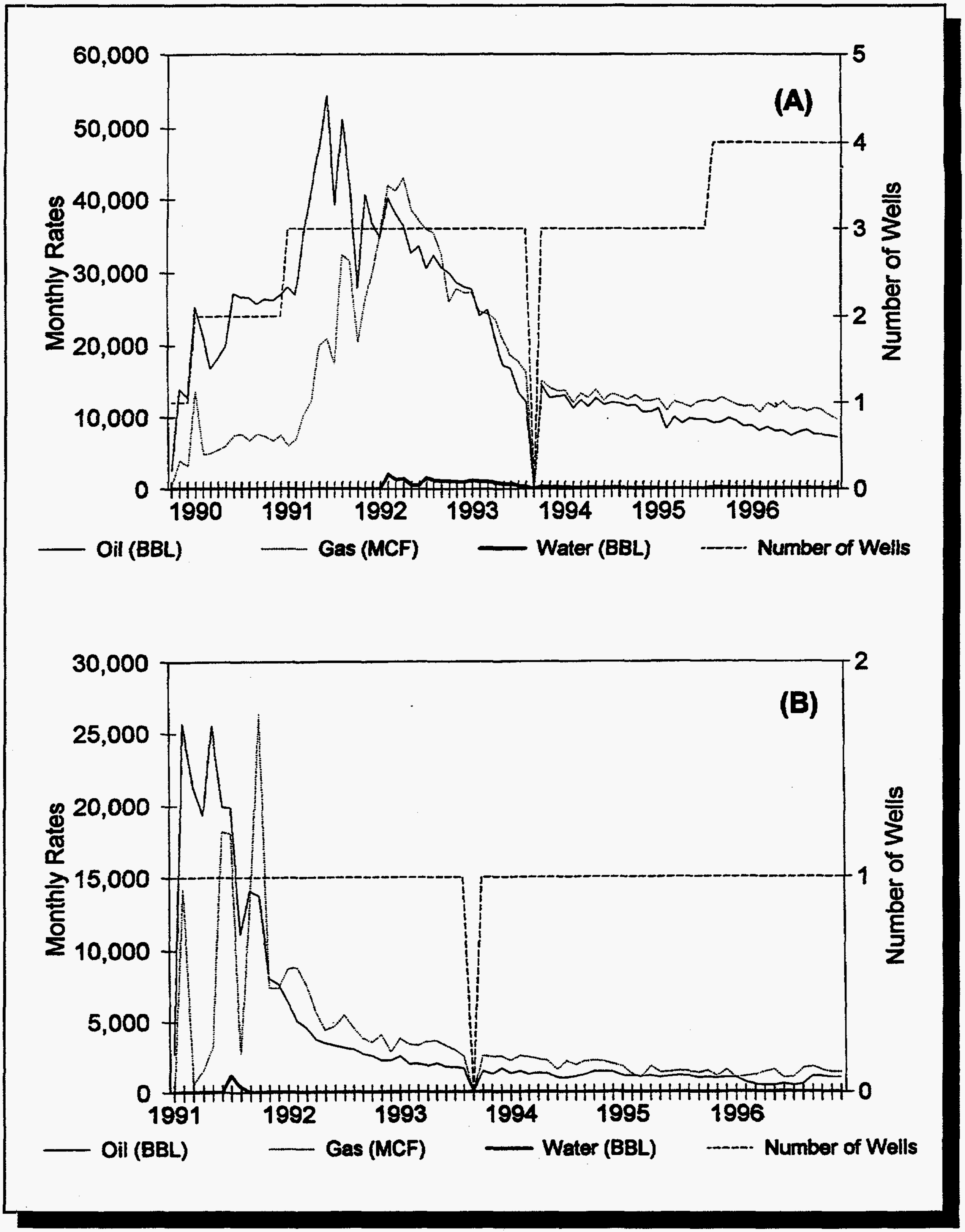

Figure 5.1. Annual production graphs as of January 1, 1997 for the (A) Anasazi, (B) Blue Hogan, (C) Heron North, (D) Mule, and Runway fields, San Juan County, Utah, Navajo Nation. Production data from the Utah Division of Oil, Gas and Mining, 1997.

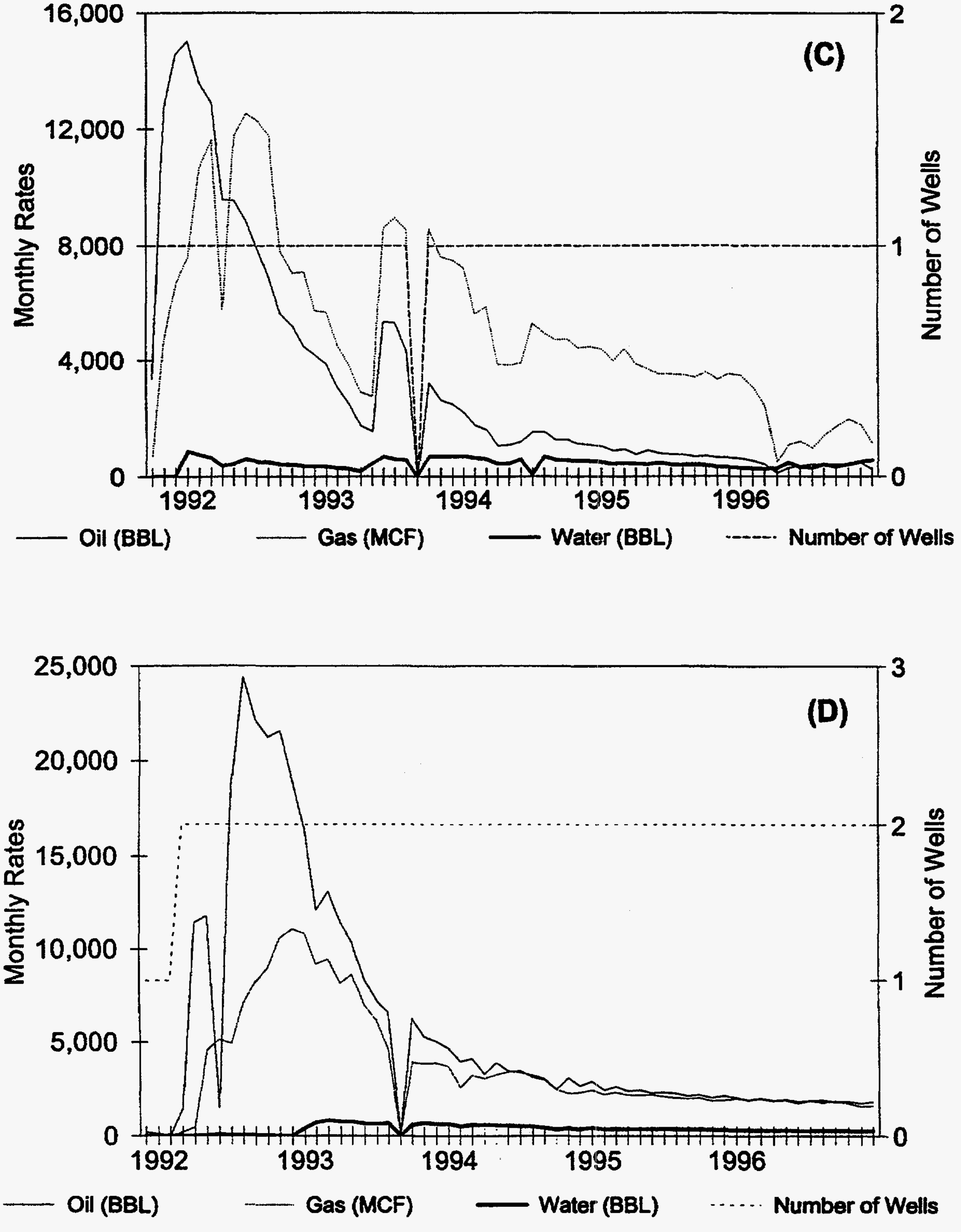

Figure 5.1 (continued)

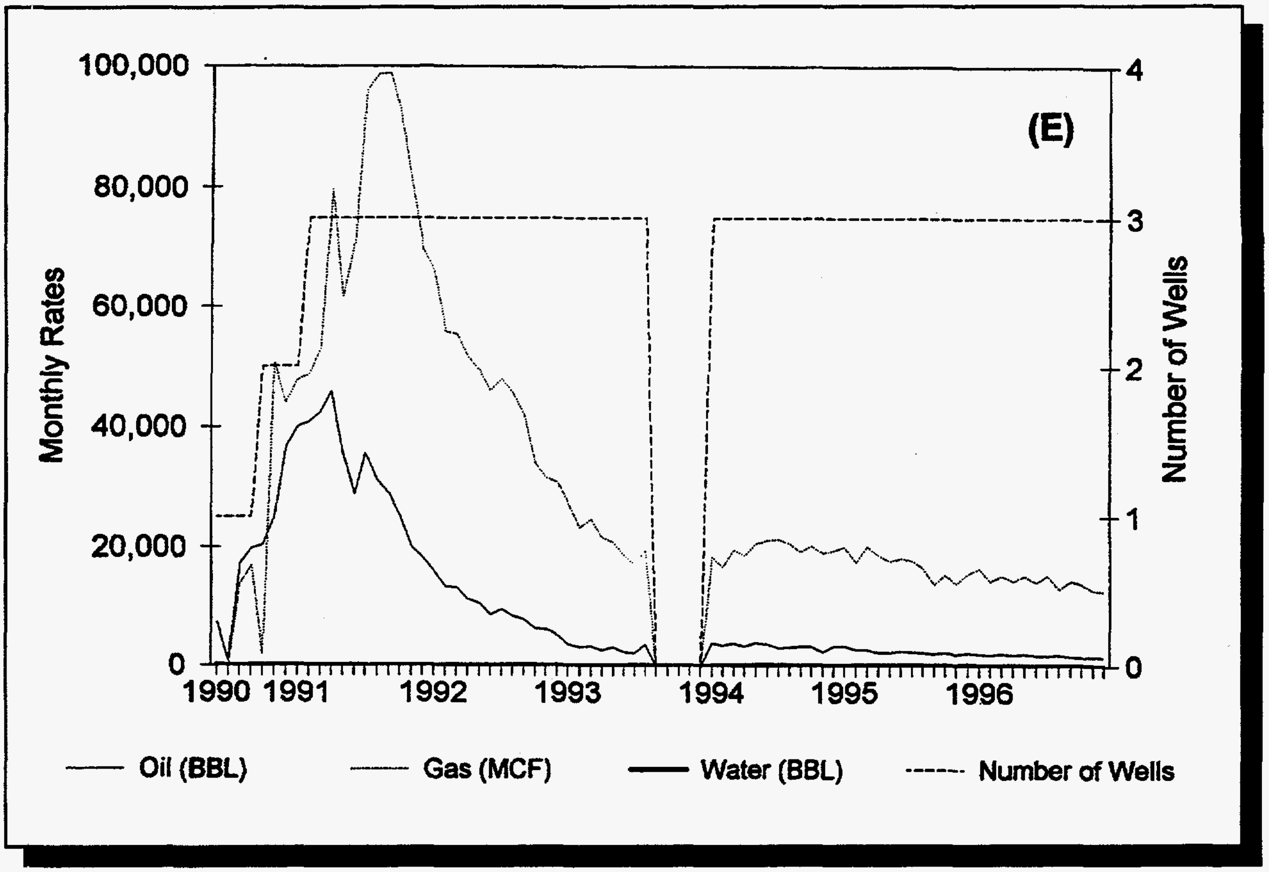

Figure 5.1 (continued)

5.2 Reservoir Engineering Analysis of Anasazi Field

Two processes, with appropriate variations, are being evaluated for selection of the best process (from a standpoint of oil recovery and economics) for implementing in a field pilot or demonstration project. The first is the waterflood, which can use fluid properties suitable for black oil reservoir studies. The second recovery process is CO_2-gas injection. Since CO_2 processes require composition data, more comprehensive fluid-property data was needed. Prior to evaluation of the two processes it will be necessary to model and history match the primary production phase of the Anasazi reservoir. Thus, the following general class of simulation studies will be performed:

1. primary depletion (history match),
2. waterflood, and
3. CO_2 flood.

A compositional simulation approach is being used to model all three processes. A compositional approach properly accounts for oil vaporization (high API gravity oils) during primary depletion and will provide the correct oil compositions to subsequently assess CO_2-flooding potential.

During this second year of the project, team members performed the following reservoir engineering analysis of Anasazi field:

1. Relative permeability measurements of the supra-mound interval (dolomite) and mound-core interval (limestone) facies using an experimental program and high-pressure, mercury injection capillary pressure measurements on end pieces from conventional core samples.

2. Completion of geologic model development of the Anasazi reservoir units for use in reservoir simulation studies including completion of a series of one-dimensional, CO_2-displacement simulations to analyze the CO_2-displacement mechanism that could operate in the Paradox basin system of reservoirs.

3. Completion of the first phase of the full field, three-dimensional Anasazi reservoir simulation model, and the start of the history matching and reservoir performance prediction phase of the simulation study.

5.2.1 Relative Permeability Data

One of the key data sets required for reservoir recovery process evaluation via simulation is relative permeability data. 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 percent was determined from the experiment.

Capillary pressure data generation, using high-pressure mercury injection (>50,000 pounds per square inch [psi]) was completed on the end pieces of the core samples used to develop relative permeability data for the dolomite and limestone productive facies from the Anasazi reservoir. The tests were conducted to compare reservoir properties of samples used for the relative permeability measurements to previously measured properties on core from the Anasazi No. 5L-3 well. Capillary pressure and pore-size-distribution data of samples from the Anasazi Nos.1 and 6H-1 wells were comparable to similar measurements taken on core samples from the Anasazi No. 5L-1 well. Pore-size distribution plots are shown in figure 5.2.

5.2.2 Development of the Anasazi Reservoir Model

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 CO_2-displacement 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 CO_2-swelling test 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 CO_2-displacement process. Results of this work provide insight into the conditions (compositions and pressures) required to develop miscibility.

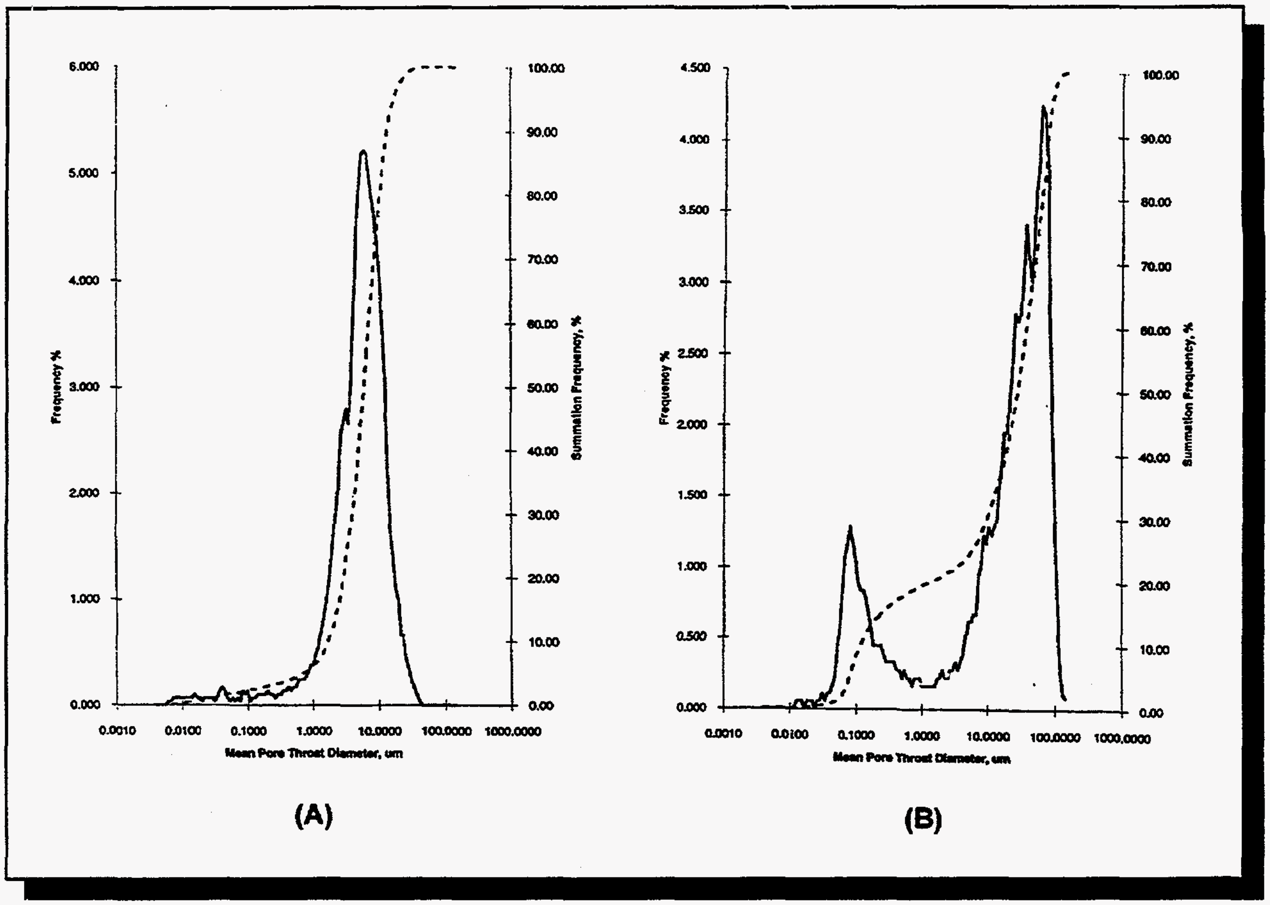

Figure 5.2. Pore-size distribution plots for Anasazi field. (A) Supra-mound interval (dolomite) facies, Anasazi No. 6H-1 well. (B) Mound-core interval (limestone) facies, Anasazi No. 1 well.

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 5.3 and 5.4 illustrate the quality of the match (computed responses are represented by solid lines and measured pressure data by the + symbol) and the reservoir parameters required to achieve this match.

Employing fluid property data (represented via a tuned equation of state) and rock property data, one-, two-, and three-dimensional models were successfully developed to simulate both primary depletion and CO_2-displacement processes. Optimum numerical solution procedures were also determined to reduce computer time required for both one- and three-dimensional simulation runs. A series of one-dimensional, CO_2-displacement tests for various reservoir operating pressures were conducted using the original Anasazi reservoir fluid composition. These tests indicated that miscibility would be developed between 2,500 and 3,000 psi. Three plots (figure 5.5) which show the variation of composition of both liquid and vapor phases as a function of time for a selected cell in the one-dimensional model, illustrate the development of miscibility (3,000 pounds per square inch absolute [psia]) or near miscibility (2,500 psia).

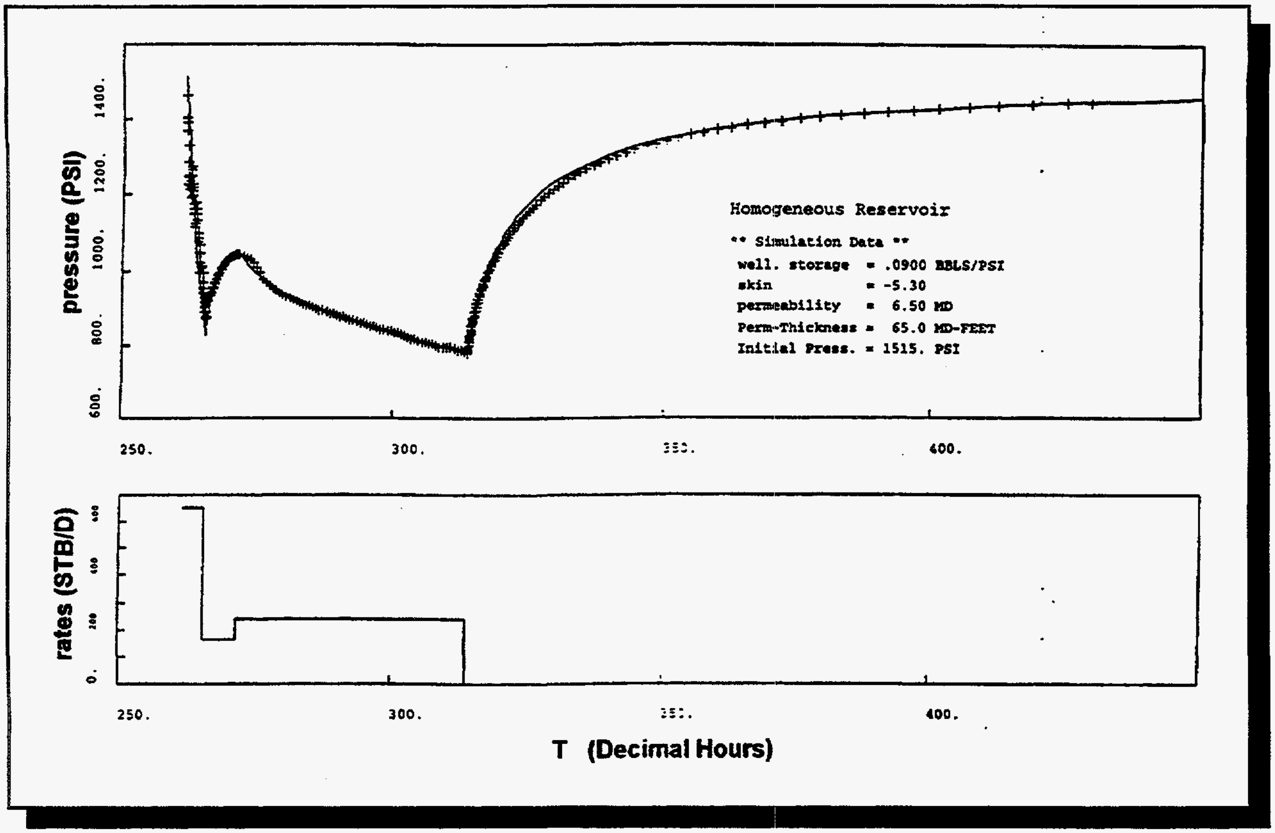

Figure 5.3. Well-flow buildup test analysis of the Big Sky No. 6E well near Clay Hill field (see figure 1.1) displaying pressure vs. time match.

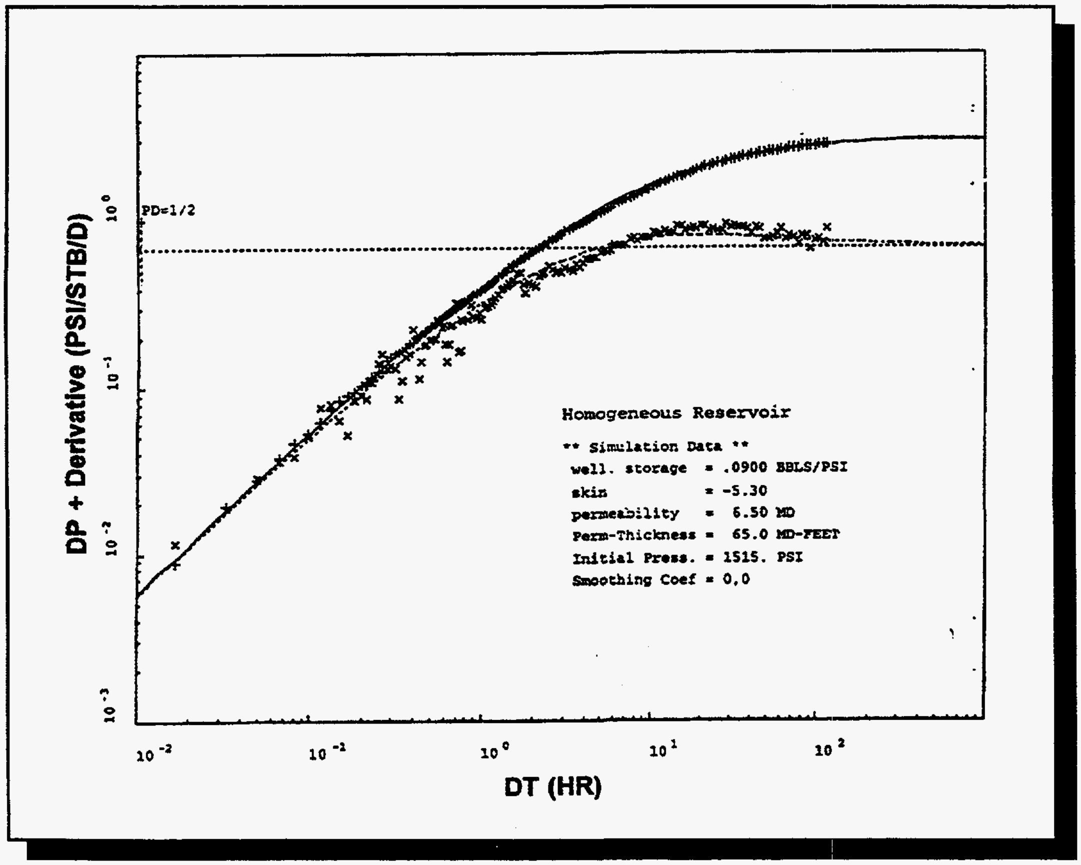

Figure 5.4. Well-flow buildup test analysis of the Big Sky No. 6E well displaying pressure difference and pressure derivative match.

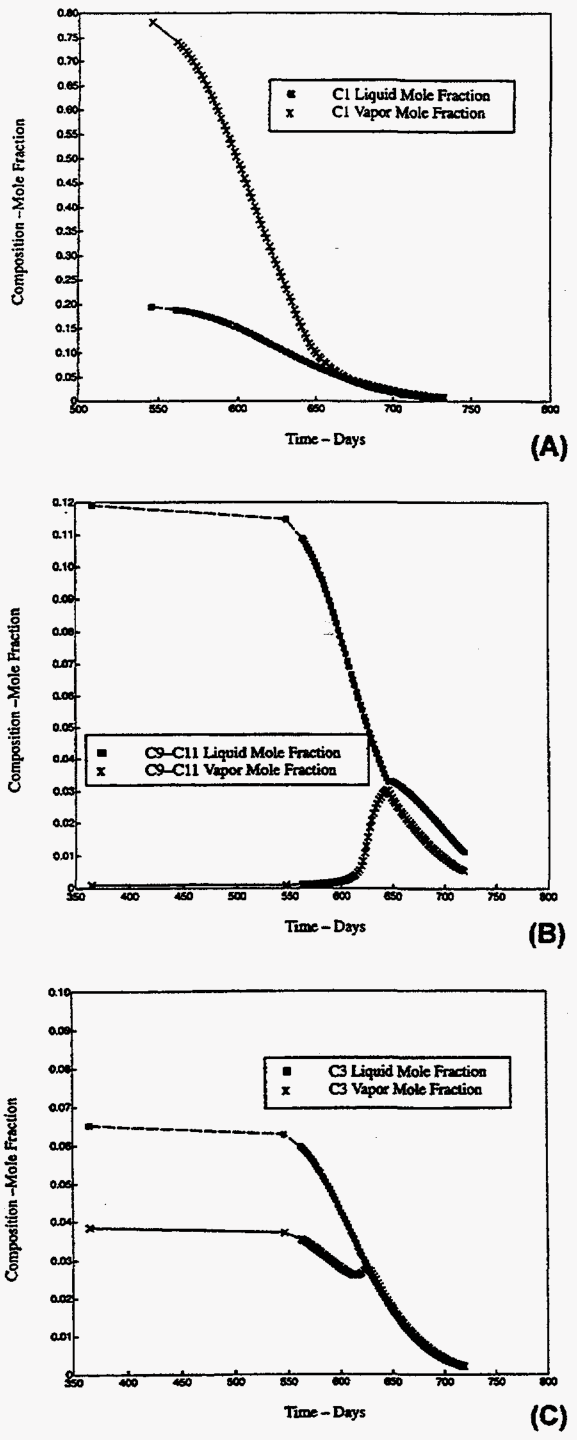

Figure 5.5. Variation of composition (mole fraction) of both liquid and vapor phases as a function of time (days) for selected cell in the one-dimensional model. (A) CO_2 displacement at 3,000 psia; composition versus time for cell 202. (B) CO_2 displacement at 2,500 psia; composition versus time for cell 217 component C9 through C11. (C) CO_2 displacement at 2,500 psia; composition versus time for cell 217 component C3.

5.2.3 History Matching and Reservoir Performance Prediction

The history matching of the primary production phase of the Anasazi field was based on one of the geostatistical realization of the reservoir geologic model. History matching involves the input of historical well/field oil production data with the predicted gas production and reservoir pressure being matched to well/field observed data. Because of the geometric and lithologic complexity of the Anasazi reservoir, a substantial history matching effort has been required. A large number of reservoir parameters and reservoir parameter combinations was investigated to match historical gas production and well to well and reservoir to reservoir (northeast to southwest buildup lobes [figure 3.4]) interaction present during the primary reservoir production phase. Reservoir and fluid properties investigated include many different combinations of these variables:

1. reservoir size/volume,
2. reservoir permeability (both horizontal and vertical) and porosity and their distribution areally as well as between the two principal reservoir facies,
3. gas relative permeability,
4. solution gas content of the original reservoir fluid,
5. rock compressibility,
6. volume of different reservoir facies,
7. transmissibility between the principal mound-core (limestone) and supra-mound (dolomite) intervals (Chidsey and others, 1996), and
8. the use of reservoir unit barriers or transmissibility reduction areas.

No local (near the wellbore) changes were employed to match production. Reservoir description changes on a regional basis were used to match the reservoir-wide fluid movement occurring within the system which in turn controlled local well behavior. Figures 5.6 and 5.7 present oil and gas production data from one of the most recent history match runs. Simulation data is represented by solid curves and the actual field production by discrete points. Figure 5.8 presents the gas saturation distribution in the reservoir for this run at December 31, 1996. Notice the segregation and accumulation of gas in the upper supra-mound interval while the lower mound-core interval remains oil saturated. Figure 5.9 presents the pressure distribution for the same time point in the simulation. Note the depressurization of the southwest and northeast lobes with the off-flank areas at higher pressure. The key reservoir description changes required to achieve this match are presented below.

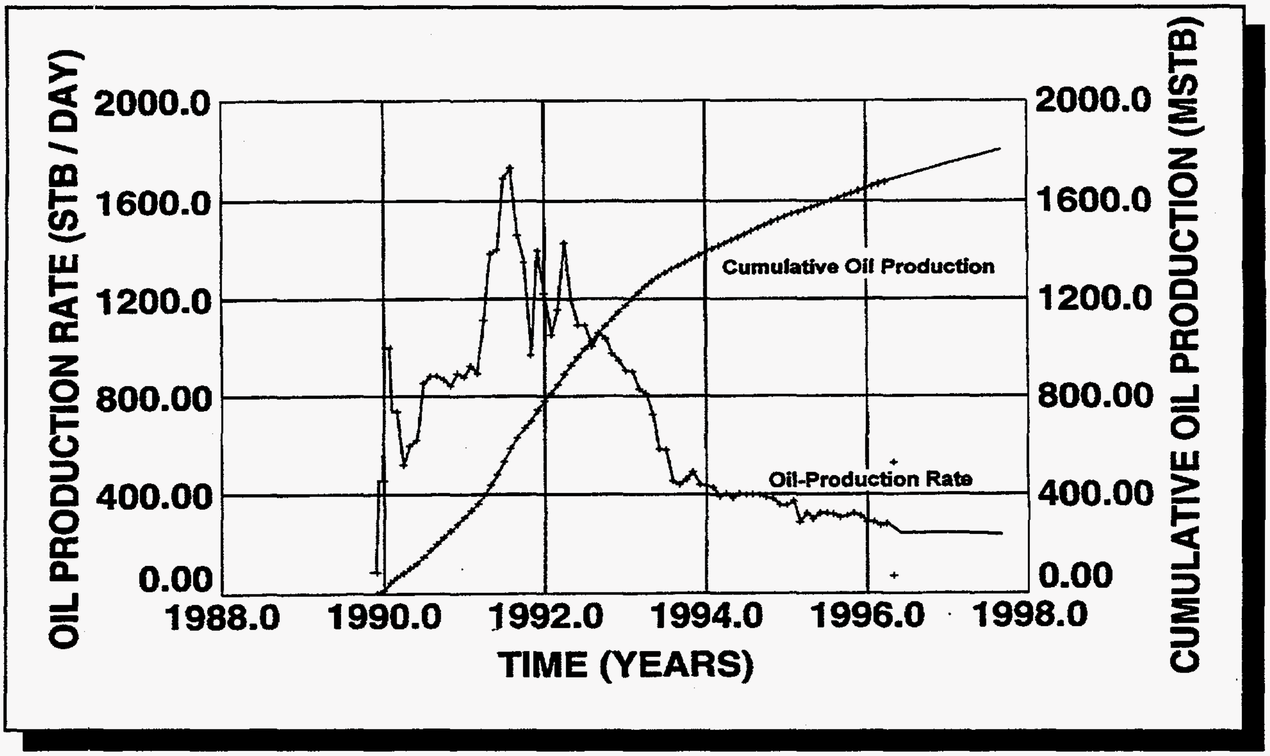

Figure 5.6. Anasazi field oil production rate and cumulative oil production vs. time from history match runs of the two-dimensional reservoir simulation. Simulation data is represented by solid curves and the actual field production by discrete points.

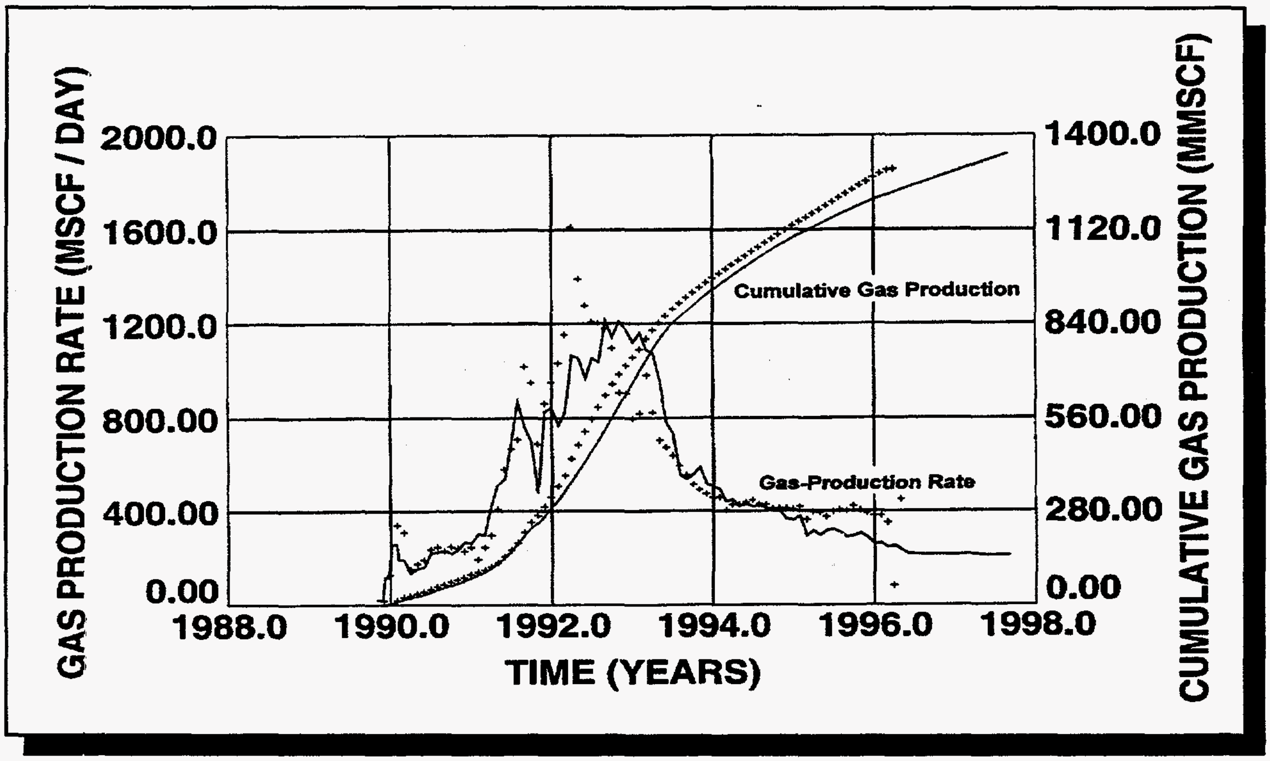

Figure 5.7. Anasazi field gas production rate and predicted cumulative gas production vs. time from history match runs of the two-dimensional reservoir simulation. Simulation data is represented by solid curves and the actual field production by discrete points.

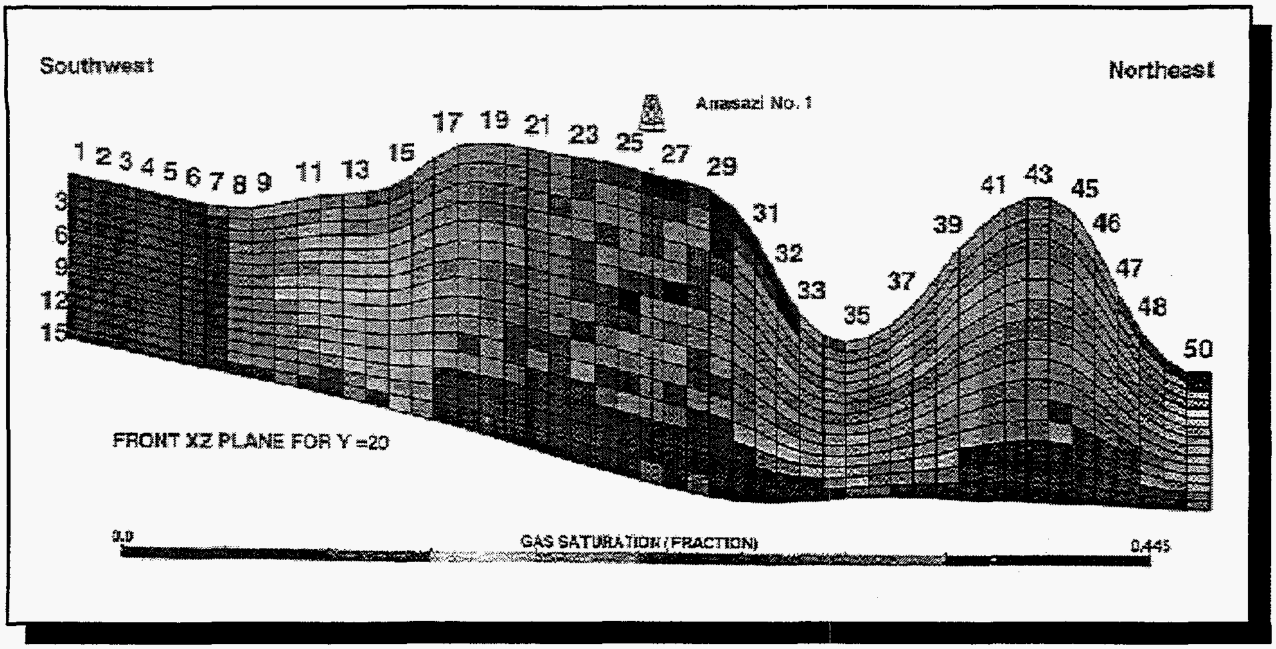

Figure 5.8. Cross section, through the Anasazi No. 1 well, of the Anasazi reservoir grid-system model illustrating gas saturation distribution as of December 31, 1996. The model uses 15 stratigraphic layers (z axis) and 50 cells (x axis).

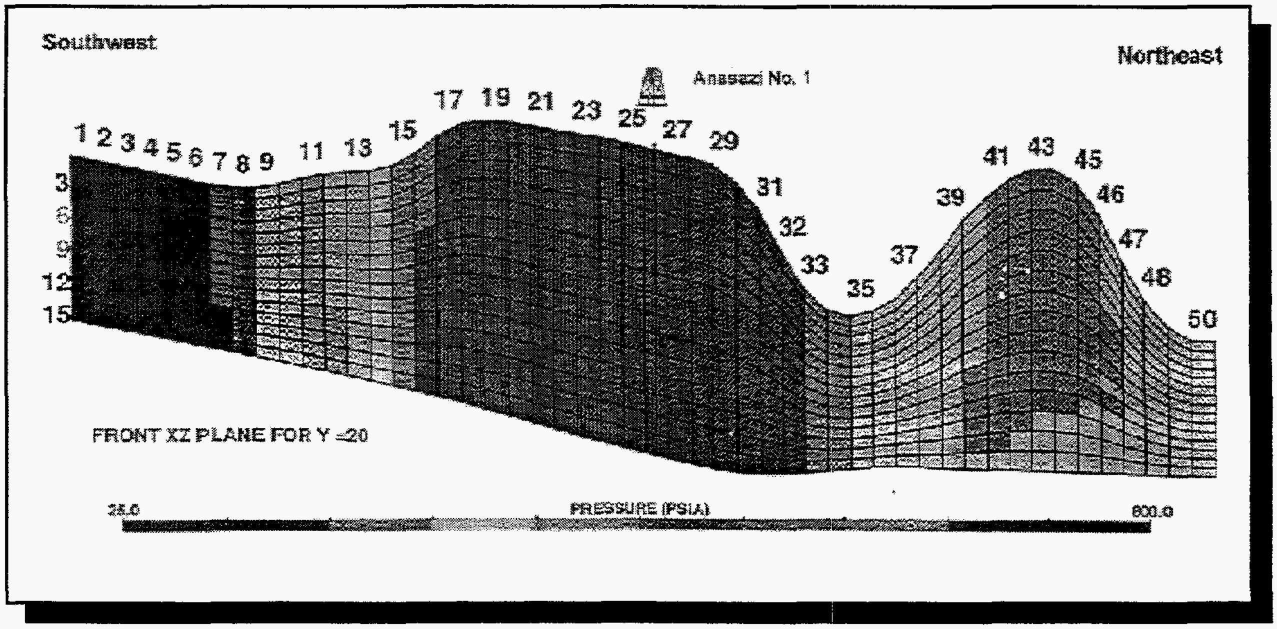

Figure 5.9. Cross section, through the Anasazi No. 1 well, of the Anasazi reservoir grid-system model illustrating reservoir pressure distribution as of December 31, 1996.

1. A substantial reduction of the pore volume of the producing element of the northeast lobe of the buildup. This was accomplished by partitioning the north and south areas of the mound.

2. Partial isolation of the drainage volumes associated with the Anasazi No. 1 and Anasazi No. 5L-3 wells (see figure 3.4 for well locations). This was accomplished by the introduction of a transmissibility reduction approximately midway between the two wells.

3. A reservoir volume expansion south and west of the Anasazi No. 5L-3 well.

4. A reduction in vertical permeability of the supra-mound interval overlying the reservoir mound-core interval in the southwest lobe of the buildup.

5. A reduction of the initial solution gas-oil ratio from that reported in the initial reservoir fluid sample analysis. This was required to better match the field observed producing gas-oil ratio prior to the reservoir pressure decreasing below the bubble point pressure (liquid expansion phase of the primary production period).

Concurrently with the completion of the history match, some initial prediction runs were made to assess the additional oil recovery that would be obtained by injecting CO_2 and repressuring the reservoir to values between 2,000 and 3,000 psi. The first set of CO_2-injection runs were designed to identify appropriate injection well locations to optimize oil recovery. One prediction case, with a single CO_2 injector located in the off-mound area of the southwest lobe, recovered an additional 1.3 million stock tank bbls (MMSTB) (206,700 m^3) of oil after eight years of CO_2 injection. The 1.3 MMSTB represents 57 percent of the volume of oil produced to date under primary production. Additional prediction case runs are planned to: (1) investigate the optimum number of injection wells, their locations, and their configuration (vertical versus horizontal), (2) evaluate reservoir operating pressure (controls miscibility), (3) investigate produced gas re-injection to reduce CO_2 utilization and cost, and (4) use of water injection instead of CO_2.

5.3 References

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6. TECHNOLOGY TRANSFER

Thomas C. Chidsey, Jr.; Utah Geological Survey

The UGS is the Principal Investigator and prime contractor for three 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 will 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 U.S. Department of Energy (DOE) and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and State agencies are co-funding the three 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 *Petroleum News, Survey Notes,* and on the project Internet home page.

Project materials, plans, and objectives were displayed at the UGS booth during the 1996 annual national convention of the AAPG in San Diego, California; the 1996 AAPG Rocky Mountain Section annual meeting in Billings, Montana; and at a UGS co-sponsored symposium entitled the *Geology and Resources of the Paradox Basin* in Durango, Colorado. Three to four UGS scientists staffed the display booth at these events. Abstracts were submitted for technical presentations at the 1997 AAPG national and regional meetings. Project displays will be included as part of the UGS booth at these meetings throughout the duration of the project.

6.1 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. The UGS *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 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 which includes those companies or individuals specifically interested in the Paradox basin project (over 250 as of February 1997) 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*, which describes the UGS/DOE cooperative studies (Paradox basin, Ferron Sandstone, and Bluebell field), 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 annual report, (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.

6.2 Workshops, Presentations, and the 1996 Paradox Basin Symposium

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, outcrop analogues, geostatistics, reservoir models, and simulations.

> "Increased Oil Production and Reserves Utilizing Secondary/Tertiary Recovery Techniques on Small Reservoirs in the Paradox Basin, Utah - A Project Overview" by T.C. Chidsey, Jr.; Improving Production from Shallow Shelf Carbonate (Class 2) Reservoirs Workshop sponsored by DOE, BDM-Oklahoma, Inc., and the Center for Energy and Economic Diversification (CEED), Midland, Texas, May 1996.
>
> "Geological and Reservoir Characterization of Shallow-shelf Carbonate Fields, Southern Paradox Basin, Utah" by T.C. Chidsey, Jr., and D.E. Eby; American Association of Petroleum Geologists Annual Convention, San Diego, California, May 1996.
>
> "Carbonate Mound Reservoirs in the Paradox Formation - An Outcrop Analogue Along the San Juan River, Southeastern Utah" by T.C. Chidsey, Jr., C.D. Morgan, D.E. Eby, Lisë Brinton, and Kris Hartmann; American Association of Petroleum Geologists Rocky Mountain Section Meeting, Billings, Montana, July 1996.
>
> "Increased Oil Production and Reserves Utilizing Secondary/Tertiary Recovery Techniques on Small Reservoirs in the Paradox Basin, Utah - A Project Overview" by Kimm Harty, UGS Deputy Director; Utah Tribal Leaders meeting of the Utah Indian Cooperative Council of the Division of Indian Affairs of the Utah Department of Community and Economic Development, Goshute Indian Reservation, Ibapah, Utah, October 1996.

The UGS co-sponsored a symposium entitled the *Geology and Resources of the Paradox Basin* held in Durango, Colorado, September 20-21, 1996. Other co-sponsors were the U.S. Bureau of Indian Affairs, Utah Geological Association, U.S. Geological Survey, Colorado Geological Survey, Four Corners Geological Society, Fort Lewis College, Ute Mountain Ute Indian Tribe, and U.S. Department of Energy. A UGS workshop presenting the results of phase 1 (budget period 1) of the Paradox basin project included the following poster displays: (1) project field summaries, (2) regional facies belts and analysis, (3) outcrop studies, (4) statistical models and reservoir simulations, and (5) technology transfer. The workshop also included a computer demonstration of the UGS-developed project database showing production data, petrophysical analysis, core descriptions, formation tops, completion results, and other information. A representative conventional core from the Anasazi No. 1 well was displayed for examination by the 120 participants (figure 6.1).

A field trip through the Paradox basin with 50 participants was also conducted on September 17-19 as part of the symposium. Project team members made presentations during visits to outcrops in Wild Horse Canyon along the San Juan River (figure 6.2) and the production facilities at the Mule field.

Figure 6.1. Participants at the UGS co-sponsored workshop, during the 1996 Paradox basin symposium in Durango, Colorado, examine core representing the type oil-producing reservoir from the Anasazi field. Photo by R.L. Bon, UGS.

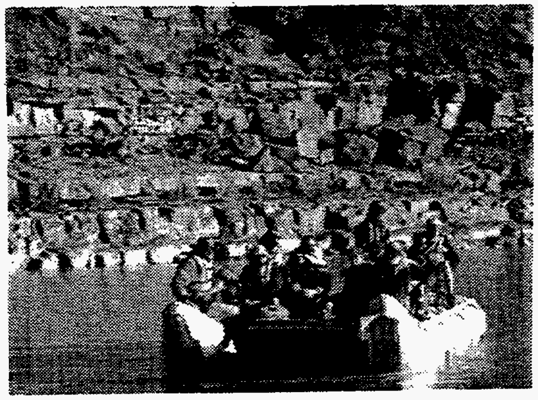

Figure 6.2. Participants preparing to examine Paradox Formation outcrops along the San Juan River, Utah, during the UGS co-sponsored field trip. Photo by R.L. Bon, UGS.

6.3 UGS Sample Library

The UGS acquired Harken's collection of core from 34 wells in the project area. This collection consists of 3,632 feet (1,107 m) of conventional core (including slabs and butts) and is now publicly available at the UGS Sample Library. The Sample Library provides service to all interested individuals and companies who require direct observation of actual samples for their research or investigations. The Paradox basin project core may be examined at the UGS Sample Library or borrowed for a period of as much as six months. Destructive sampling is occasionally permitted with UGS approval. The UGS requires copies of all reports, photographs, and analyses from investigations using borrowed UGS samples; this information can be held confidential for one year upon request but then is available for public examination.

6.4 Project Publications

Bon, R.L., 1996, Paradox basin project set to blast off: Utah Geological Survey, Survey Notes, v. 28, no. 2, p. 12.

Chidsey, T.C., Jr., 1997, 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/14988-8, 117 p.

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---1996, Mule, *in* Hill, B.G., and Bereskin, S.R., editors, Oil and gas fields of Utah: Utah Geological Association 22 (Addendum), non-paginated.

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U.S. Department of Energy, 1996, Increased oil production and reserves utilizing secondary/tertiary recovery techniques on small reservoirs in the Paradox basin, Utah, *in* Contracts for field projects and supporting research on enhanced oil recovery, reporting period April-June 1995: Progress Review No. 83, DOE/BC--95/3, p. 85-87.

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