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HETEROGENEOUS SHALLOW-SHELF CARBONATE BUILDUPS IN THE PARADOX BASIN, UTAH AND COLORADO: TARGETS FOR INCREASED OIL PRODUCTION AND RESERVES USING HORIZONTAL DRILLING TECHNIQUES

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Heterogeneous Shallow-Shelf Carbonate Buildups in the Paradox Basin, Utah and Colorado: Targets for Increased Oil Production and Reserves Using Horizontal Drilling Techniques

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ABSTRACT

The Paradox Basin of Utah, Colorado, Arizona, and New Mexico contains nearly 100 small oil fields producing from carbonate buildups within the Pennsylvanian (Desmoinesian) Paradox Formation. These fields typically have one to 10 wells with primary production ranging from 700,000 to 2,000,000 barrels (111,300-318,000 m^3) of oil per field and a 15 to 20 percent recovery rate. At least 200 million barrels (31.8 million m^3) of oil will not be recovered from these small fields because of inefficient recovery practices and undrained heterogeneous reservoirs. Several fields in southeastern Utah and southwestern Colorado are being evaluated for horizontal drilling from existing vertical field wells based upon geological characterization and reservoir modeling case studies. The results of these studies can be applied to similar fields in the Paradox Basin and the Rocky Mountain region, the Michigan and Illinois Basins, and the Midcontinent region.

This report covers research activities for the second half of the first project year (September 6, 2000, through April 5, 2001). This work includes description and analysis of cores, correlation of geophysical well logs, reservoir mapping, petrographic description of thin sections, cross plotting of permeability and porosity data, and development of horizontal drilling strategies for the Cherokee and Bug fields in San Juan County, Utah. Geological characterization on a local scale focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization, within these fields. This study utilizes representative core, geophysical logs, and thin sections to characterize and grade each field's potential for drilling horizontal laterals from existing development wells.

The typical vertical sequence or lithofacies from the Cherokee and Bug fields, as determined from conventional core, was tied to its corresponding log response to identify reservoir and non-reservoir rock and determine potential units suitable for horizontal drilling projects. Structure contour maps on the top of the upper Ismay zone and the Chimney Rock shale and isochore maps of the upper Ismay and lower Desert Creek for Cherokee and Bug fields, respectively, were constructed to show carbonate buildup trends, define limits of field potential, and also indicate possible horizontal drilling targets.

In order to determine the diagenetic histories of the various Ismay and Desert Creek reservoirs, petrographic descriptions of 44 thin sections were completed from representative core samples. The diagenetic fabrics and porosity types found at Cherokee and Bug fields are indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. The reservoir quality of Cherokee and Bug fields has been affected by multiple generations of dissolution, anhydrite plugging, and various types of cementation which act as barriers or baffles to fluid flow. The most significant and unique diagenetic characteristics were intense, late-stage microporosity and early-stage micro-box-work porosity. Based on cross plots of permeability and porosity data, the reservoir quality of the rocks in Cherokee and Bugs fields is most dependant on pore types and diagenesis.

Strategies for horizontal drilling include the following targets: depositional facies in the Ismay and Desert Creek zones, microporosity in the Ismay zone, and micro-box-work porosity in the Desert Creek zone.

EXECUTIVE SUMMARY

The project's primary objective is to enhance domestic petroleum production by demonstration and transfer of horizontal drilling technology in the Paradox Basin, Utah, Colorado, Arizona, and New Mexico. If this project can demonstrate technical and economic feasibility, then the technique can be applied to approximately 100 additional small fields in the Paradox Basin alone, and result in increased recovery of 25 to 50 million barrels (4-8 million m^3) of oil. This project is designed to characterize several shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation, choose the best candidate(s) for a pilot demonstration project to drill horizontally from existing vertical wells, monitor well performance(s), and report associated validation activities.

The Utah Geological Survey heads a multidisciplinary team to determine the geological and reservoir characteristics of typical small shallow-shelf carbonate reservoirs in the Paradox Basin. The Paradox Basin technical team consists of the Utah Geological Survey (prime contractor), Colorado Geological Survey, Eby Petrography & Consulting Inc., and Seeley Oil Company. This research is funded by the Class II Oil Revisit Program of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research activities for the second half of the first project year (September 6, 2000, through April 5, 2001). This work includes description and analysis of cores, correlation of geophysical well logs, reservoir mapping, petrographic description of thin sections, cross plotting of permeability and porosity data, and development of horizontal drilling strategies for the Cherokee and Bug fields in San Juan County, Utah. From these evaluations, untested or under-produced reservoir compartments can be identified as targets for horizontal drilling. The results of this study can be applied to similar reservoirs in many U.S. basins.

Reservoir data (porosity and permeability), cores and cuttings, geophysical logs, various reservoir maps, and other information are being collected from the case-study fields and adjacent regional exploratory wells. Well locations, production reports, completion tests, core analysis, formation tops, and other data are being compiled and entered in a Utah Geological Survey database. Core photographs and descriptions were compiled for case-study field wells with special emphasis on identifying bounding surfaces and depositional environments of possible flow units. Typical vertical sequences or cycles of lithofacies from each field, as determined from conventional core, were tied to corresponding geophysical log responses. Structure contour maps on the top of the upper Ismay zone and the Chimney Rock shale and isochore maps of the upper Ismay and lower Desert Creek for Cherokee and Bug fields, respectively, showed carbonate buildup trends, defined limits of field potential, and also indicated possible horizontal drilling targets.

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Cherokee and Bug fields are indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. Based on petrographic descriptions of 44 thin sections from representative core samples, the quality of the reservoirs in Cherokee and Bug fields appears to have been affected by multiple generations of dissolution, anhydrite plugging, and various types of cementation which act as barriers or baffles to fluid flow. The most significant and unique diagenetic characteristic observed at Cherokee field was intense, late-stage microporosity developed along hydrothermal solution fronts. Bug field shows extensive, early-stage, micro-box-work porosity due to dissolution related to subaerial exposure of the carbonate buildup. Based on cross plots of permeability and porosity data, the reservoir quality of the

rocks in Cherokee and Bug fields is most dependant on pore types and diagenesis, rather than facies, carbonate fabric, or mineralogy. The microporosity in Cherokee field and the micro-box-work porosity in Bug field represent important sites for untapped hydrocarbons and possible targets for horizontal drilling.

Based on these findings, three strategies for horizontal drilling are being developed for Cherokee, Bug, and similar fields in the Paradox Basin. All strategies involve drilling stacked, parallel horizontal laterals. Depositional facies are targeted in both the Ismay and Desert Creek zones where multiple buildups can be penetrated with two opposed sets of stacked, parallel horizontal laterals. The hydrothermally induced microporosity in the Ismay zone does not appear to be facies dependent and therefore could be drained with radially stacked, horizontal laterals and splays. Finally, much of the elongate, brecciated beach-mound depositional facies and micro-box-work porosity found in the Desert Creek zone could be penetrated by opposed sets of stacked, parallel horizontal laterals. However, these strategies are preliminary and will be further refined as additional data is collected and analyzed, and three-dimensional reservoir models developed for the case-study fields in the Paradox Basin.

INTRODUCTION

Geologic Setting

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending evaporitic basin that predominately developed during the Pennsylvanian (Desmoinesian), about 330 to 310 million years ago (Ma). During the Pennsylvanian, a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The

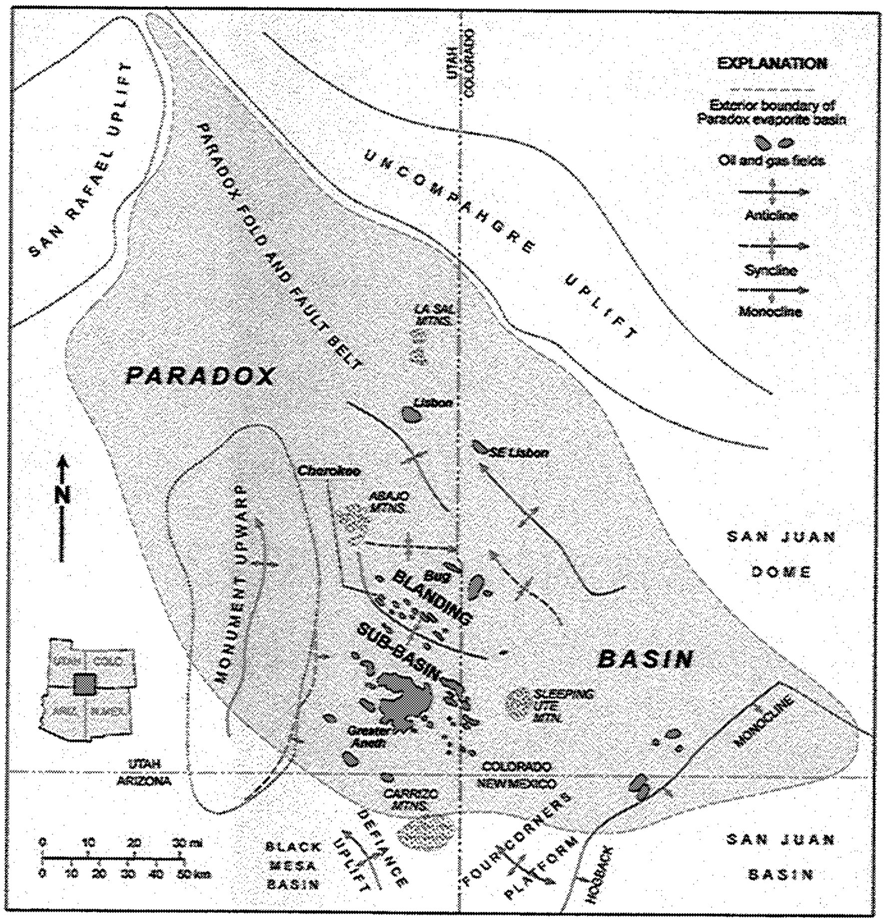


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large basement-involved, high-angle reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993). The Paradox Basin is surrounded by other uplifts and basins that formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1).

The Paradox Basin can generally be divided into two areas: the Paradox fold and fault belt in the north, and the Blanding sub-basin in the south-southwest (figure 1). Most oil production comes from the Blanding sub-basin. The source of the oil is several black, organic-rich shales within the Paradox Formation (Hite and others, 1984; Nuccio and Condon, 1996). The relatively undeformed Blanding sub-basin developed on a shallow-marine shelf which locally contained algal-mound and other carbonate buildups in a subtropical climate.

The two main producing zones of the Paradox Formation are informally named the Ismay and the Desert Creek (figure 2). The Ismay zone is dominantly limestone comprising equant buildups of phylloid-algal material with locally variable small-scale subfacies (figure 3A) and capped by anhydrite. The Ismay produces oil from fields in the southern Blanding sub-basin (figure 4). The Desert Creek zone is dominantly dolomite comprising regional nearshore shoreline trends with highly aligned, linear facies tracts (figure 3B). The Desert Creek produces oil in fields in the central Blanding sub-basin (figure 4). Both the Ismay and Desert Creek buildups generally trend northwest-southeast. Various facies changes and extensive diagenesis have created complex reservoir heterogeneity within these two diverse zones.

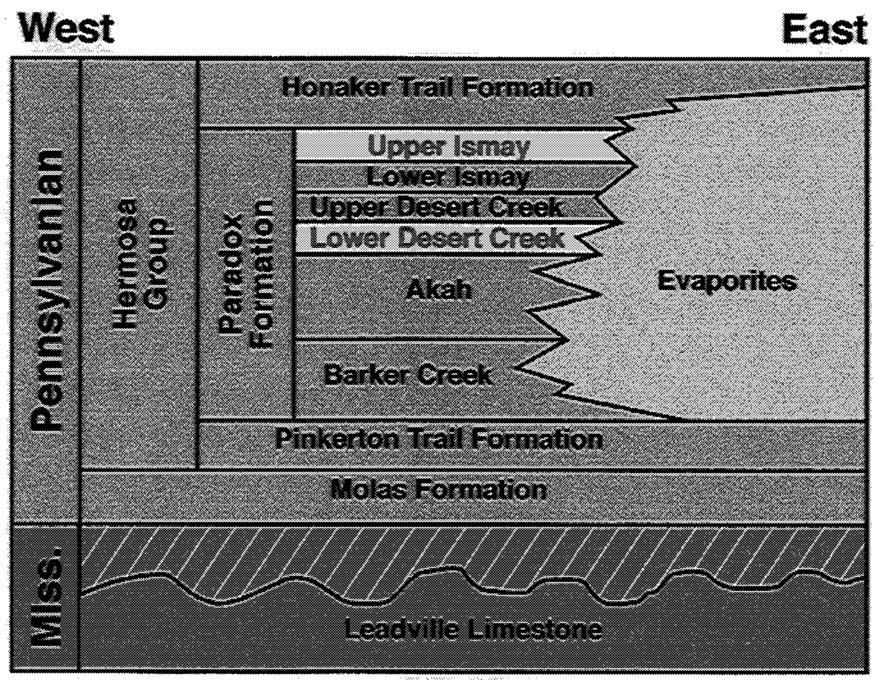


Figure 2. Pennsylvanian stratigraphy of the southern Paradox Basin including informal zones of the Paradox Formation.

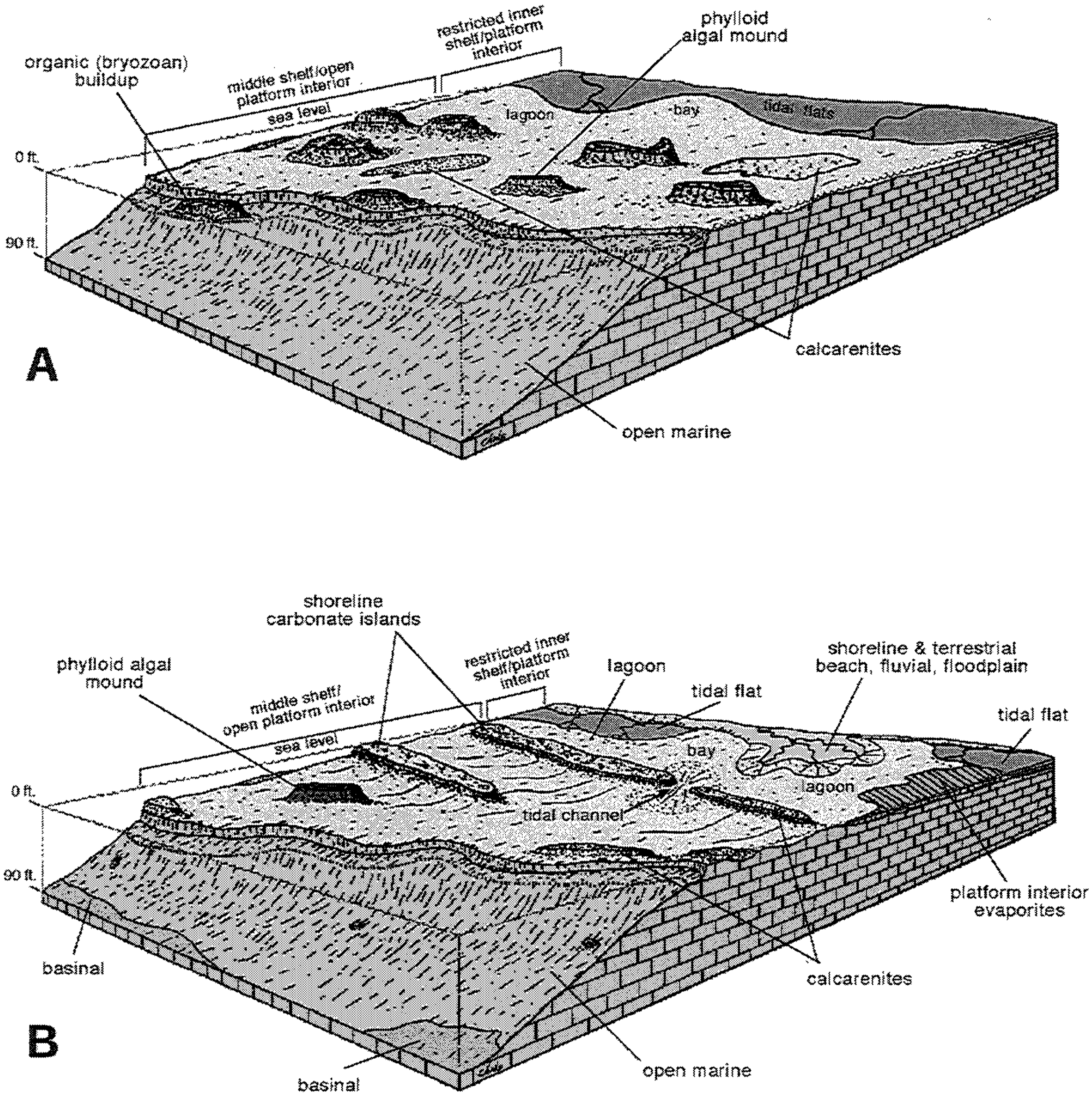


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

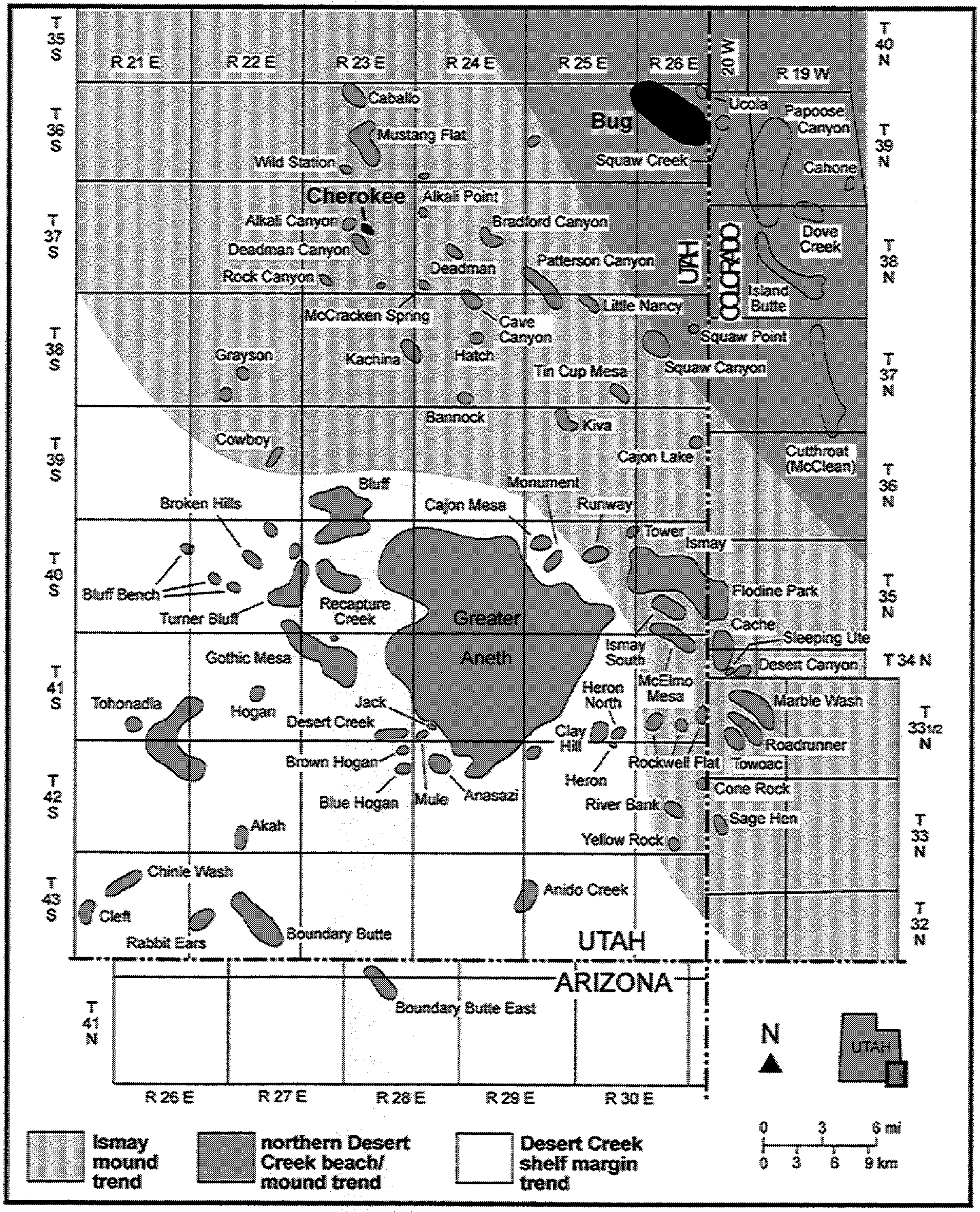


Figure 4. Map showing the project study area and fields within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

Project Overview

Over 400 million barrels (64 million m^3) of oil have been produced from the shallow-shelf carbonate reservoirs in the Pennsylvanian Paradox Formation in the Paradox Basin. With the exception of the giant Greater Aneth field, the other 100 plus oil fields in the basin typically contain 2 to 10 million barrels (0.3-1.6 million m^3) of original oil in place. Most of these fields are characterized by high initial production rates followed by a very short productive life (primary), and hence premature abandonment. Only 15 to 25 percent of the original oil in place is recoverable during primary production from conventional vertical wells.

An extensive and successful horizontal drilling program has been conducted in the giant Greater Aneth field. However, to date, only two horizontal wells have been drilled in small Ismay and Desert Creek fields. The results from these wells were disappointing due to poor understanding of the carbonate facies and diagenetic fabrics that create reservoir heterogeneity. These small fields, and similar fields in the basin, are at high risk of premature abandonment. At least 200 million barrels (31.8 million m^3) of oil will be left behind in these small fields because current development practices leave compartments of the heterogeneous reservoirs undrained. Through proper geological evaluation of the reservoirs, production may be increased by 20 to 50 percent through the drilling of low-cost single or multilateral horizontal legs (figure 5) from existing vertical development wells. In addition, horizontal drilling from existing wells minimizes surface disturbances and costs for field development, particularly in the environmentally sensitive areas of southeastern Utah and southwestern Colorado.

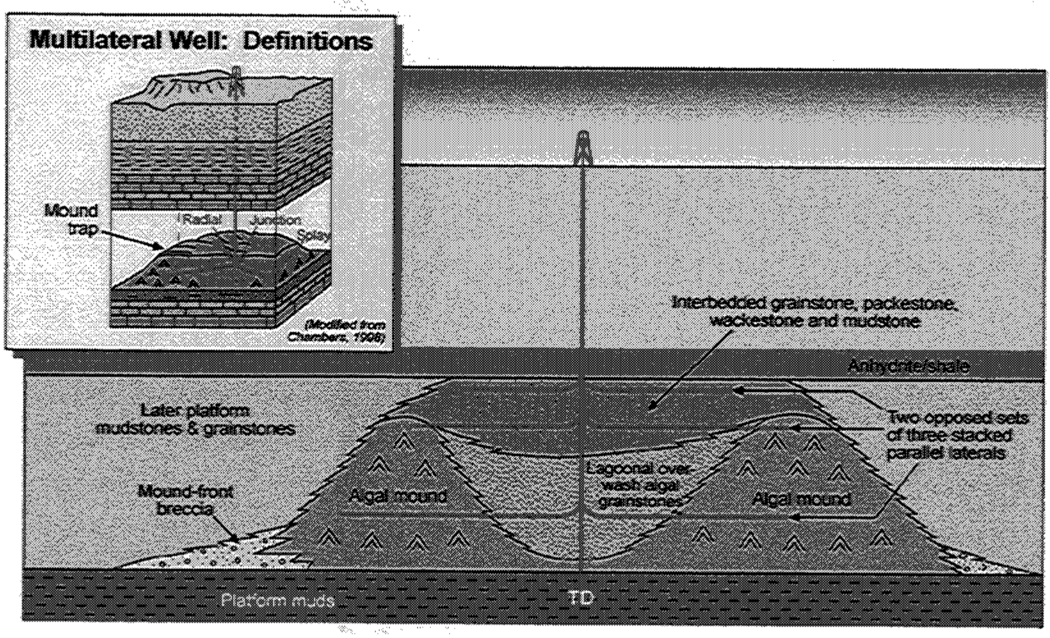


Figure 5. Schematic diagram of Ismay zone drilling targets by multilateral (horizontal) legs from an existing field well.

The Utah Geological Survey (UGS), Colorado Geological Survey (CGS), Eby Petrography & Consulting, Inc., and Seeley Oil Company have entered into a cooperative agreement with the U.S. Department of Energy as part of its Class II Oil Revisit Program. A three-phase, multidisciplinary approach will be used to increase production and reserves from the shallow-shelf carbonate reservoirs in the Ismay and Desert Creek zones of the Paradox Basin. Phase 1 is the geological and reservoir characterization of selected, diversified small fields, including Cherokee and Bug fields in San Juan County, Utah (figure 4), to identify those field(s) having the greatest potential as targets for increased well productivity and ultimate recovery in a pilot demonstration project. This phase will include: (a) determination of regional geological setting; (b) analysis of the reservoir heterogeneity, quality, lateral continuity, and compartmentalization within the fields; (c) construction of lithologic, microfacies, porosity, permeability, and net pay maps of the fields; (d) determination of field reserves and recovery; and (e) integration of geological data in the design of single or multiple horizontal laterals from existing vertical wells.

Phase 2 is a field demonstration project of the horizontal drilling techniques identified as having the greatest potential for increased field productivity and ultimate recovery. The demonstration project will involve drilling one or more horizontal laterals from the existing vertical field well(s) to maximize production from the zones of greatest potential.

Phase 3 includes: (a) reservoir management and production monitoring, (b) economic evaluation of the results, and (c) determination of the ability to transfer project technologies to other similar fields in the Paradox Basin and throughout the U.S.

Phases 1, 2, and 3 will have continuous, but separate, technical transfer activities including: (a) an industry outreach program and project newsletters; (b) a core workshop/ seminars in Salt Lake City; (c) publications and technical presentations; (d) a project home page on the Utah Geological Survey and Colorado Geological Survey Internet web sites; (e) digital databases, maps, and reports; (f) a summary of regulatory, economic, and financial needs; and (g) annual meetings with a Technical Advisory Board and Stake Holders Board.

Project Benefits and Potential Application

The overall benefit of this multi-year project would be enhanced domestic petroleum production by demonstrating and transferring an advanced-oil-recovery technology throughout the small oil fields of the Paradox Basin. Specifically, the benefits expected from the project are: (1) increasing recovery and reserve base by identifying untapped compartments created by reservoir heterogeneity; (2) preventing premature abandonment of numerous small fields; (3) increasing deliverability by horizontally drilling along the reservoir's optimal fluid-flow paths; (4) identifying reservoir trends for field extension drilling and stimulating exploration in Paradox Basin fairways; (5) reducing development costs by more closely delineating minimum field size and other parameters necessary for horizontal drilling; (6) allowing for minimal surface disturbance by drilling from existing vertical field wells; (7) allowing limited energy investment dollars to be used more productively; and (8) increasing royalty income to the Federal, state, and local governments, the Ute Mountain Ute Indian Tribe, and fee owners. These benefits may also apply to other areas including: algal-mound and carbonate buildup reservoirs on the eastern and northwest shelves of the Permian Basin in Texas, Silurian pinnacle and patch reefs of the Michigan and Illinois Basins, and shoaling carbonate island trends of the Williston Basin.

The results of this project are transferred to industry and other researchers through establishment of technical advisory and stake holders boards, an industry outreach program, digital project databases, and web page. Project results will be disseminated via technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and papers in newsletters and various technical or trade journals.

GEOLOGICAL CHARACTERIZATION OF CASE-STUDY FIELDS, SAN JUAN COUNTY, UTAH - RESULTS AND DISCUSSION

Two Utah fields were selected for local-scale evaluation during Budget Period I of the project: Cherokee in the Ismay trend and Bug in the Desert Creek trend (figure 4). Others may be evaluated later. This evaluation included data collection, core photography and description, determination of a typical vertical sequence from conventional core tied to its corresponding log response, reservoir mapping, determination of diagenetic fabrics from thin sections, and plots of core plug porosity versus permeability of these fields. This geological characterization focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within the fields. From these evaluations, untested or under-produced compartments can be identified as targets for horizontal drilling. The models resulting from the geological and reservoir characterization of these fields can be applied to similar fields in the basin (and other basins as well) where data might be limited.

Case-Study Fields

Cherokee Field

Cherokee field (figure 4) is a phylloid-algal buildup capped by anhydrite that produces from porous algal limestone and dolomite in the upper Ismay zone. The net reservoir thickness is 27 feet (8.2 m), which extends over a 320-acre (130 ha) area. Porosity averages 12 percent with 8 millidarcies (md) of permeability in vuggy and intercrystalline pore systems. Water saturation is 38.1 percent (Crawley-Stewart and Riley, 1993).

Cherokee field was discovered in 1987 with the completion of the Meridian Oil Company Cherokee Federal 11-14, NE1/4NW1/4 section 14, T. 37 S., R. 23 E., Salt Lake Base Line and Meridian (SLBL&M); initial flowing potential was 53 barrels of oil per day (BOPD) (8.4 m^3), 990 thousand cubic feet of gas per day (MCFGPD) (28 MCMPD), and 26 barrels of water (4.1 m^3). There are currently four producing (or shut-in) wells and two dry holes in the field. The well spacing is 80 acres (32 ha). The present field reservoir pressure is estimated at 150 pounds per square inch (psi) (1,034 kpa). Cumulative production as of March 1, 2001, was 180,725 barrels of oil (28,735 m^3), 3.6 billion cubic feet of gas (BCFG) (0.1 BCMG), and 1,313 barrels of water (209 m^3) (Utah Division of Oil, Gas and Mining, 2001). The original estimated primary recovery is 172,000 barrels of oil (27,348 m^3) and 3.28 BCFG (0.09 BCMG) (Crawley-Stewart and Riley, 1993). The fact that both these estimates have been surpassed suggests significant additional reserves could remain.

Bug Field

Bug field (figure 4) is an elongate, northwest-trending carbonate buildup in the lower Desert Creek zone. The producing units vary from porous dolomitized bafflestone to packstone and wackestone. The trapping mechanism is an updip porosity pinchout. The net reservoir thickness is 15 feet (4.6 m) over a 2,600-acre (1,052 ha) area. Porosity averages 11 percent in moldic, vuggy, and intercrystalline networks. Permeability averages 25 to 30 md, but ranges from less than 1 to 500 md. Water saturation is 32 percent (Martin, 1983; Oline, 1996).

Bug field was discovered in 1980 with the completion of the Wexpro Bug No. 1, NE1/SE1/4 section 12, T. 36 S., R. 25 E., SLBL&M, for an initial flowing potential of 608 BOPD (96.7 m^3), 1,128 MCFGPD (32 MCMPD), and 180 barrels of water (28.6 m^3). There are currently eight producing (or shut-in) wells, five abandoned producers, and two dry holes in the field. The well spacing is 160 acres (65 ha). The present reservoir field pressure is 3,550 psi (24,477 kpa). Cumulative production as of March 1, 2001, was 1,614,639 barrels of oil (256,728 m^3), 4.36 BCFG (0.12 BCMG), and 3,160,928 barrels of water (502,588 m^3) (Utah Division of Oil, Gas and Mining, 2001). Estimated primary recovery is 1,600,000 bbls (254,400 m^3) of oil and 4 BCFG (0.1 BCMG) (Oline, 1996). Again, since the original reserve estimates have been surpassed and the field is still producing, significant additional reserves likely remain.

Field Data Collection and Compilation

Reservoir data, cores and cuttings, geophysical logs, various reservoir maps, and other information from the project fields and regional exploratory wells are being collected by the UGS and CGS. Well locations, production data, completion tests, basic core analysis, formation tops, porosity and permeability data, and other data are being compiled and entered in a database developed by the UGS. This database, INTEGRAL, is a geologic-information database that links a diverse set of geologic data to records using MS Access™. 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 database containing information on the geological and reservoir characterization study will be available at the UGS's and CGS's Paradox Basin project Internet web sites at the conclusion of the project.

All available conventional cores from the Cherokee and Bug fields were photographed and described (table 1). Special emphasis was placed on identifying the flow unit's bounding surfaces and depositional environments. 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.

Geological characterization on a local scale focussed on reservoir heterogeneity, quality, and lateral continuity as well as possible compartmentalization within Cherokee and Bug fields. This utilized representative core and modern geophysical well logs to characterize and initially grade various intervals in the fields for horizontal drilling suitability.

Table 1. List of well conventional slabbed core examined and described from project fields in the Paradox Basin of Utah and Colorado.

Well	Location	API No.	Cored Interval (ft)	Field	Stratigraphic Zone	Samples For Thin Sections	P&P*	Repository†
May-Bug 2	7-36S-26E, UT	43-037-30543	6290-6333	Bug	Desert Creek	5	yes	UGS
Bug 3	7-36S-26E, UT	43-037-30544	6316-6358	Bug	Desert Creek	1	no	UGS
Bug 4	16-36S-26E, UT	43-037-30542	6278-6322	Bug	Desert Creek	4	Yes	UGS
Bug 7A	7-36S-26E, UT	43-037-30730	6345-6400	Bug	Desert Creek	2	no	UGS
Bug 8	8-36S-26E, UT	43-037-30589	5737-5796.1	Bug	Desert Creek	0	no	UGS
Bug 10	22-36S-26E, UT	43-037-30591	6300-6346.5	Bug	Desert Creek	3	Yes	UGS
Bug 13	17-36S-26E, UT	43-037-30610	5913-5951.3	Bug	Desert Creek	4	Yes	UGS
Bug 16	17-36S-26E, UT	43-037-30607	6278-6333	Bug	Desert Creek	3	Yes	UGS
Cherokee 22-14	14-37S-23E, UT	43-037-31367	5768-5880	Cherokee	Ismay	17	Yes	UGS
Cherokee 33-14	14-37S-23E, UT	43-037-31316	5770-5799	Cherokee	Ismay	5	Yes	UGS

* P&P = Porosity and permeability data from core-plug analysis.
† UGS = Utah Geological Survey, Salt Lake City, Utah; Triple O Slabbing, Denver, Colorado

The typical vertical sequence or cycle of lithofacies from the Cherokee and Bug fields, as determined from conventional core, was tied to its corresponding log response (figures 6 and 7). These sequences graphically include: (1) carbonate fabric, pore type, physical structures, texture, framework grain, and facies (as defined by Chidsey and others, 2001) described from core; (2) plotted porosity and permeability analysis from core plugs; and (3) gamma-ray and neutron-density curves from geophysical well logs. The graphs can be used for identifying reservoir and non-reservoir rock, determining potential units suitable for horizontal drilling projects, and comparing field to non-field areas.

Reservoir Mapping

Structure contour maps on the top of the upper Ismay zone and the Chimney Rock shale (the marker bed just below the lower Desert Creek zone) of the Paradox Formation were constructed for Cherokee and Bug fields, respectively. Isochore maps of the upper Ismay and lower Desert Creek were generated for reservoir units containing 6 percent or more porosity based on the average of the neutron and density porosity values. The maps show well names, Ismay or Desert Creek completions, completion attempts, drill-stem tests, wells with core, and display the subsea top and interval thickness for each well. These maps were combined to show carbonate buildup trends, define limits of field potential, and indicate possible horizontal drilling targets (figures 8 and 9).

These maps incorporated unit tops and thickness from all geophysical well logs in the areas determined using the correlation scheme (Chidsey and others, 2001). The correlation scheme identifies major zone contacts, seals or barriers, baffles, producing or potential reservoirs, and depositional facies.

Depositionally, rock units are divided into seals or barriers (anhydrites and shales), mound (carbonate buildup), and off mound. Porosity units, reservoir or potential reservoir layers, were identified within the mound and off-mound intervals. The mound and some of the off-mound units are part of the clean carbonate - an interval where carbonate mudstone and shale are generally absent. The top and base of all these intervals (seals, mound, clean carbonate, as well as porosity units) were determined. The intervening units represent the baffles or non-reservoir rocks such as non-porous packestone or wackestone. The mound/ mound cap intervals usually have porosity greater than 6 percent while the clean carbonate intervals are defined by lithology only (such as bafflestone or grainstone), although there may be occasional isolated porosity zones. The top and base of the mound/mound cap intervals are often equivalent to the top and base of the clean carbonate intervals. In addition, the top and base of the mound/mound cap intervals may be equivalent to the top and base of the thinner off-mound clean carbonate intervals.

In Cherokee field, six porosity units were identified from geophysical well logs, five of which occur in the upper Ismay mound and the other one in the lower part of clean carbonate. The lower porosity unit exhibits a "false porosity" on geophysical well logs which led the operator to perforate the interval and attempt a completion. However, examination of core, thin sections, and porosity and permeability data from core plug analysis shows the unit is incapable of fluid flow due to low permeability. Therefore, porosity units 1 through 5 were mapped together to produce a gross interval isochore which represents the actual producing reservoir (figure 8).

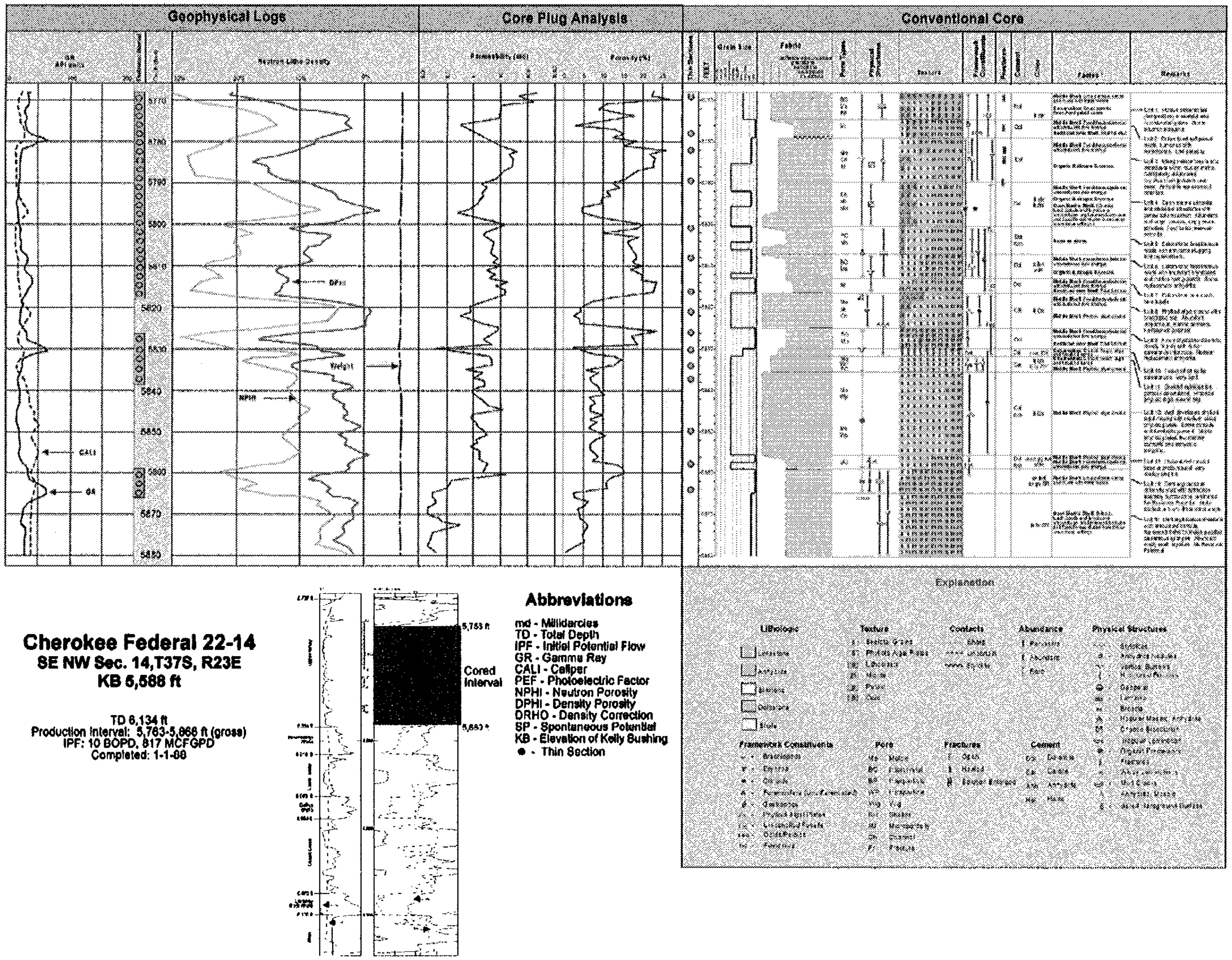


Figure 6. Typical vertical sequence from Cherokee field, including geophysical well logs, porosity/permeability plots, and core description, of the upper Ismay zone, Cherokee No. 22-14 well, San Juan County, Utah.

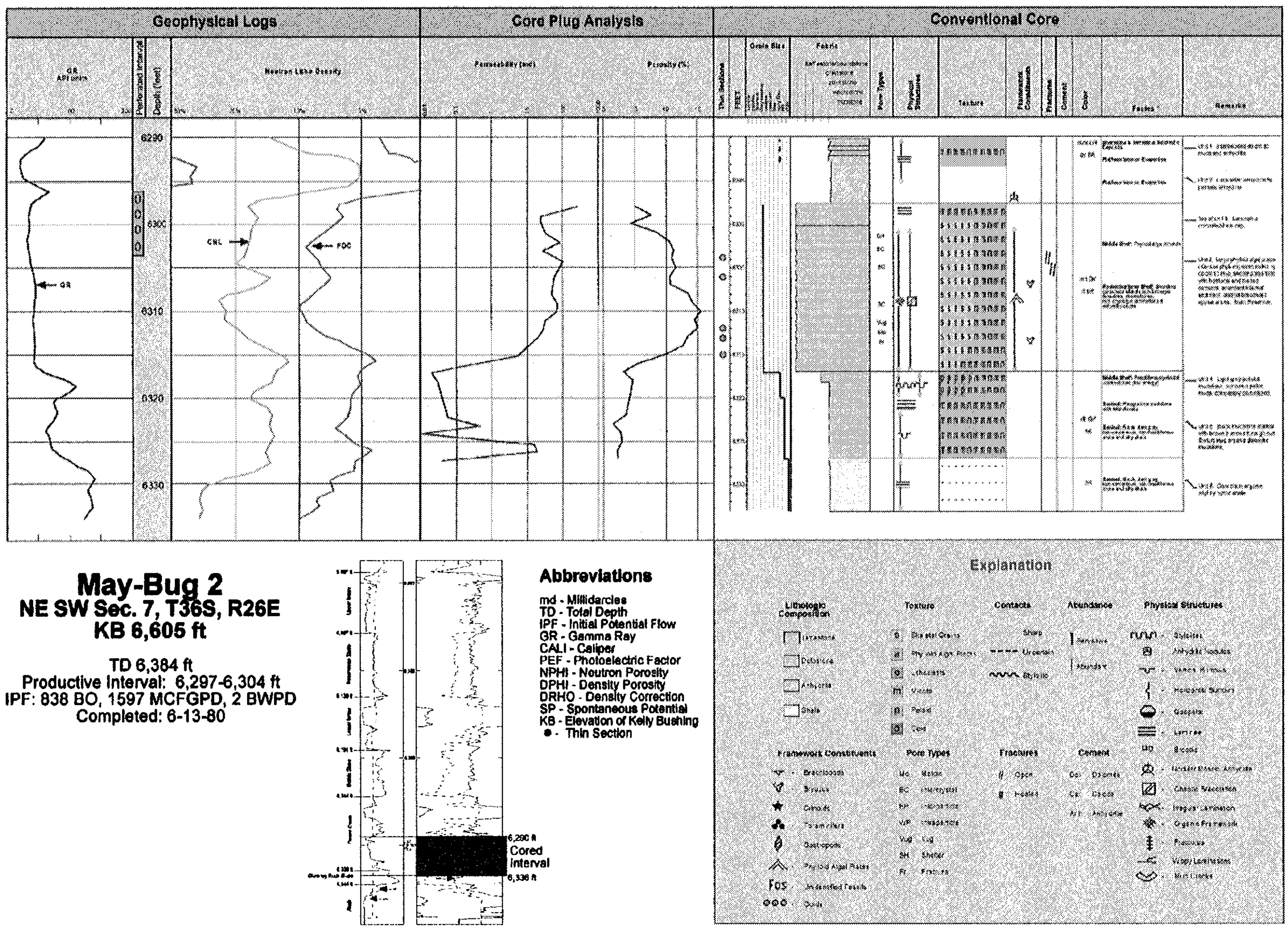
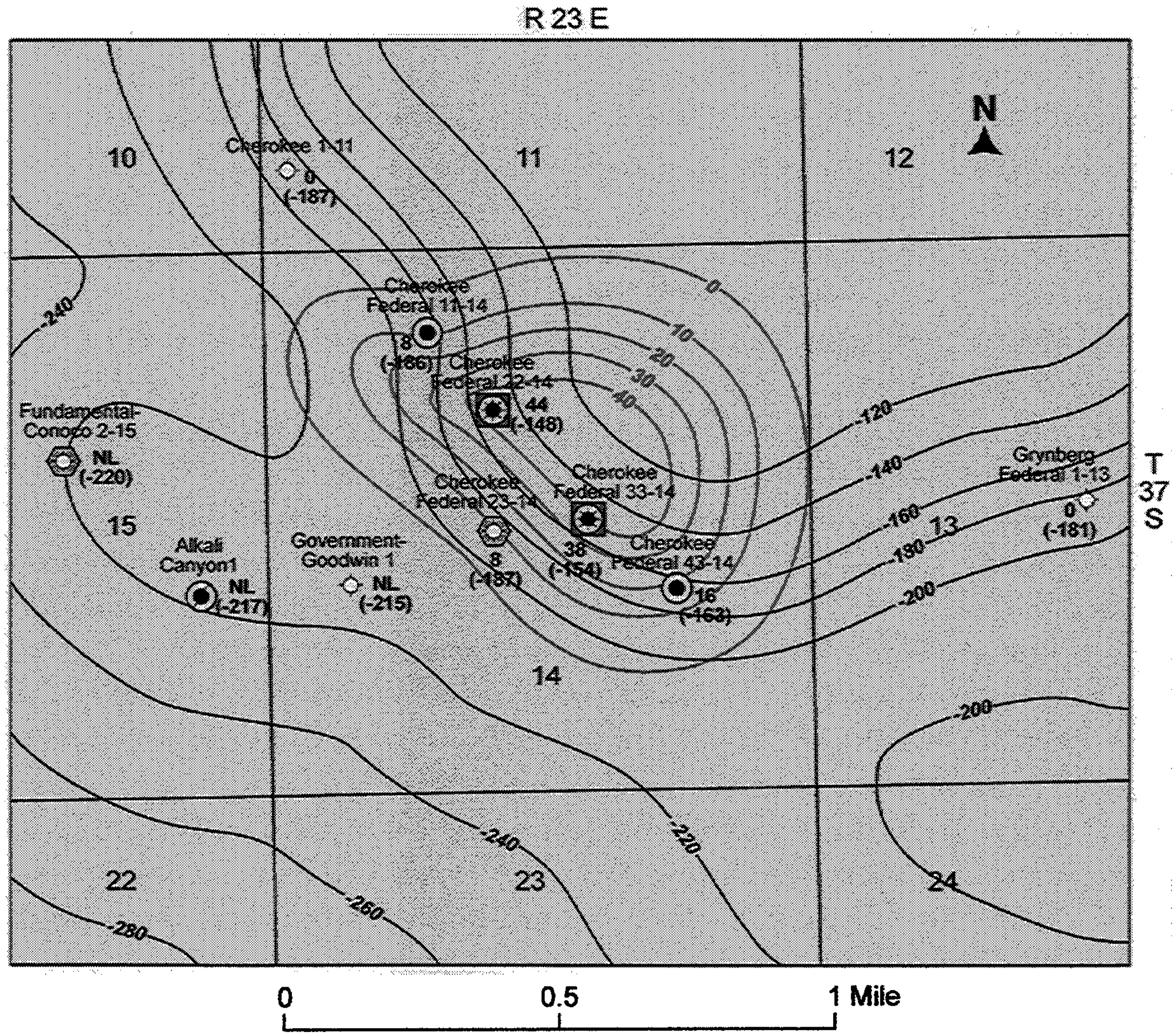


Figure 7. Typical vertical sequence from Bug field, including geophysical well logs, porosity/permeability plots, and core description, of the lower Desert Creek zone, May-Bug No. 2 well, San Juan County, Utah.



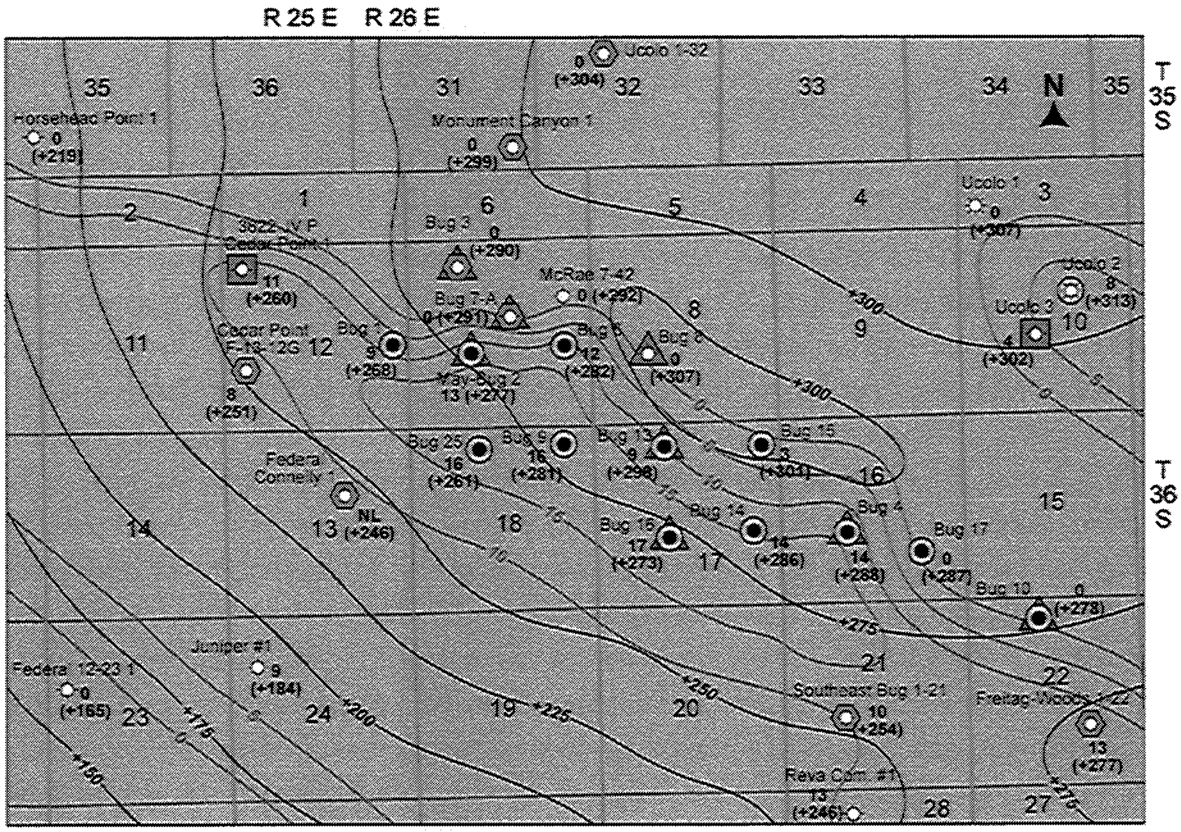
Upper Ismay Isochore
Porosity Units 1-5
Contour Interval = 10 ft

Structure Contour
Top of Ismay
Contour Interval = 20 ft
Datum = Sea Level

Explanation

- Plugged and abandoned
- Ismay drill-stem test
- Ismay completion
- Abandoned Ismay producer
- Ismay completion/core
- NL No neutron/density log

Figure 8. Combined upper Ismay zone structure contour map and isochore map for porosity units 1 through 5, Cherokee field, San Juan County, Utah.



0 0.5 1 1.5 2 Miles

Isochore
Lower Desert Creek Mound
Contour Interval = 5 ft
Porosity > 6%

Structure Contour
Top of Chimney Rock Shale
Contour Interval = 25 ft
Datum = Sea Level

Explanation
- Plugged and abandoned
- Producing gas
- Desert Creek drill-stem test
- Desert Creek completion
- Desert Creek completion attempt
- Desert Creek core
- NL No neutron/density log

Figure 9. Combined Chimney Rock shale structure contour map and isochore map for the lower Desert Creek mound cap/mound core, Bug field, San Juan County, Utah.

In the lower Desert Creek zone of Bug field, the top of the mound/mound cap interval is equivalent to the top of the clean carbonate interval. In addition, the top mound/mound cap interval is equivalent to the top of the thin off-mound clean carbonate interval. The reservoir porosity unit is the entire mound/mound cap interval (figure 9).

The structure contour, isochore, and other maps produced for Cherokee and Bug fields, such as anhydrite and shale isochore maps, will be incorporated into the three-dimensional reservoir models developed later in the project and will be used for: (1) predicting changes in reservoir and non-reservoir rocks across the field, (2) comparing field to non-field areas, (3) estimating the reservoir properties and identifying facies in wells which were not cored, and (4) determining potential units suitable for horizontal drilling projects.

Reservoir Diagenetic Analysis

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Cherokee and Bug fields can be indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. In order to determine the diagenetic histories of the various Ismay and Desert Creek reservoirs, 44 thin sections of representative samples were selected from the conventional cores of each field for petrographic description and possible geochemical analysis. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. Each thin section was photographed with additional close-up photos of: (1) typical preserved primary and secondary pore types, (2) cements, (3) sedimentary structures, (4) fractures, and (5) pore plugging anhydrite and halite.

Typical geochemical and petrographic techniques that will be employed include: (1) epi-fluorescence and cathodoluminescence petrography for the sequence of diagenesis, (2) stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites, (3) strontium isotopes for tracing the origin of fluids responsible for different diagenetic events, (4) scanning electron microscope analysis of various dolomites to determine reservoir quality of the dolomites as a function of diagenetic history, and (5) analysis of bitumen plugging pore throats.

Reservoir diagenetic fabrics and porosity types of these carbonate buildups were analyzed to: (1) determine the sequence of diagenetic events, (2) predict facies patterns, and (3) provide data input for reservoir modeling studies. Diagenetic characterization focussed on reservoir heterogeneity, quality, and compartmentalization within the two fields. All depositional, diagenetic, and porosity information will be combined with each field's production history in order to analyze the potential for success of each horizontal drilling candidate. Of special interest is the determination of the most effective pore systems for oil drainage versus storage.

Diagenetic Characterization of Cherokee Field

The upper Ismay zone in Cherokee field consists of both limestone and dolomite, although there appears to be more dolomite in core than observed in thin section. Petrographic analysis shows the typical mound-facies limestone consists of skeletal phylloid-algal bafflestone with anhydrite plugging early pore space. The calcarenite facies consists of skeletal grainstone limestone, with primary interparticle and intraparticle porosity, and early moldic porosity. Some mixing-zone dolomite and dog-tooth spar (meteroic cement) are present. The low-energy, middle-shelf facies typically consists of dolomite, packstone/wackestone, with peloids, crinoids, and bryozoans. Early dolomitization and late solution-enlarged channels, and anhydrite and bitumen plugging are common.

The most significant and unique diagenetic characteristic observed in the Cherokee field thin sections was extensive microporosity. In fact, much of the "dolomite" observed on the slabbed surface of the core is alteration which features microporosity. Figure 10 is a photomicrograph of peloidal packstone/grainstone dominated by microporosity. The sequence of diagenetic events consisted of: (1) early dolomitization by hypersaline or mixing zone brines, (2) styolitization, (3) late dissolution/micropores, (4) anhydrite replacement, and (5) bitumen plugging. Our preliminary interpretation is that the intense microporosity developed late, along solution fronts by the action of aggressive hydrothermal solutions from depth (carbon dioxide escaping from Mississippian Leadville Limestone or from deep decarboxylation of organic matter). At any rate, this microporosity represents an important site for untapped hydrocarbons and possible targets for horizontal drilling.

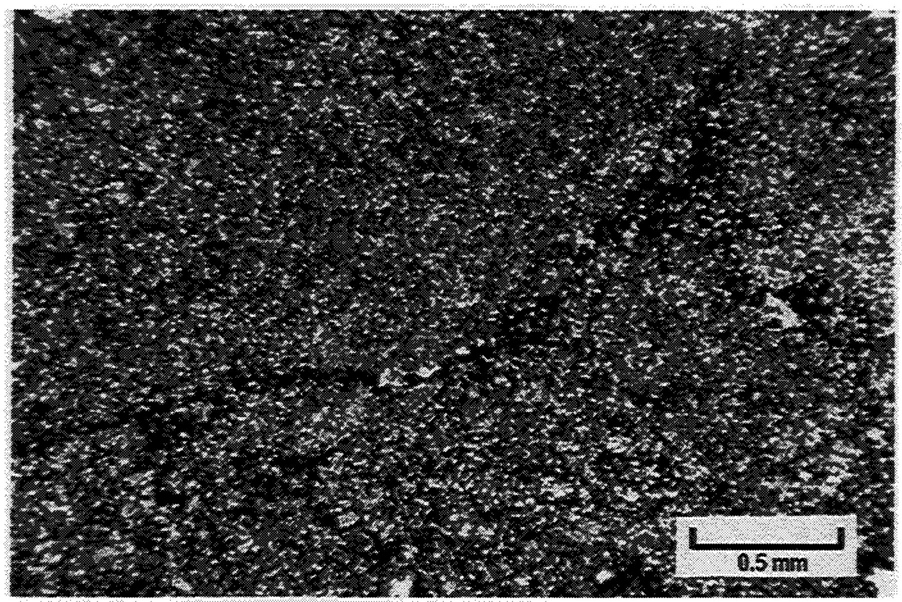


Figure 10. Photomicrograph (plane light) of a peloidal packstone/grainstone dominated by microporosity. Cherokee No. 22-14, 5,768.7 feet (1,758.2 m), porosity = 22.9 percent, permeability = 215 millidarcies.

Diagenetic Characterization of Bug Field

The lower Desert Creek zone in Bug field consists entirely of dolomite. The pore system observed in thin section shows a reservoir that has been predominantly affected by subaerial exposure. Solution-enlarged grain molds (sometimes originally phylloid-algal plates) and fractures are common; both of these types of pores are often lined with black bitumen. The remaining matrix consists of tight dolomite. Remnants of primary, interparticle pores are also observed between small pisolites and grain aggregates, but are often lined or plugged with late anhydrite cements or bitumen. The result is that both effective and ineffective pores are present.

The most significant and unique diagenetic characteristic observed in the Bug field thin sections was extensive "micro-box-work" porosity. Figure 11 is a photomicrograph showing the pattern of patchy dolomite dissolution which includes a micro-box-work pattern of pores. Some of the pores in this view occur between elongate, rectilinear networks of dolomite "lathes." Our preliminary interpretation is that the intense micro-box-work porosity developed early from subaerial exposure of the phylloid-algal buildup. Like the microporosity in Cherokee field, the micro-box-work porosity represents an important site for untapped hydrocarbons and possible targets for horizontal drilling.

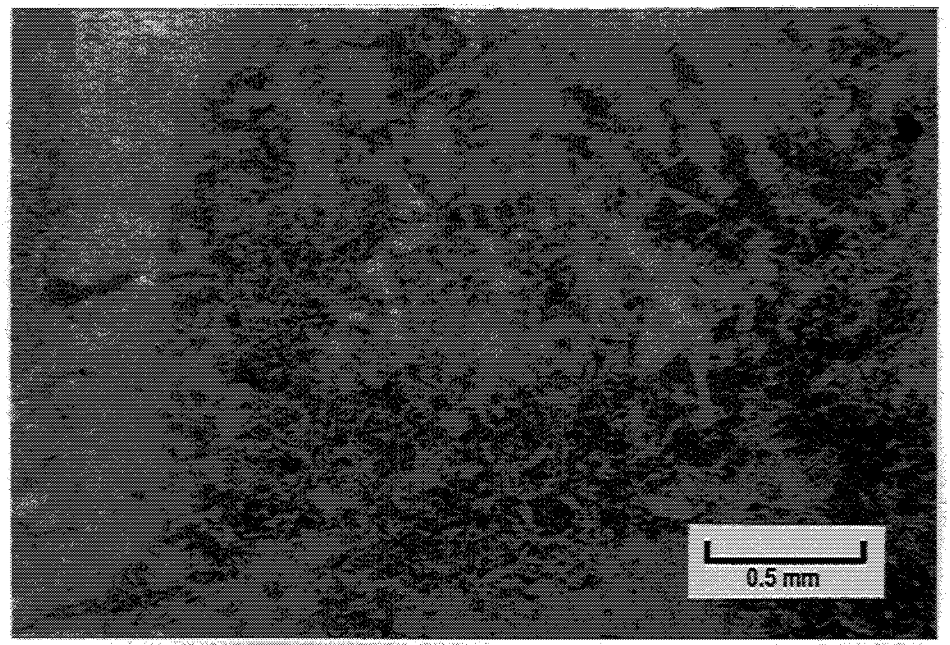


Figure 11. Photomicrograph (plane light with white card technique [diffused light using a piece of paper on the stage of the microscope]) showing a pattern of patchy dolomite dissolution which includes a "micro-box-work" pattern of pores (in blue). Bug No. 10, 6,327.5 feet (1,928.5 m), porosity = 10.5 percent, permeability = 7.5 millidarcies.

Porosity and Permeability Cross Plots

Porosity and permeability data from core plugs were obtained from the two Cherokee wells and five of the eight Bug wells that were cored (table 1). Cross plots of these data are used to: (1) determine the most effective pore systems for oil storage versus drainage, (2) identify reservoir heterogeneity, (3) predict potential untested compartments, (4) infer porosity and permeability trends where core-plug data are not available, and (5) match diagenetic processes, pore types, mineralogy, and other attributes to porosity and permeability distribution. Approximately 50 porosity and permeability cross plots were constructed using the available data. Data classes within the plots included perforated limestone intervals, perforated dolomite intervals, total perforated intervals, reservoir facies, carbonate fabric, pore type, and core with a 6 percent porosity cutoff.

In general, preliminary analysis of these plots shows that those zones that have been dolomitized have better reservoir potential than those that remain limestone (figure 12). The dominant pore type (microporosity/channel, moldic, intercrystalline, interparticle, and shelter/ vuggy) was assigned to each porosity/permeability data point that was cross plotted. The graph for the Cherokee No. 22-14 well from Cherokee field indicates that those samples representing microporosity have the best reservoir potential, while those representing intercrystalline porosity have the poorest reservoir potential (figure 13). The graph for the May-Bug No. 2 well from Bug field indicates that those samples representing intercrystalline porosity with micro-box-work dolomite have the best reservoir potential (figure 14). The dominant facies type (mound/breccia, calcarenites, and open marine and middle/inner shelf) was also assigned to each porosity/permeability data point that was cross plotted. No specific trend between facies type and porosity/permeability was identified, although in Cherokee field better reservoir qualities are generally found in calcarenite facies than in other facies, and in Bug field (figure 15) the better reservoir qualities are found in mound/breccia facies. Thus, our initial conclusion is that the reservoir quality of the rocks in Cherokee and Bug fields is most dependant on pore types and diagenesis.

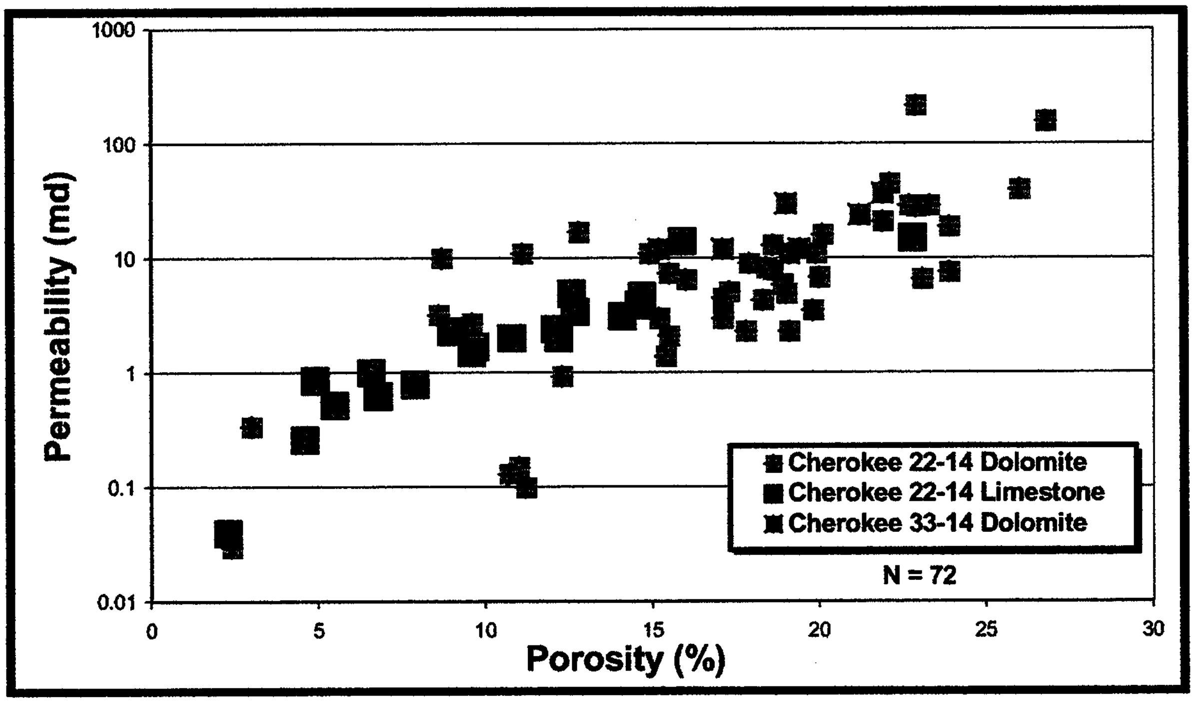


Figure 12. Cherokee field permeability versus porosity cross plot of perforated limestone and dolomite intervals.

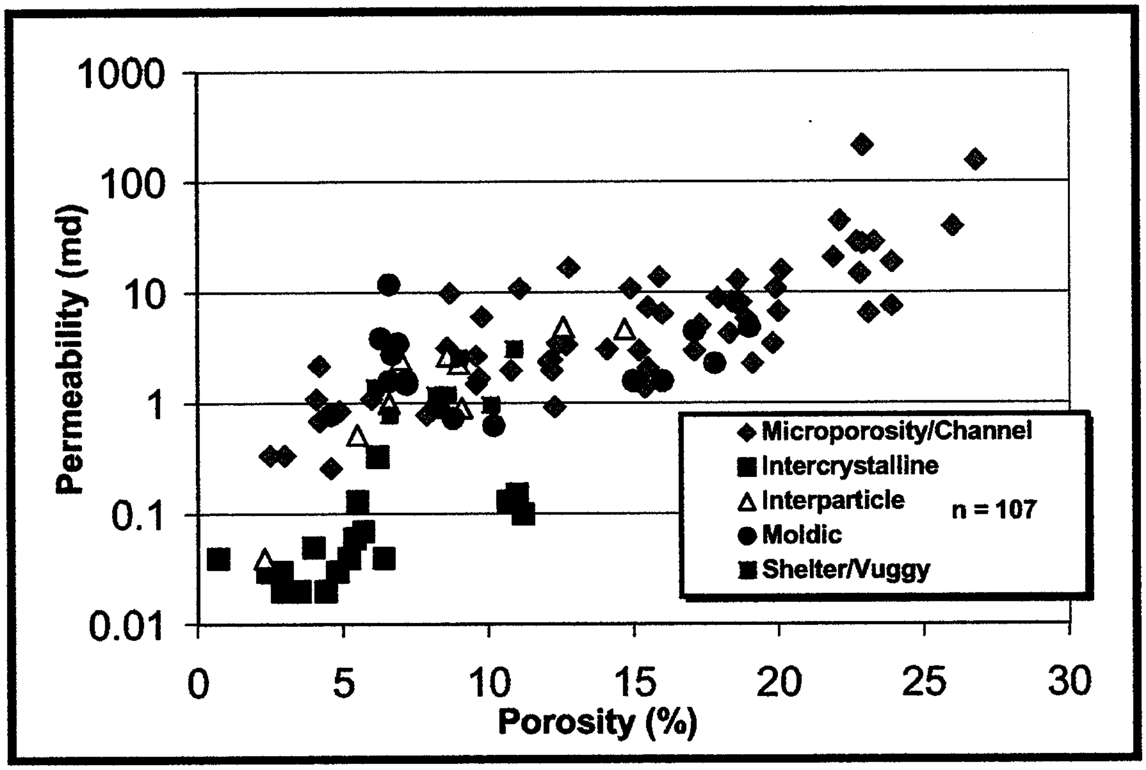


Figure 13. Cherokee No. 22-14 well permeability versus porosity cross plot by pore types and diagenesis.

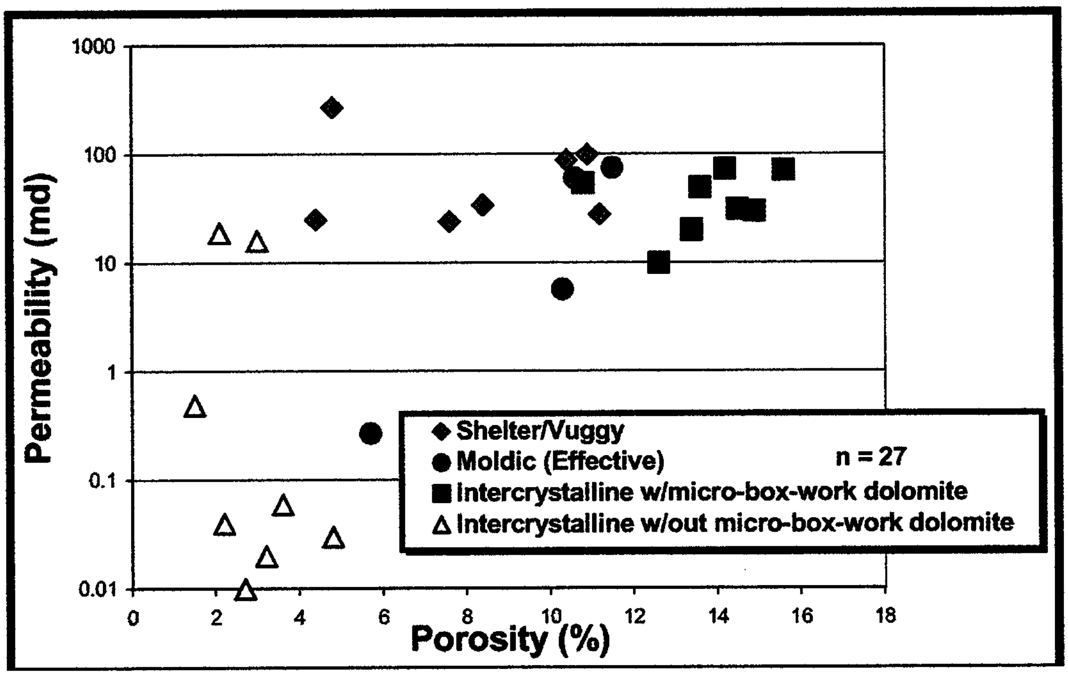


Figure 14. May-Bug No. 2 well permeability versus porosity cross plot by pore types and diagenesis.

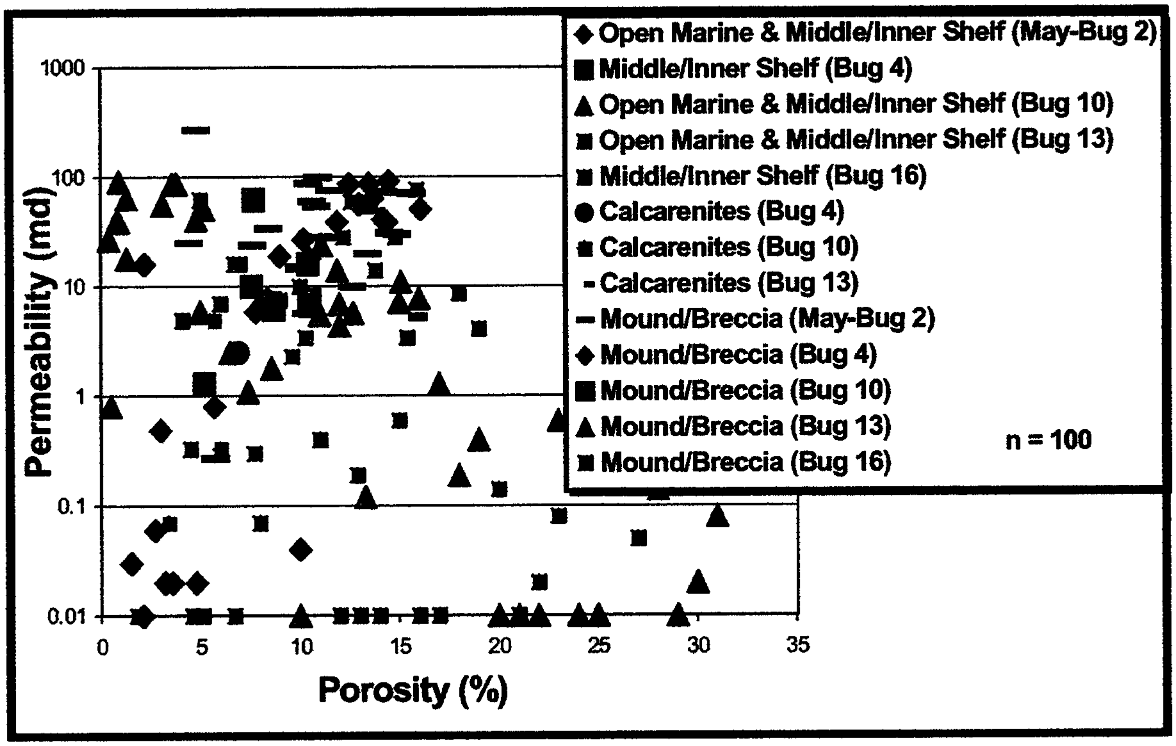


Figure 15. Bug field permeability versus porosity cross plot by facies.

CONCLUSIONS

The Blanding sub-basin within the Pennsylvanian Paradox Basin developed on a shallow-marine shelf that locally contained algal-mound and other carbonate buildups. The two main producing zones of the Paradox Formation are the Ismay and the Desert Creek. The Ismay zone is dominantly limestone comprising equant buildups of phylloid-algal material. The Ismay is productive in fields of the southern Blanding sub-basin. The Desert Creek zone is dominantly dolomite comprising regional nearshore shoreline trends with highly aligned, linear facies tracts. Two Utah fields were selected for evaluation on a local scale: Cherokee in the Ismay trend and Bug in the Desert Creek trend.

The typical vertical sequence or lithofacies from the Cherokee and Bug fields, as determined from conventional core and tied to its corresponding log response, helped identify reservoir and non-reservoir rock (such as false porosity zones on geophysical well logs) and determine potential units suitable for horizontal drilling projects. Structure contour maps on the top of the upper Ismay zone and the Chimney Rock shale and isochore maps of the upper Ismay and lower Desert Creek for Cherokee and Bug fields, respectively, showed carbonate buildup trends, defined limits of field potential, and also indicated possible horizontal drilling targets.

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Cherokee and Bug fields are indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. The reservoir quality of Cherokee and Bug fields has been affected by multiple generations of dissolution, anhydrite plugging, and various types of cementation which act as barriers or baffles to fluid flow. The most significant and unique diagenetic characteristic observed in thin sections from Cherokee field was intense, late-stage microporosity development along hydrothermal solution fronts. The thin sections from Bug field show extensive, early-stage micro-box-work porosity due to dissolution related to subaerial exposure of the carbonate buildup. Based on cross plots of permeability and porosity data, the reservoir quality of the rocks in Cherokee and Bugs fields is most dependant on pore types and diagenesis. The microporosity in Cherokee field and the micro-box-work porosity in Bug field represent important sites for untapped hydrocarbons and possible targets for horizontal drilling.

Based on these findings, three strategies for horizontal drilling are being developed for Cherokee, Bug, and similar fields in the Paradox Basin (figure 16). All strategies involve drilling stacked, parallel horizontal laterals. Depositional facies are targeted in both the Ismay and Desert Creek zones of Cherokee and Bug fields where, for example, multiple buildups can be penetrated with two opposed sets of stacked, parallel horizontal laterals (figure 16A). The hydrothermally induced microporosity in the Ismay zone of Cherokee field does not appear to be facies dependent and therefore could be drained with radially stacked, horizontal laterals and splays (figure 16B). Finally, much of the elongate, brecciated beach-mound depositional facies and micro-box-work porosity in the Desert Creek zone of Bug field could be penetrated by opposed sets of stacked, parallel horizontal laterals (figure 16C). However, these strategies are preliminary and will be further refined as additional data are collected and analyzed, and three-dimensional reservoir models are developed for these fields.

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A

B

C

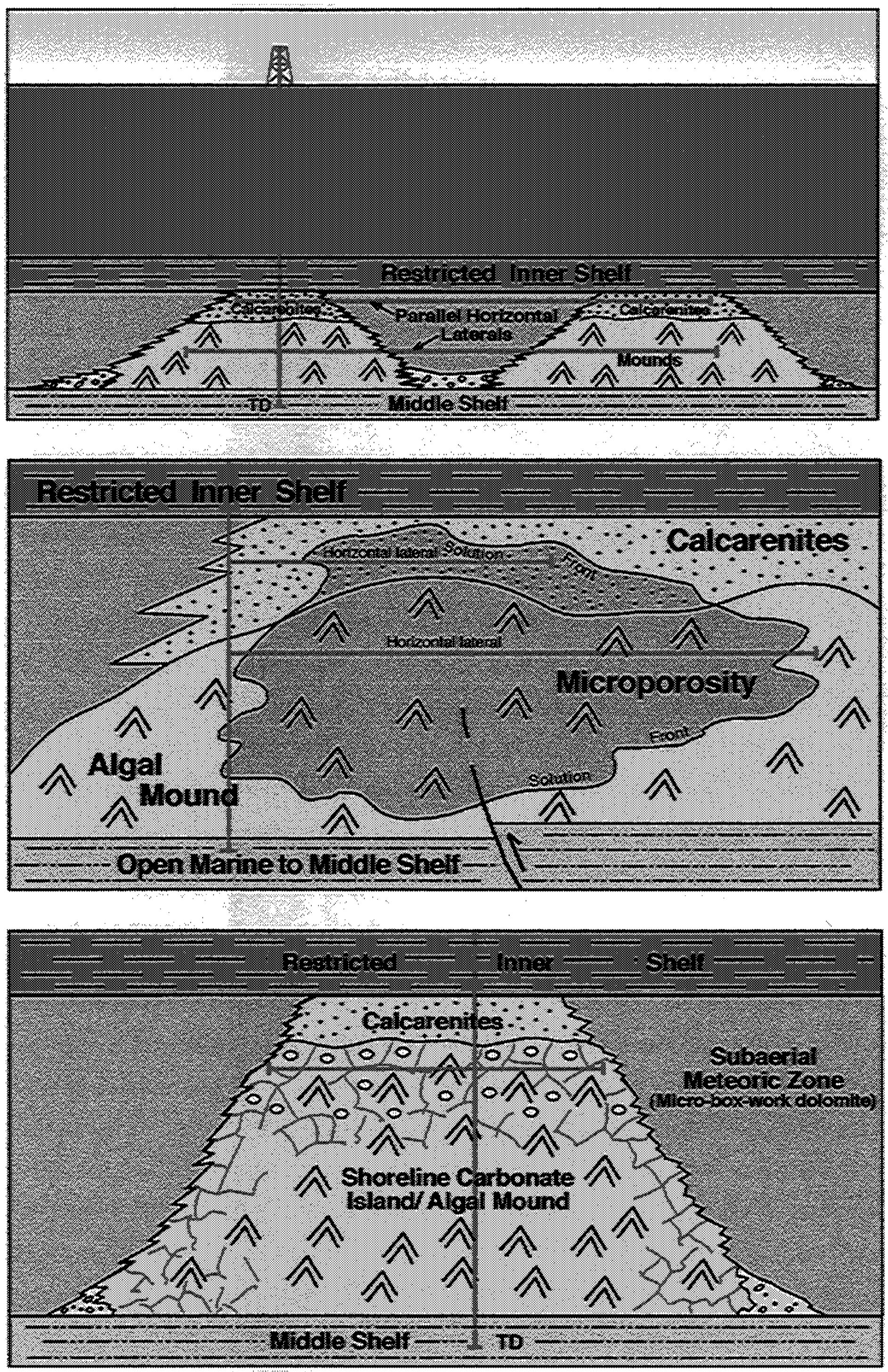

Figure 16. Strategies for horizontal drilling: (A) depositional facies in the Ismay and Desert Creek zones of Cherokee and Bug fields, (B) microporosity in the Ismay zone of Cherokee field, and (C) depositional facies and diagenetic fabrics (micro-box-work porosity) in the Desert Creek zone of Bug field.

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