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

SEMI-ANNUAL TECHNICAL PROGRESS REPORT

April 6, 2003 - October 5, 2003

by

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Kevin McClure and Craig D. Morgan
Utah Geological Survey
David E. Eby, Eby Petrography & Consulting, Inc.
and
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Contract No. DE-FC26-00BC15128

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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 as candidates for horizontal drilling and enhanced oil recovery from existing vertical wells based upon geological characterization and reservoir modeling case studies. Geological characterization on a local scale is focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible reservoir compartmentalization, within these fields. This study utilizes representative cores, geophysical logs, and thin sections to characterize and grade each field's potential for drilling horizontal laterals from existing development wells. The results of these studies can be applied to similar fields elsewhere 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 first half of the fourth project year (April 6 through October 5, 2003). The work included (1) analysis of well-test data and oil production from Cherokee and Bug fields, San Juan County, Utah, and (2) diagenetic evaluation of stable isotopes from the upper Ismay and lower Desert Creek zones of the Paradox Formation in the Blanding sub-basin, Utah.

Production "sweet spots" and potential horizontal drilling candidates were identified for Cherokee and Bug fields. In Cherokee field, the most productive wells are located in the thickest part of the mound facies of the upper Ismay zone, where microporosity is well developed. In Bug field, the most productive wells are located structurally downdip from the updip porosity pinch out in the dolomitized lower Desert Creek zone, where micro-box-work porosity is well developed. Microporosity and micro-box-work porosity have the greatest hydrocarbon storage and flow capacity, and potential horizontal drilling target in these fields.

Diagenesis is the main control on the quality of Ismay and Desert Creek reservoirs. Most of the carbonates present within the lower Desert Creek and Ismay have retained a marine-influenced carbon isotope geochemistry throughout marine cementation as well as through post-burial recycling of marine carbonate components during dolomitization, stylolitization, dissolution, and late cementation. Meteoric waters do not appear to have had any effect on the composition of the dolomites in these zones. Light oxygen values obtained from reservoir samples for wells located along the margins or flanks of Bug field may be indicative of exposure to higher temperatures, to fluids depleted in ^{18}O relative to sea water, or to hypersaline waters during burial diagenesis. The samples from Bug field with the lightest oxygen isotope compositions are from wells that have produced significantly greater amounts of hydrocarbons. There is no significant difference between the oxygen isotope compositions from lower Desert Creek dolomite samples in Bug field and the upper Ismay limestones and dolomites from Cherokee field. Carbon isotopic compositions for samples from Patterson Canyon field can be divided into two populations: isotopically heavier mound cement and isotopically lighter oolite and banded cement.

Technology transfer activities consisted of exhibiting a booth display of project materials at the annual national convention of the American Association of Petroleum Geologists, a technical presentation, a core workshop, and publications. The project home page was updated on the Utah Geological Survey Internet web site.

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 of Utah and Colorado. 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 field(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 (subcontractor), Eby Petrography & Consulting Inc. (subcontractor), and Seeley Oil Company (subcontractor and industry partner). 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 first half of the fourth project year (April 6, 2003, through October 5, 2003). This work included (1) analysis of well-test data and oil production from Cherokee and Bug fields, San Juan County, Utah, and (2) diagenetic evaluation of stable isotopes from the upper Ismay and lower Desert Creek zones of the Paradox Formation in the Blanding sub-basin, Utah. From these, and other, project evaluations, untested or under-produced reservoir compartments and trends can be identified as targets for horizontal drilling. The results of this study can be applied to similar reservoirs in many U.S. basins.

Production "sweet spots" and potential horizontal drilling candidates were identified for Cherokee and Bug fields. In Cherokee field, the most productive wells are located on the crest of the structural nose where the upper Ismay zone buildup developed and in the thickest part of the mound facies. These wells likely penetrated a thick section of microporosity - pore type with the greatest hydrocarbon storage capacity and potential horizontal drilling target in the field. In Bug field, the most productive wells are located structurally downdip from the updip porosity pinch out that forms the trap, and in the main part of the lower Desert Creek zone carbonate buildup. These wells likely penetrated significant micro-box-work porosity - the diagenetic pore type with the greatest hydrocarbon storage and flow capacity in this dolomitized reservoir.

Diagenesis is the main control on the quality of Ismay and Desert Creek reservoirs. Most of the carbonates present within the lower Desert Creek and Ismay have retained a marine-influenced carbon isotope geochemistry throughout marine cementation as well as through post-burial recycling of marine carbonate components during dolomitization, stylolitization, dissolution, and late cementation. Meteoric waters do not appear to have had any effect on the composition of these lower Desert Creek dolomites. Based on Bug field dolomite samples, the lower Desert Creek zone shows carbon isotope compositions that are very close in value to modern marine carbonates and Holocene botryoidal, marine, aragonite cements. As with the Bug field dolomite samples, the Cherokee field carbonates fall within the same range of carbon isotope compositions as modern marine sediments, skeletons, and marine cements.

Light oxygen values obtained from reservoir samples for wells located along the margins or flanks of Bug field may be indicative of exposure to higher temperatures, to fluids depleted in ^{18}O relative to sea water, or to hypersaline waters during burial diagenesis. The samples from Bug field with the lightest oxygen isotope compositions are from wells that have produced significantly higher amounts of hydrocarbons. There is no significant difference between the oxygen isotope compositions from lower Desert Creek dolomite samples in Bug field and the upper Ismay limestones and dolomites from Cherokee field.

Carbon isotopic compositions for samples of an upper Ismay cemented limestone buildup in Patterson Canyon field can be divided into two populations with regard to carbon isotopic composition: isotopically heavier mound cement and isotopically lighter oolite and banded cement. Mound cements were confined to a “closed hydrologic system” that allowed a fluid with heavier carbon to evolve. The oolite and banded cement therein may have formed in a more open system allowing exchange with isotopically lighter waters which were involved in the lithification and diagenesis of the capping oolite.

Technology transfer activities consisted of exhibiting a booth display of project objects and results at the 2003 annual national convention of the American Association of Petroleum Geologists in Salt Lake City, Utah. The technical team also presented a project short course/ core workshop and a poster technical presentation at the convention. Cores, regional facies maps, diagenetic analysis, and horizontal drilling recommendations were part of these presentations. The project home page was updated on the Utah Geological Survey Internet web site. Project team members also published an abstract and semi-annual report detailing project progress and results.

INTRODUCTION

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 of southeastern Utah and southwestern Colorado (figure 1). The two main producing zones of the

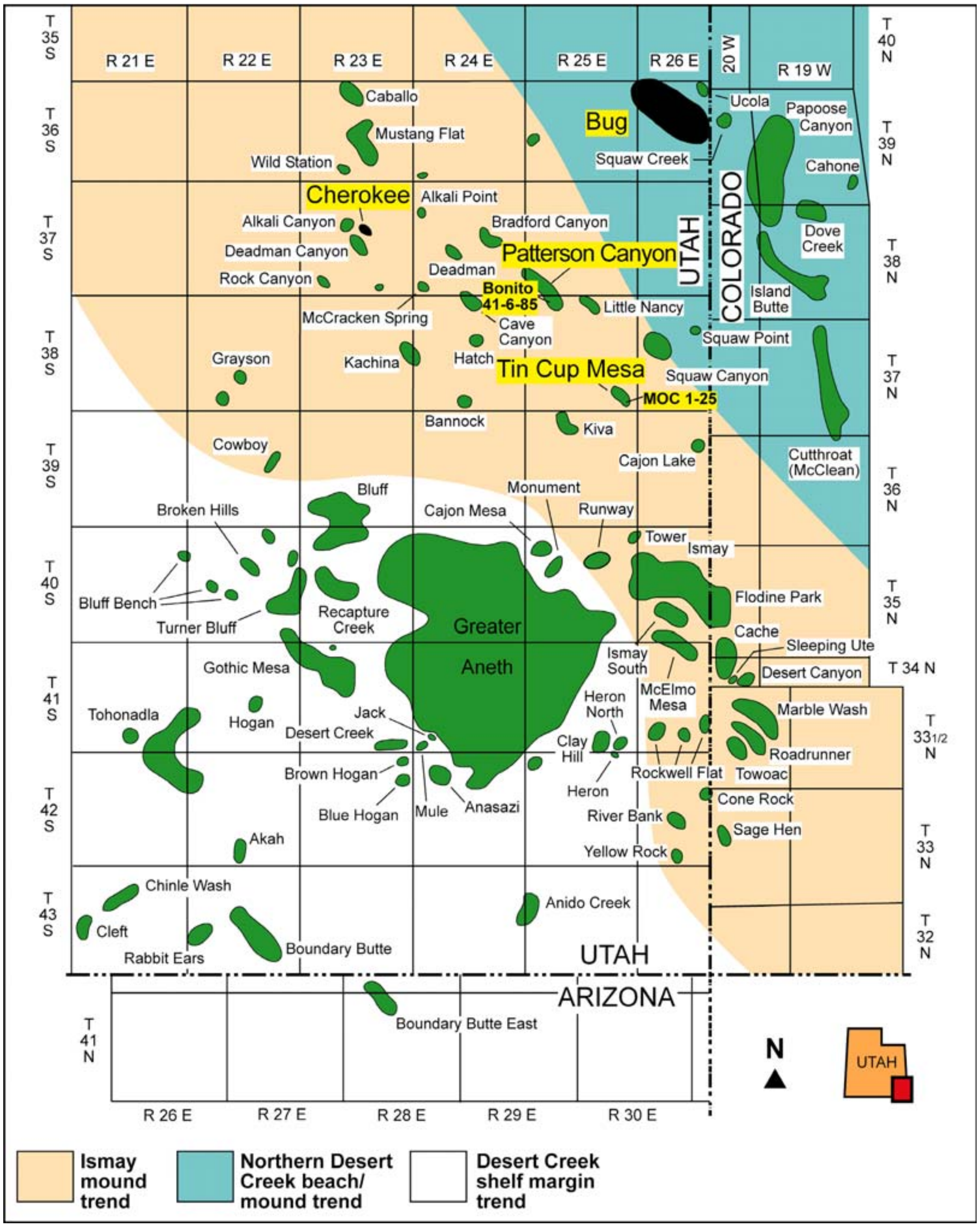

Figure 1. Map showing project study area and fields (case-study fields in black) within the Ismay and Desert Creek producing trends, Utah and Colorado. Fields sampled for isotope analyses are highlighted in yellow.

Paradox Formation are informally named the Ismay and the Desert Creek (figure 2). Reservoirs within the Utah portion of the upper Ismay zone of the Paradox Formation are dominantly limestones composed of small, phylloid-algal buildups; locally variable, inner-shelf, skeletal calcarenites; and rare, open-marine, bryozoan mounds (figure 3A). The Ismay produces oil from fields in the southern Blanding sub-basin (figure 1). 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 1). 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.

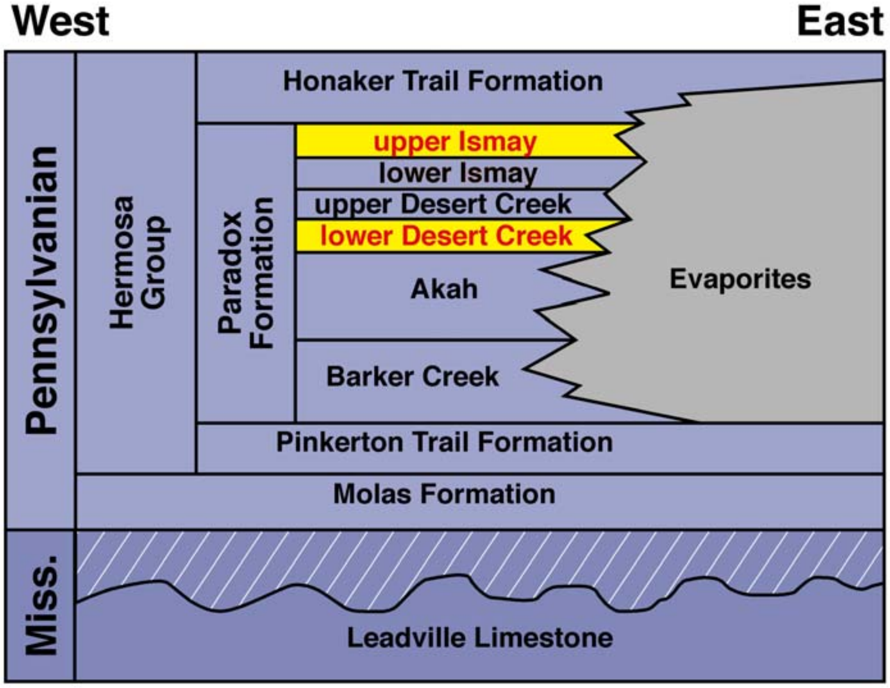

Figure 2. Pennsylvanian stratigraphy of the southern Paradox Basin including informal zones of the Paradox Formation; the upper Ismay and lower Desert Creek zones productive in case-study fields are highlighted.

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 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.

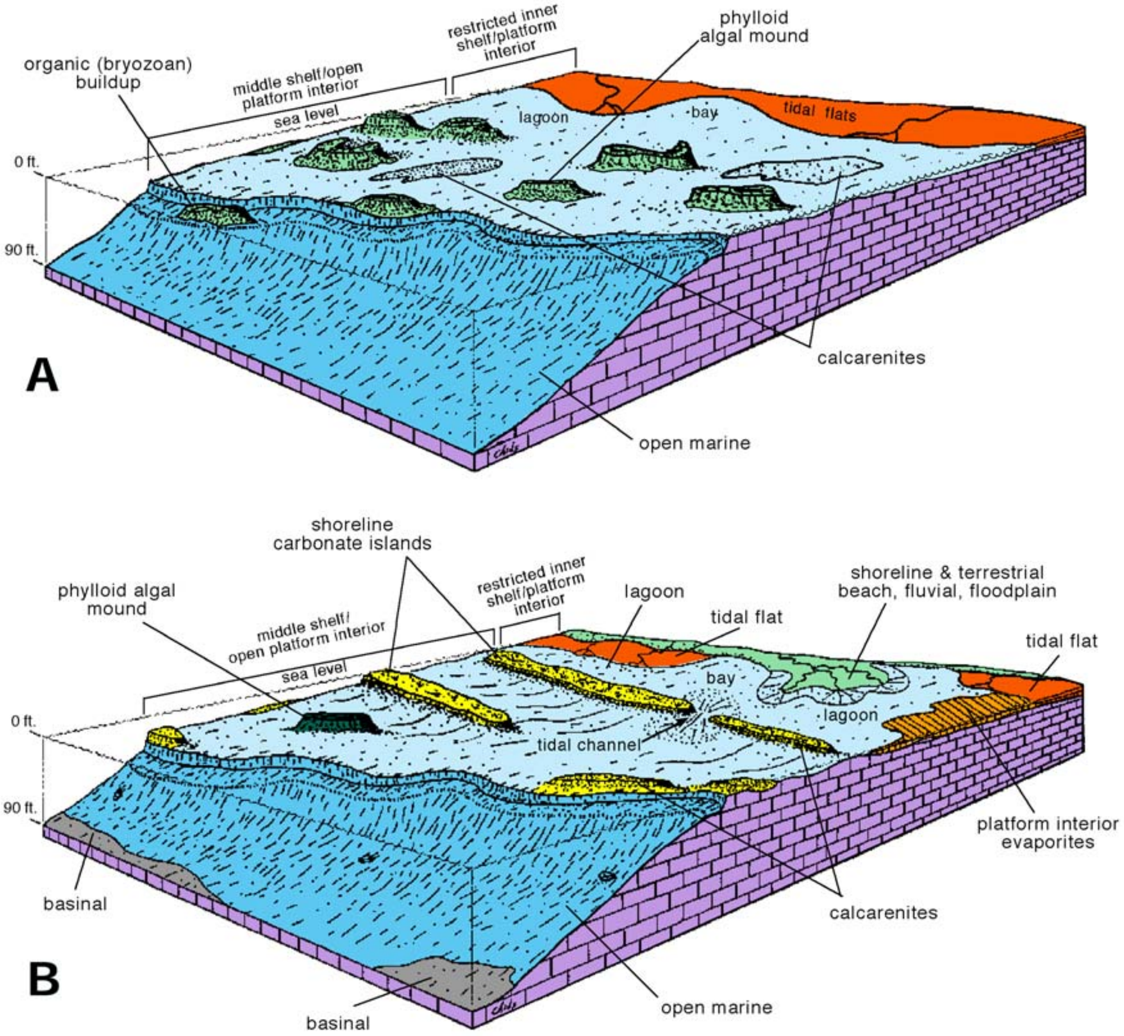

Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado (tan and blue areas shown in figure 1).

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 (DOE) 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 1), 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 includes: (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; (b) a core workshop/seminar 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 well pads; (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 northwestern 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 project web pages. Project results will be disseminated via technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and papers in various technical or trade journals.

CASE-STUDY FIELDS

Two Utah fields were selected for local-scale evaluation and geological characterization: Cherokee in the Ismay trend and Bug in the Desert Creek trend (figure 1). This evaluation included (1) analysis of well-test data and oil production, and (2) diagenetic evaluation of stable isotopes from the upper Ismay and lower Desert Creek zones of the Paradox Formation. 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.

Cherokee Field

Cherokee field (figure 1) 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 potential flow (IPF) 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 three producing (or shut-in) wells, one abandoned producer, 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 June 1, 2003, was 182,071 barrels of oil (28,949 m^3), 3.65 billion cubic feet of gas (BCFG) (0.1 BCMG), and 3,358 barrels of water (534 m^3) (Utah Division of Oil, Gas and Mining, 2003). 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 1) 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 IPF of 608 BOPD (96.7 m^3), 1,128 MCFGPD (32 MCMPD), and 180 barrels of water (28.6 m^3). There are currently seven producing (or shut-in) wells, six 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 June 1, 2003, was 1,622,020 barrels of oil (257,901 m^3), 4.47 BCFG (0.13 BCMG), and 3,181,448 barrels of water (505,850 m^3) (Utah Division of Oil, Gas and Mining, 2003). 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.

PRODUCTION ANALYSIS – RESULTS AND DISCUSSION

Before reservoir-modeling studies could be conducted for the Cherokee and Bug fields, analyses of production data were required. These data were compiled through two principal tasks: (1) review of existing well-completion data, and (2) determination of production history from monthly production reports available through the Utah Division of Oil, Gas and Mining. This information was merged with geological characterization data and incorporated into the interpretation of reservoir models. Production "sweet spots" and potential horizontal drilling candidates, both wells and fields, were identified. Using the results, various horizontal drilling methods and the ultimate recovery can be estimated for Cherokee and Bug fields.

Well-Test Data Evaluation

Well-test data can provide key insight into the nature of reservoir heterogeneities, and also provide "large-scale" quantitative data on actual reservoir properties and facies from case-study reservoirs. Although a number of well tests have been conducted in all of the target reservoirs, only the IPF well tests were determined to provide quantitative reservoir property information. IPF well tests were graphed and plotted for each well (figures 4 through 7). The graphs include both oil (in BOPD) and gas (in MCFPD) production.

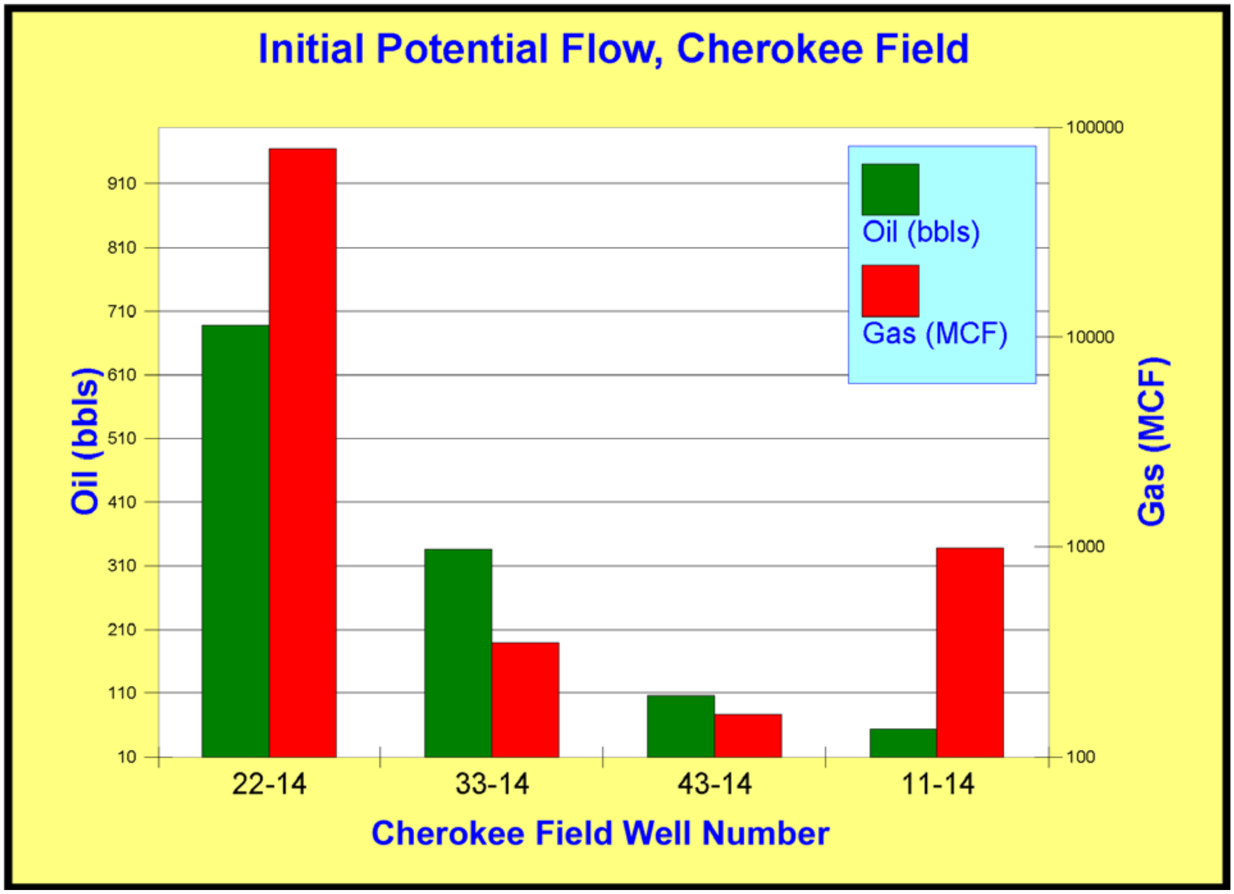

Figure 4. Initial potential flow of oil and gas, from upper Ismay producing wells, in Cherokee field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

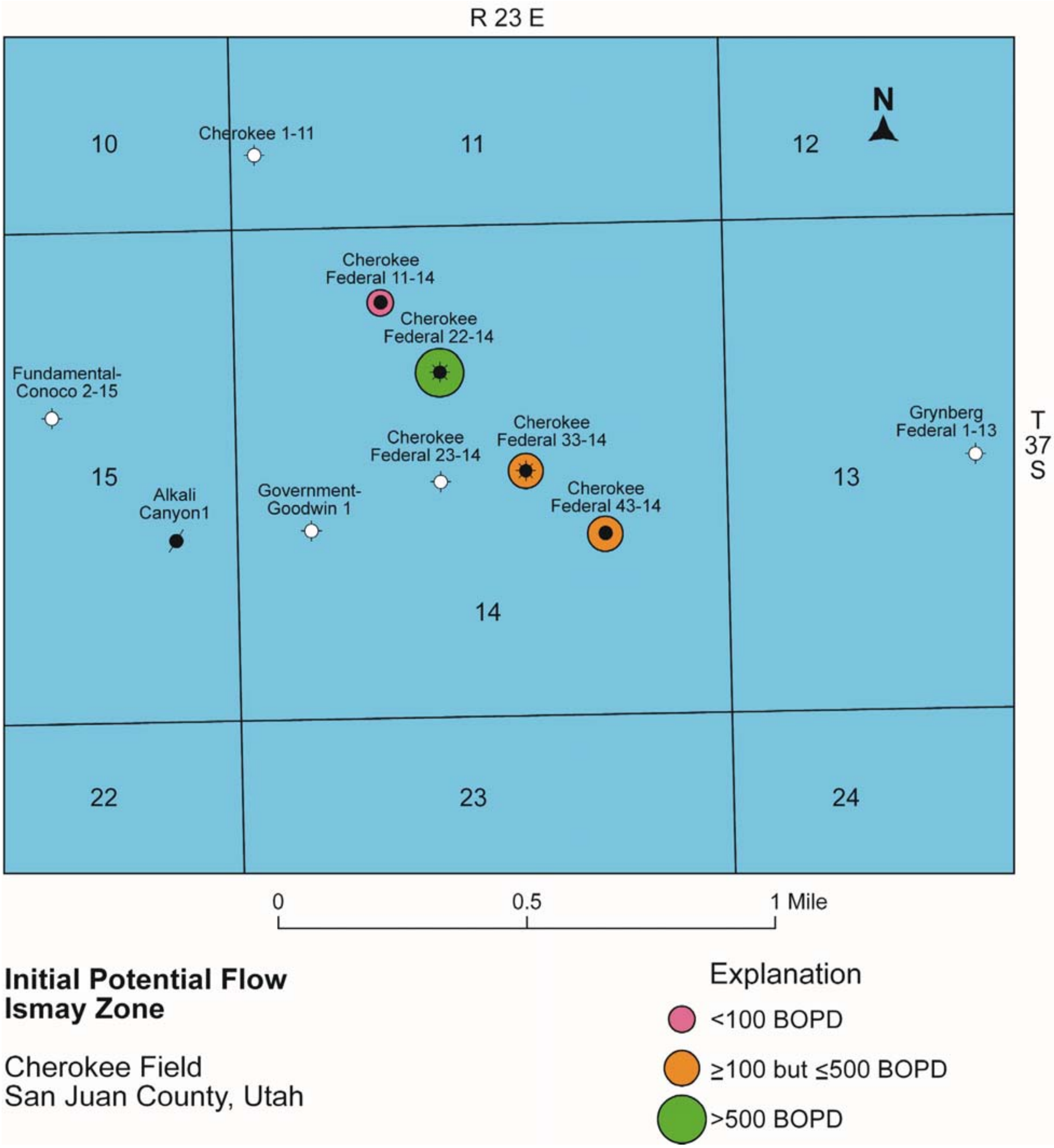

Figure 5. Bubble map of initial potential flow, of oil in BOPD, from upper Ismay producing wells in Cherokee field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

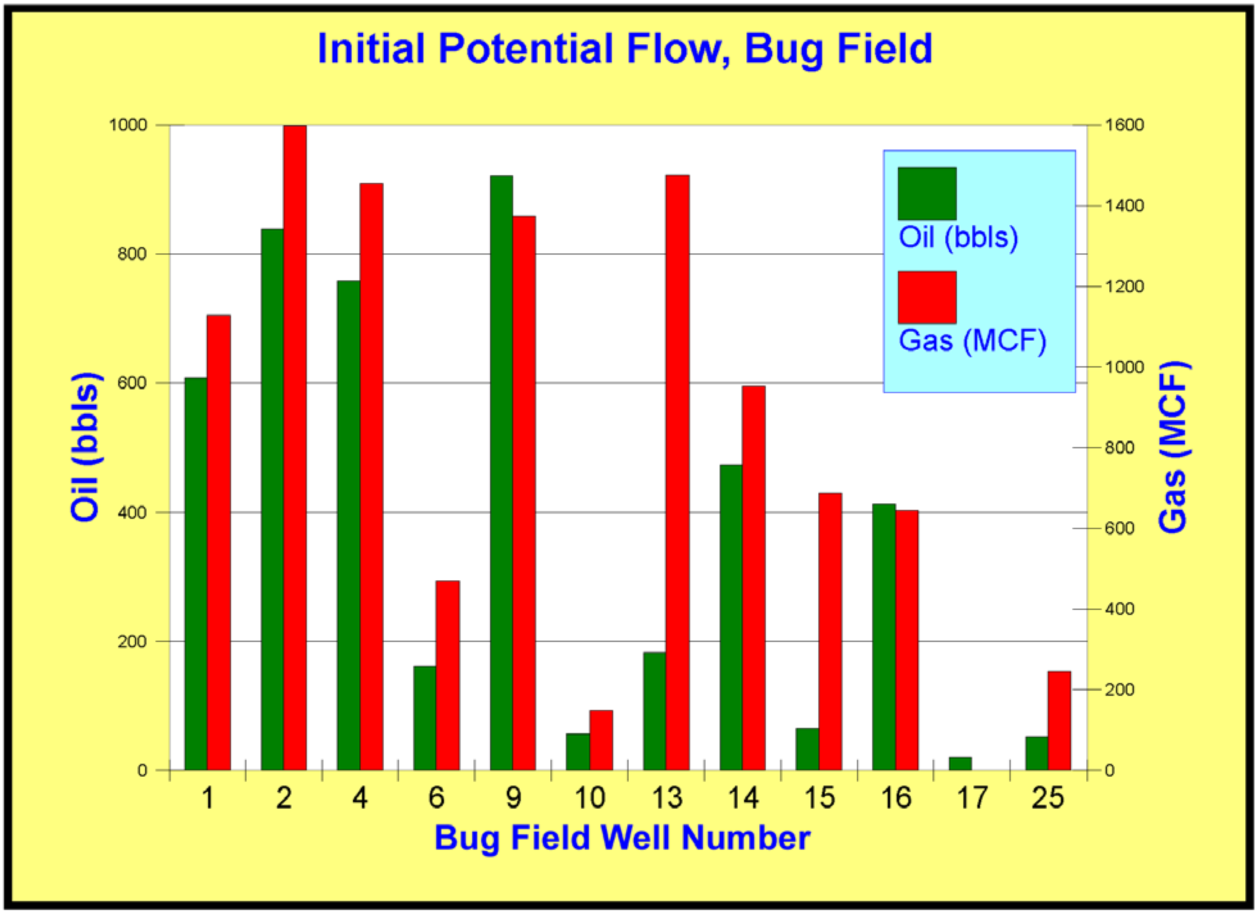

Figure 6. Initial potential flow of oil and gas, from lower Desert Creek producing wells, in Bug field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

In Cherokee field, the highest IPF was recorded from the Cherokee Federal No. 22-14 well (figures 4 and 5), located on the crest of the structural nose where the upper Ismay zone buildup developed and in the thickest part of the mound facies (figures 8 and 9). The lowest recorded IPF was recorded from the Cherokee Federal No. 11-14 well (figures 5 and 6), located on the structural low and on the thin flank of the mound buildup (figures 8 and 9). Both wells had relatively high gas-to-oil ratios (GOR) in comparison to the other two producing field wells (figure 4) in the southeastern part of the field (figure 5).

In Bug field, the highest IPFs were recorded from the Bug No. 1, May Bug No. 2, Bug No. 9, and Bug No. 4 wells (figures 6 and 7), located structurally downdip from the updip porosity pinch out that forms the trap, and in the main part of the lower Desert Creek zone carbonate buildup (figures 10 and 11); Bug No. 9 was tested from the thickest section of the mound. These wells penetrated both the phylloid-algal mound and the shoreline carbonate island facies of the carbonate buildup. The lowest recorded IPFs were from wells closest to the updip porosity pinch out, or downdip near the oil/water contact (figures 6, 7, and 10). These wells penetrated only the phylloid-algal mound facies (figure 11).

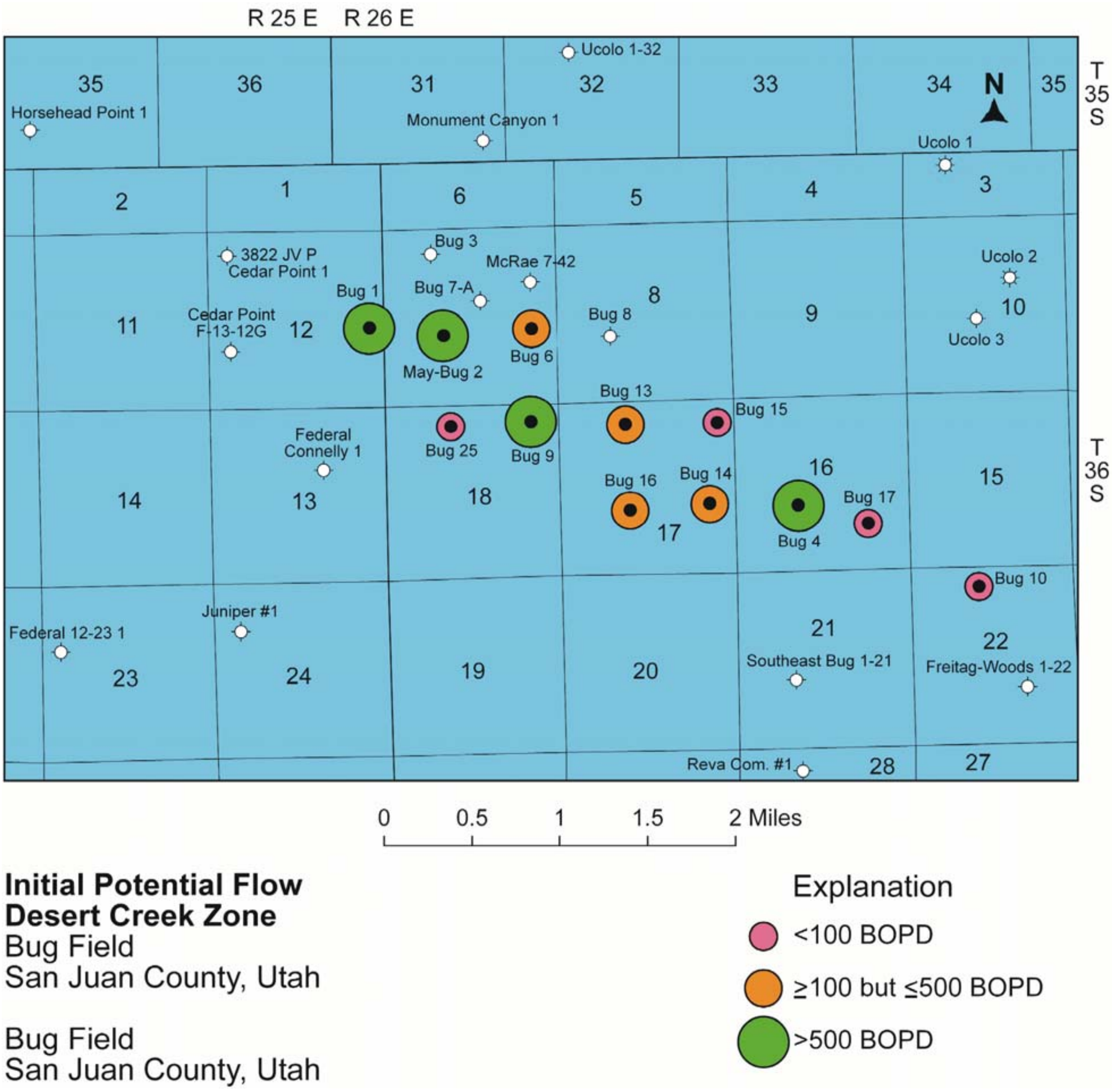

Figure 7. Bubble map of initial potential flow, of oil in BOPD, from lower Desert Creek producing wells in Bug field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

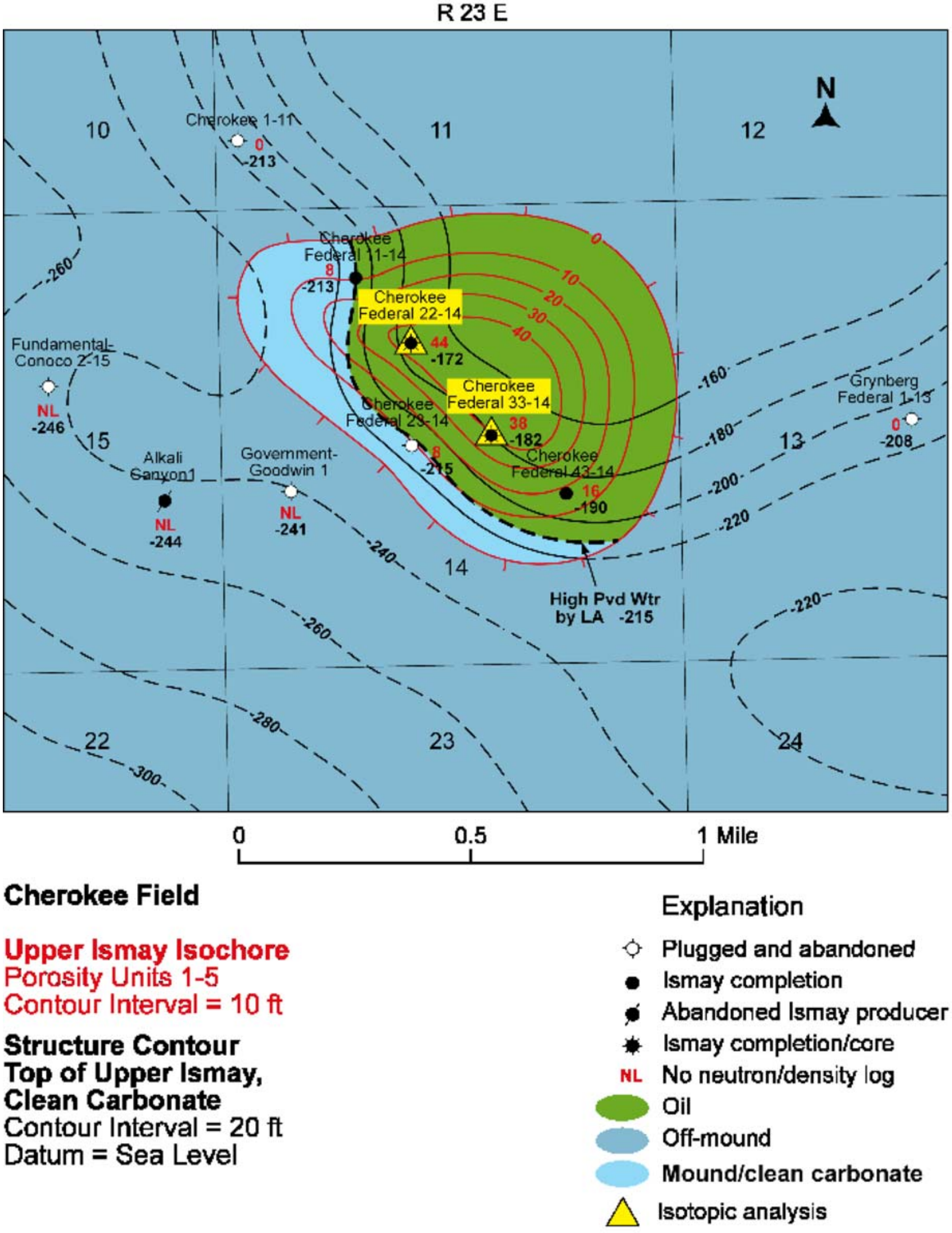

Figure 8. Map of combined top of "clean carbonate" structure and isochore of porosity units 1 through 5, upper Ismay zone, Cherokee field, San Juan County, Utah. Well cores used for isotope sampling for this study are highlighted with a yellow triangle.

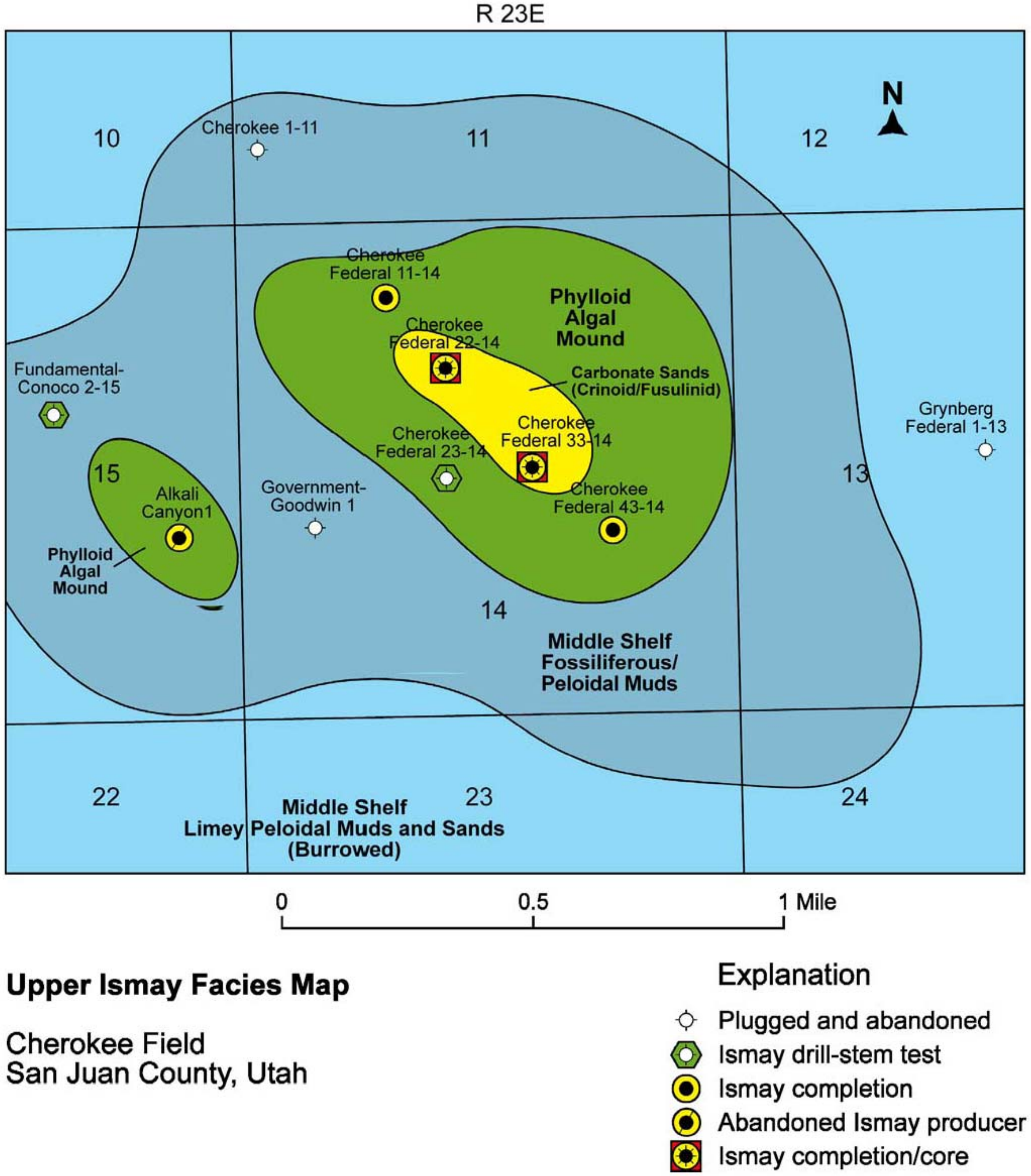

Figure 9. Upper Ismay zone facies map, Cherokee field, San Juan County, Utah.

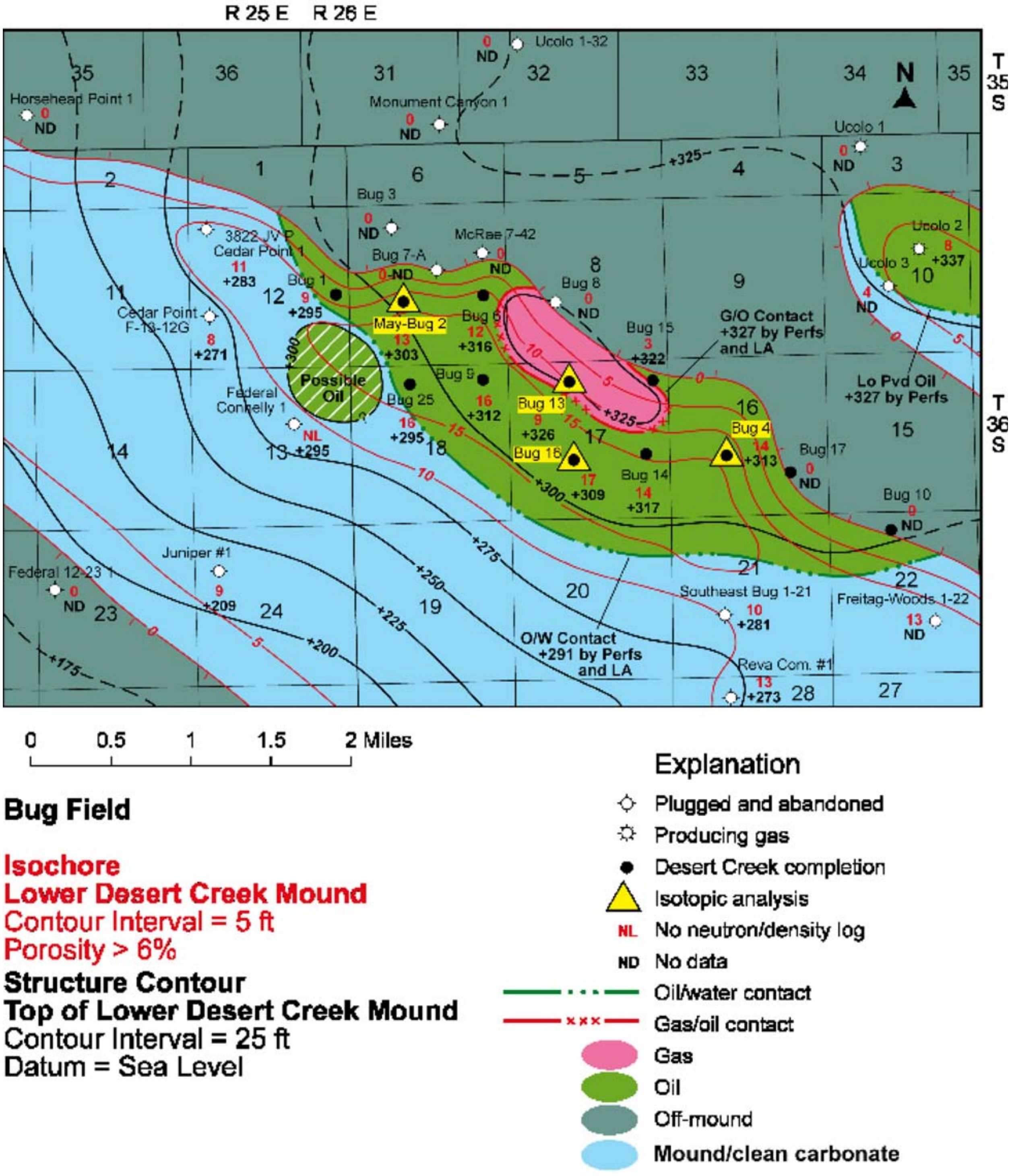

Figure 10. Map of combined top of structure and isochore of lower Desert Creek zone mound, Bug field, San Juan County, Utah. Well cores used for isotope sampling for this study are highlighted with a yellow triangle.

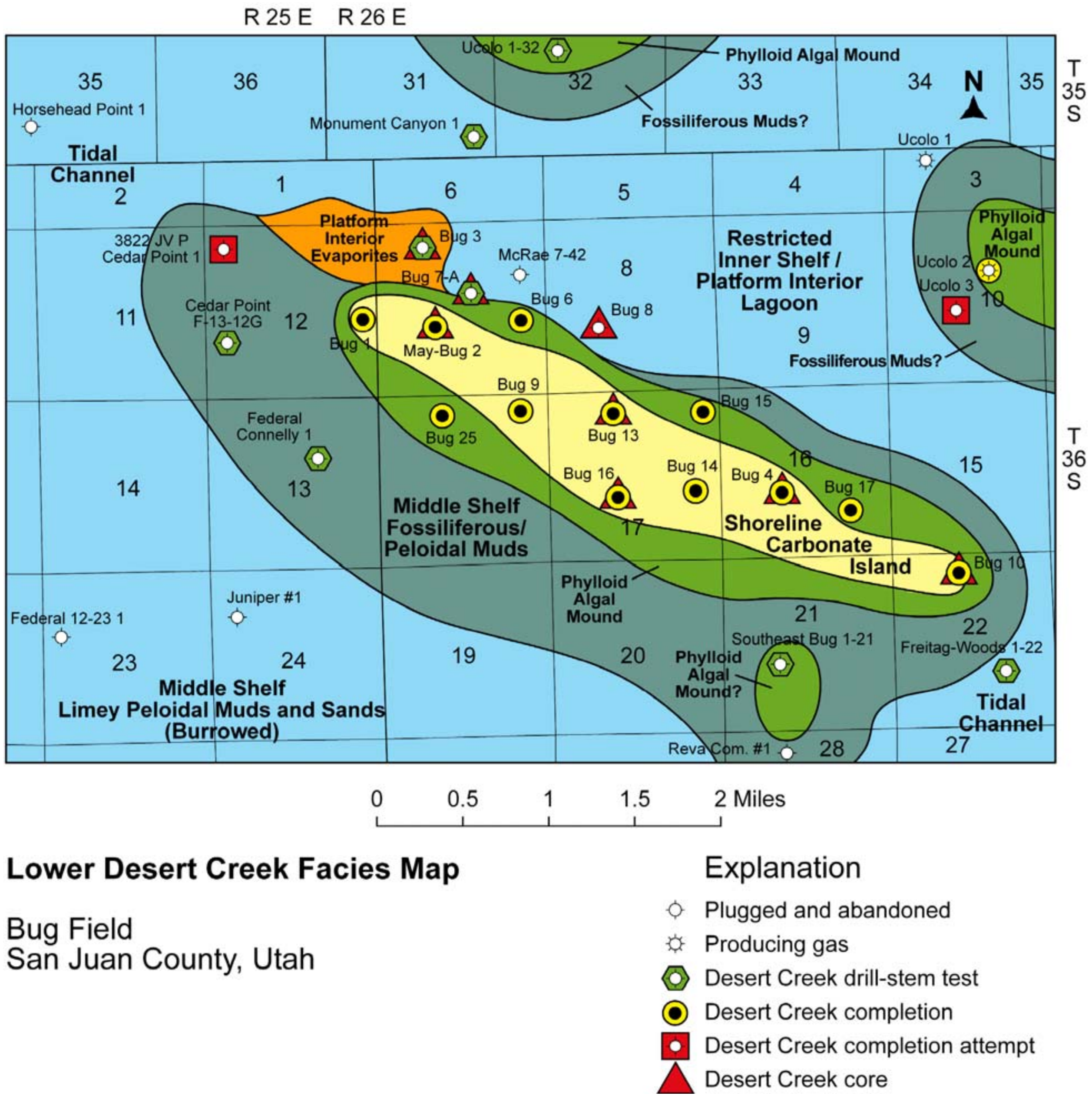

Figure 11. Lower Desert Creek zone facies map, Bug field, San Juan County, Utah.

Cumulative Production

Oil and gas production from Cherokee field has shown a steady decline since peaking in the late 1980s (figure 12). Cumulative production was graphed and plotted for each well (figures 13 through 16). The graphs include both oil and gas production. In Cherokee field, the largest volume of oil has been produced from the Cherokee Federal No. 33-14 well, while the highest volume of gas has been produced from the Cherokee Federal No. 22-14 well (figures 13 and 14). Both wells are located on the crest of the structural nose and in the thickest part of the mound facies (figures 8 and 9). The Cherokee Federal No. 22-14 well is slightly higher structurally than the Cherokee Federal No. 33-14 well, possibly accounting for the significantly greater volume of gas production. These wells penetrated both the phylloid-algal mound and the crinoid/fusulinid-bearing carbonate sand facies of the carbonate buildup (figure 9). The Cherokee Federal No. 33-14 well may have encountered a significantly thicker section of microporosity and microfractures than other wells resulting in greater oil production. Microporosity is present in cores from both the Cherokee Federal No. 33-14 and Cherokee Federal No. 22-14 wells (figure 15). This unique pore type represents the greatest hydrocarbon storage capacity and potential horizontal drilling target in the field. The lowest volumes of hydrocarbon production are from wells on both the structural and mound flanks. These wells are likely close to the oil/water contact (its exact elevation is unknown) and have penetrated only the phylloid-algal mound buildup.

In Bug field, oil and gas production peaked in 1982, and has shown a steady decline in oil and gas since 1985 and 1989 respectively (figure 16). The largest volumes of oil have been produced from the May Bug No. 2 and Bug No. 14 wells (figures 17 and 18). These wells, plus the Bug No. 4 and Bug No. 9 wells, have each produced over 200,000 barrels of oil. They are all located structurally downdip from the updip porosity pinch out, and in the main part of the lower Desert Creek zone carbonate buildup (figures 10 and 11). These wells penetrated both the phylloid-algal mound and the shoreline carbonate island facies. However, there are other wells that penetrated this same facies combination, such as Bug No.16 well, yet have produced lower volumes of oil. These wells may have encountered fewer microfractures and less micro-box-work porosity (figure 19), a prime diagenetic pore type in this dolomitized reservoir, which is thought to account for the greatest hydrocarbon storage and flow capacity in the field. The lowest volumes of hydrocarbon production are from wells closest to the updip porosity pinch out (Bug No. 15 and No. Bug 17) or downdip near the oil/water contact (Bug No. 25) (figures 10, 17, and 18). These wells penetrated only the phylloid-algal mound facies (figure 11). The Bug No. 13 and Bug No. 15 wells are the structurally highest wells in the field and are located near a presumed gas cap, thus their production history shows high GORs.

ISOTOPIC GEOCHEMISTRY – RESULTS AND DISCUSSION

Modification of rock fabrics and porosity within the lower Desert Creek and upper Ismay zones of the Blanding sub-basin study area is quite complex. Diagenesis played a major role in the development of reservoir heterogeneity in Bug, Cherokee, and Patterson Canyon fields as well as throughout the Paradox Formation fields. Diagenetic processes started during deposition and continued throughout burial history (figure 20).

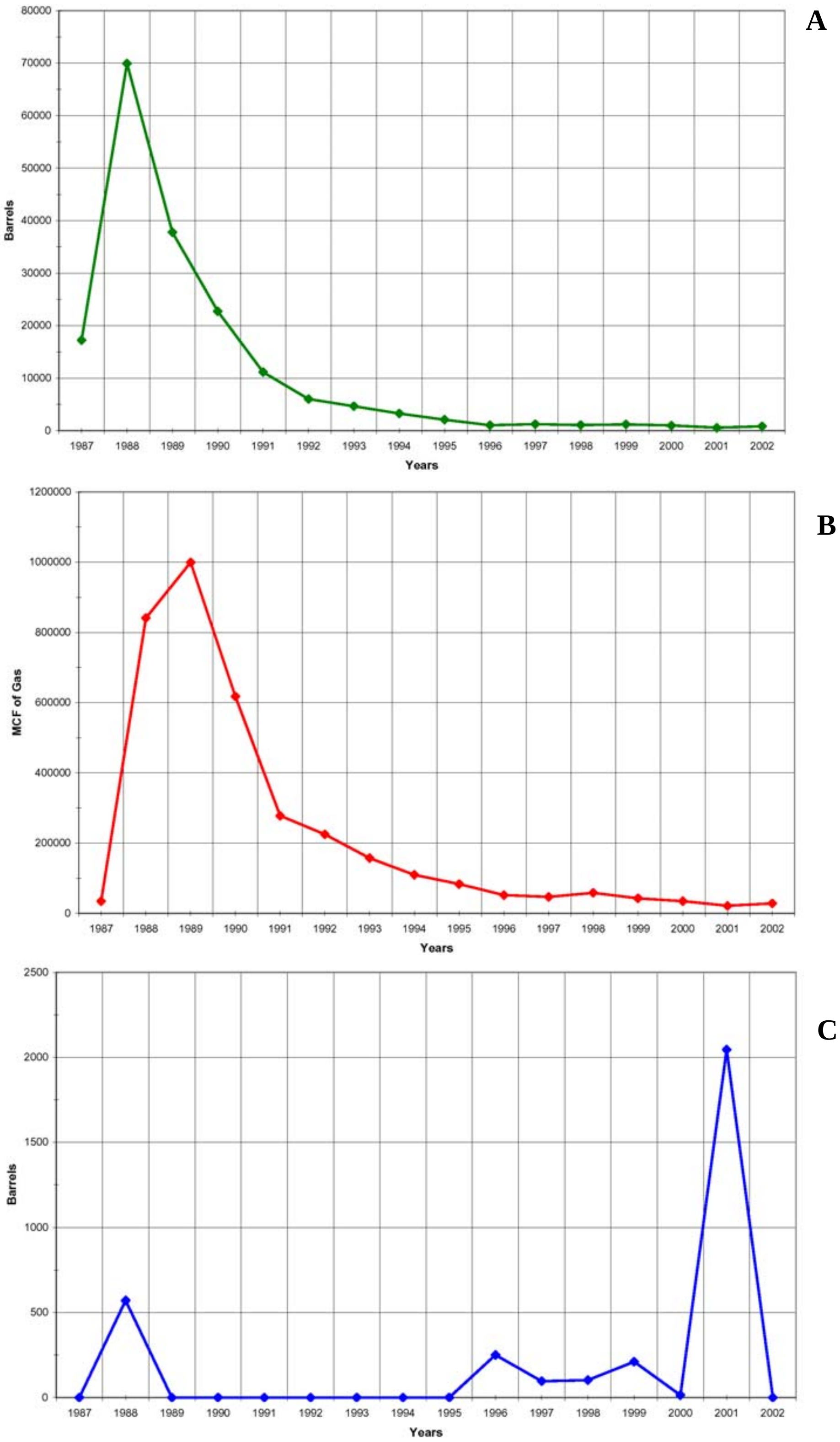

Figure 12. Historical oil (A), gas (B), and water (C) production for Cherokee field (data source Utah Division of Oil, Gas and Mining).

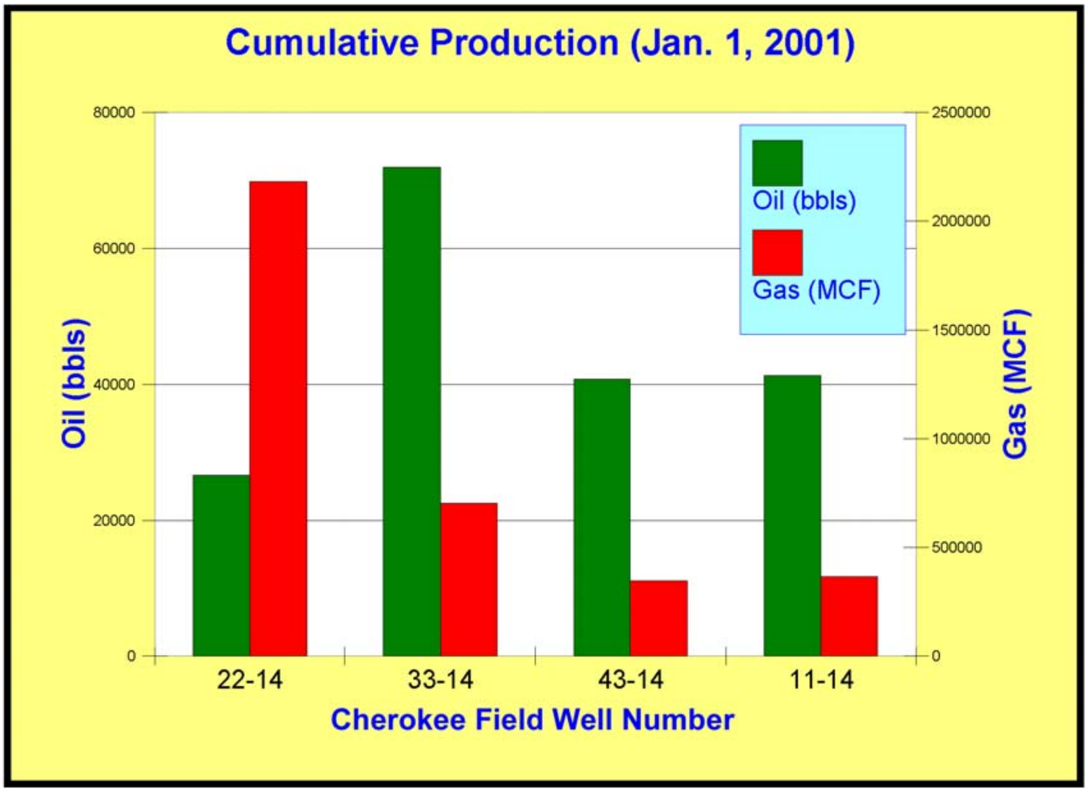

Figure 13. Cumulative production of oil and gas, from upper Ismay producing wells, in Cherokee field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

Stable isotope geochemistry has been used in recent years to provide insights into the chemical differences between preserved remnants of depositional components from various diagenetic events in carbonate rocks as recognized from core examination and thin section petrography. Figure 21 shows a graph of carbon versus oxygen isotope compositions for a range of carbonate rock types from various published sources as compiled by Roylance (1990). Broad fields of carbon and oxygen isotope compositions for various carbonate rock settings are indicated, including modern marine ("subsea") cements, various marine skeletons and sediments, deep-water ("pelagic") limestones, Pleistocene carbonates, and meteoric carbonates ("speleothems and veins").

Previous Work

The only previously published isotope composition data for lower Desert Creek rocks for the project area was completed at the Marathon Petroleum Technology Lab in Littleton, Colorado for the M.S. thesis work of Roylance (1984). That data and the location of the wells sampled can be seen in tables 1 and 2, and figures 10 and 22. Brinton (1986) collected and interpreted a robust data set of carbon and oxygen isotopes (84 samples) from four cores in Ismay field, Utah and Colorado, which is outside the project area. Comments about the general isotopic ranges of various diagenetic rock components within the Ismay zone in cores from Ismay and Greater Aneth fields (outside of the Blanding sub-basin project area) have been published by Dawson (1988).

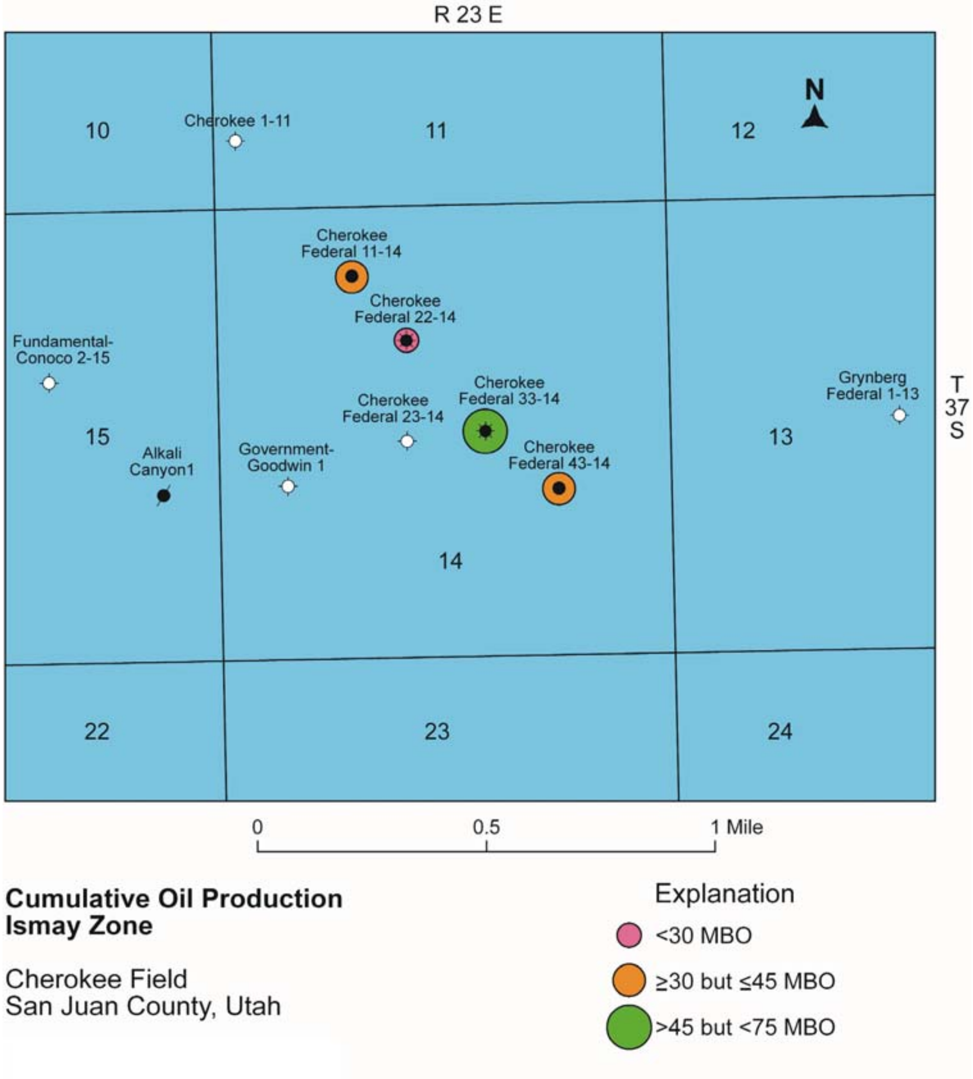

***Figure 14.** Bubble map of cumulative production, of oil in thousands of barrels of (MBO), from upper Ismay producing wells in Cherokee field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).*

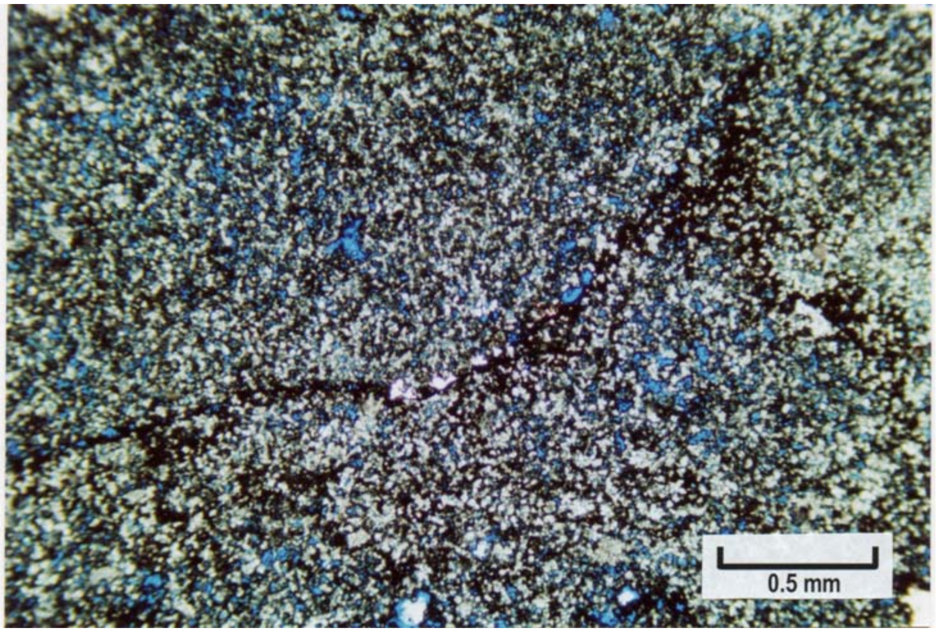

***Figure 15.** Photomicrograph (plane light) of a peloidal packstone/ grainstone dominated by microporosity (in blue). Cherokee No. 22-14, 5,768.7 feet (1,758.2 m), porosity = 22.9 percent, permeability = 215 millidarcies.*

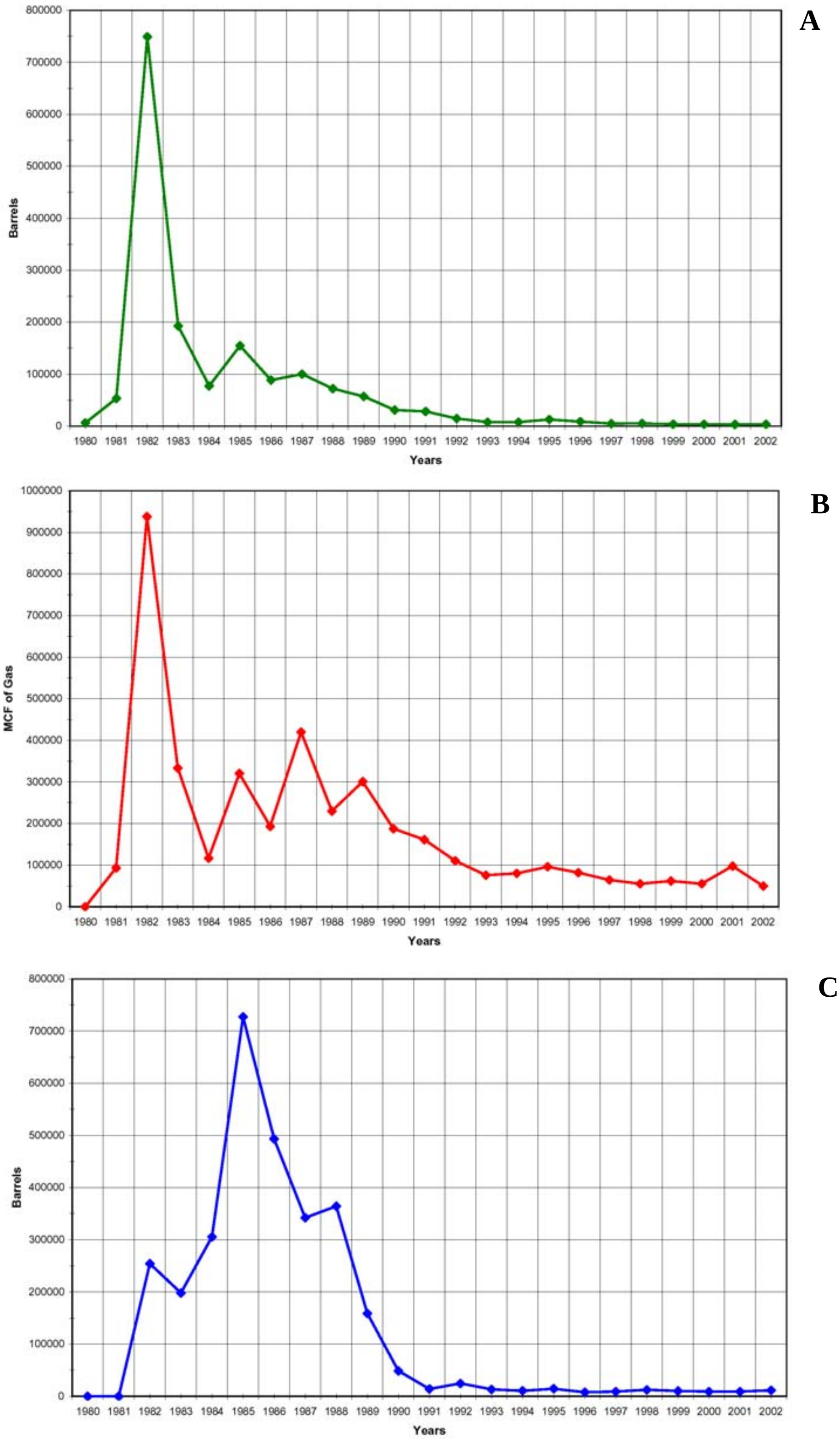

Figure 16. Historical oil (A), gas (B), and water (C) production for Bug field (data source Utah Division of Oil, Gas and Mining).

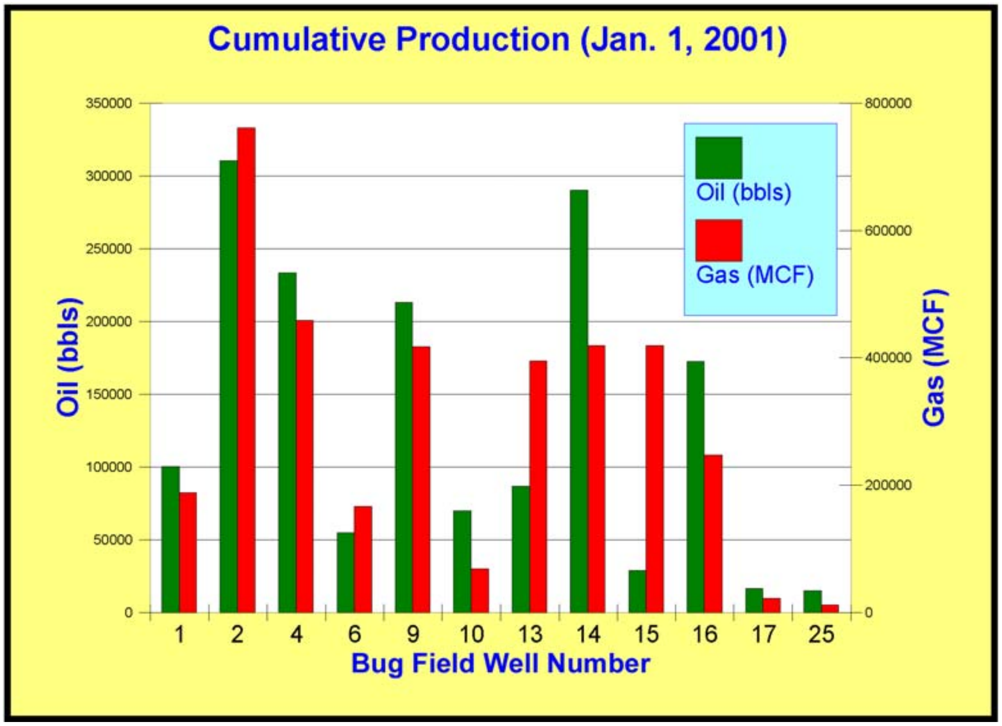

Figure 17. Cumulative production of oil and gas, from lower Desert Creek producing wells, in Bug field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

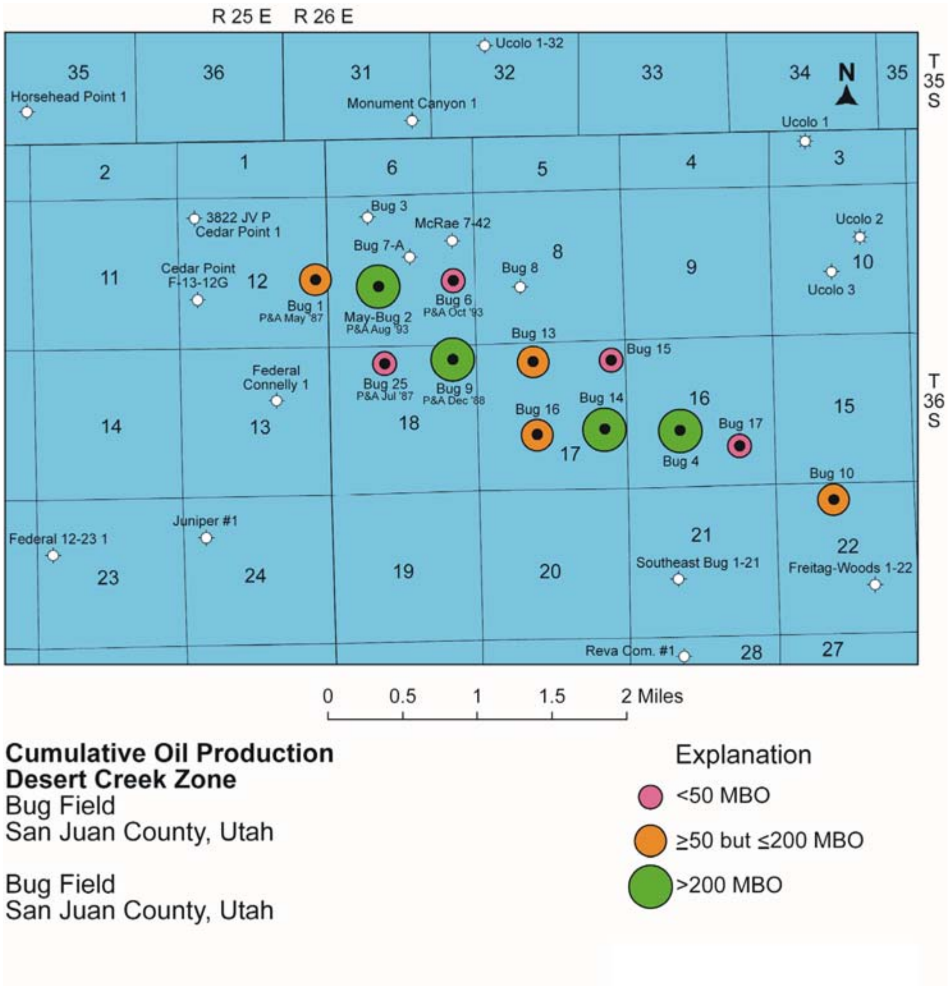

Figure 18. Bubble map of cumulative production, of oil in thousands of barrels of (MBO), from lower Desert Creek producing wells in Bug field, San Juan County, Utah (data source Utah Division of Oil, Gas and Mining).

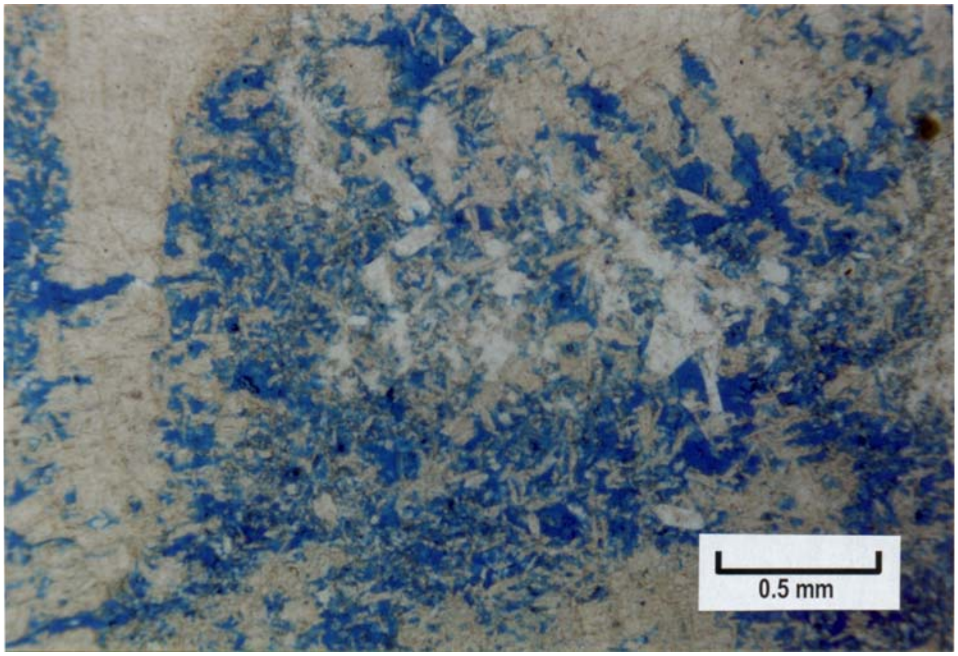

Figure 19. Photomicrograph (plane light with white card technique [diffused light using a piece of paper on the stage of the microscope]) showing a pattern of patchy dolomite dissolution which includes a "micro-box-work" pattern of pores (in blue). Bug No. 10, 6,327.5 feet (1,928.5 m), porosity = 10.5 percent, permeability = 7.5 millidarcies.

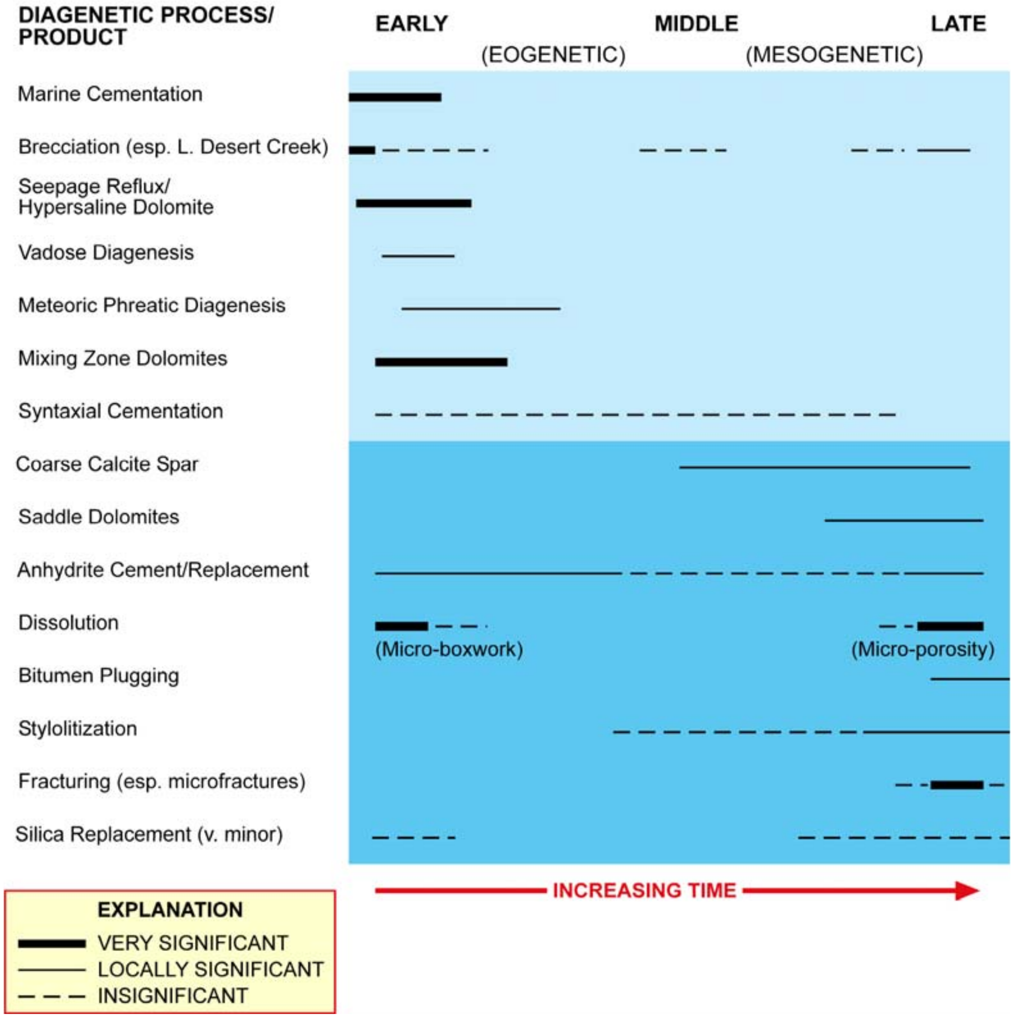

Figure 20. Diagenetic sequence diagram for Bug and Cherokee fields.

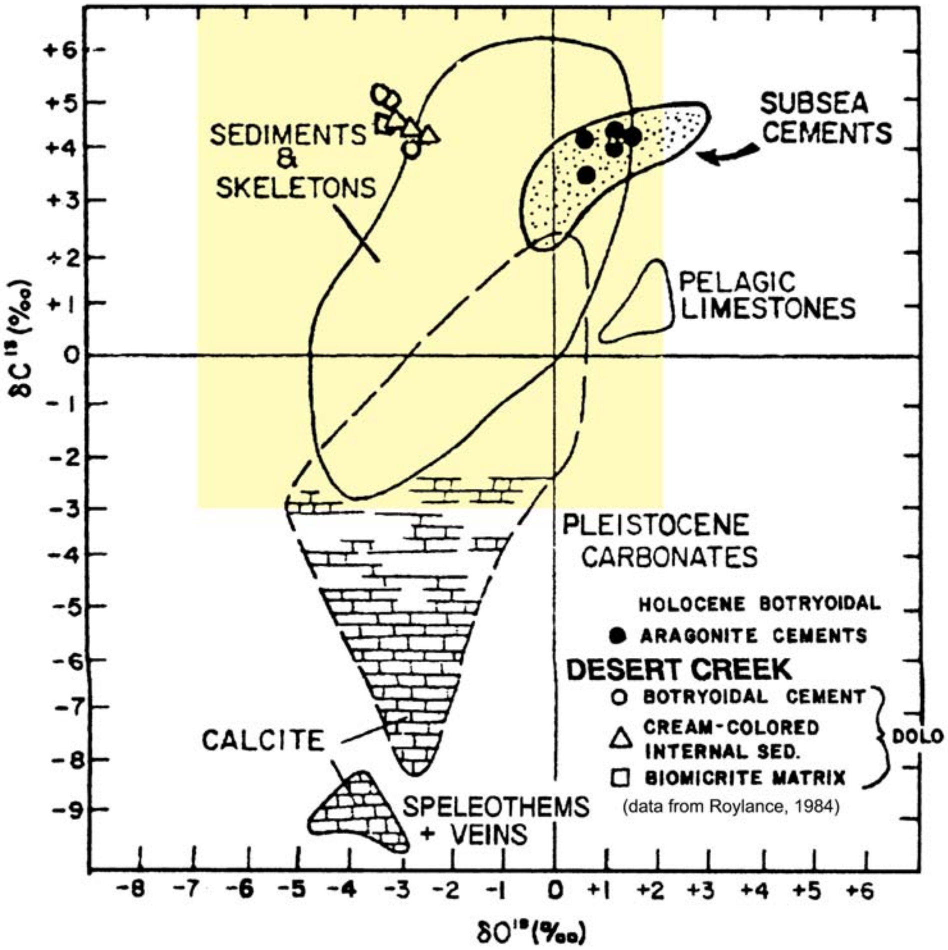

Figure 21. Graph of carbon versus oxygen isotope compositions. Other compositional facies compiled from various published work (modified from James and Ginsburg, 1979 by Roylance, 1990). The yellow area in this cross plot is the same part of the graph shown in figures 22, 24, 25, 26, 28, and 30 of this study.

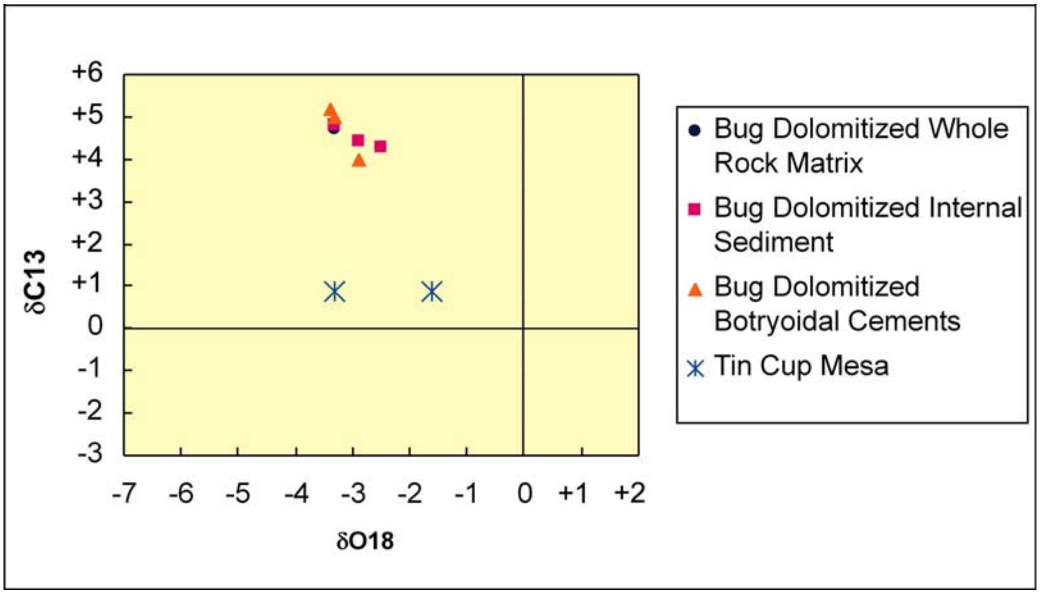

Figure 22. Graph of carbon versus oxygen compositions for Bug and Tin Cup Mesa fields determined by Roylance, 1984.

Table 1. Location of cores used in the isotope geochemistry study.

Zones	Well Name	Location
Lower Desert Creek	*Wexpro May-Bug 2 (this study)	NE1/4 SW1/4 Sec. 7, T36S, R26E UT
	*Wexpro Bug 4 (this study)	NE1/4 SW1/4 Sec. 16, T36S, R26E UT
	*Wexpro Bug 13 (Roylance, 1984)	NE1/4 NW1/4 Sec. 17, T36S, R26E UT
	*Wexpro Bug 16 (Roylance, 1984)	NE1/4 SW1/4 Sec. 17, T36S, R26E UT
	MOC Tin Cup Mesa 1-25	SW1/4 NW1/4 Sec. 25, T38S, R25E UT
Upper Ismay	†Cherokee 22-14 (this study)	SE1/4 NW1/4 Sec. 14, T38S, R23E UT
	†Cherokee 33-14 (this study)	NE1/4 NW1/4 Sec. 14, T38S, R23E UT
	Samedan Bonito 41-6-85 (this study)	NE 1/4 NE1/4 Sec. 6, T38S, R25E UT

*Well locations are shown in figure 8
†Well locations are shown in figure 10

Table 2. Previous stable carbon and oxygen isotope data from lower Desert Creek zone, Bug and Tin Cup Mesa fields (analyses from Roylance, 1984).

Sample Groups:	del 13C	del 18O
BUG FIELD - Lower Desert Creek Cores Dolomitized Whole Rock Matrix (biomicrite in algal bafflestone)		
Bug 13: 5940.7'C	+4.7	-3.3
Dolomitized Internal Sediment (within phylloid-algal bafflestone)		
Bug 13: 5939.3'A	+4.4	-2.9
Bug 13: 5940.7'A	+4.3	-2.5
Bug 16: 6313.4'A	+4.8	-3.3
Dolomitized Botryoidal Cements		
Bug 13: 5939.3'B	+5.0	-3.3
Bug 13: 5940.7'B	+4.0	-2.9
Bug 16: 6313.4'B	+5.2	-3.4
TIN CUP MESA FIELD - Lower Desert Creek Cores Limestone Whole Rock Matrix (calcite fraction [micrite and crinoid, bryozoan and brachiopod fragments] of dolomitized bioclastic wackestone)		
Tin Cup Mesa #1-25: 5667' calcite	+0.9	-3.3
Dolomite Fraction of Whole Rock Matrix (dolomitized micrite matrix of bioclastic wackestone)		
Tin Cup Mesa #1-25: 5667' dolomite	+0.9	-1.6

Methodology

Isotopic composition analyses for carbon and oxygen were completed for a variety of whole rock and diagenetic phases for core samples from the lower Desert Creek zone from Bug field and the upper Ismay zone from Cherokee field (tables 1, 3, and 4). In addition, a series of samples from whole rock, dolomite, and various cement generations were selected from an upper Ismay buildup in a recently drilled well at Patterson Canyon field (the Samedan Bonito No. 41-6-85, completed in July 2002) containing well-cemented oolitic beds and phylloid-algal mound fabrics (table 5). Figure 1 shows the location of the fields or well names sampled for isotope geochemistry. Individual samples were collected as powdered rock using a Dremel drill equipped with precision bits. All analyses were completed at the Brigham Young University (BYU) Department of Geology Stable Isotope Laboratory, Provo, Utah. The internal standard used in the BYU lab is the UCLA Carrara marble. The accepted values for this internal standard were matched consistently during the analysis of the Paradox core samples selected for this study. All isotopic compositions are reported relative to PeeDee Belemnite (PDB) (see Land, 1980, figure 6 for definition relative to SMOW).

Table 3. New stable carbon and oxygen isotope data from lower Desert Creek zone Bug field dolomites.

Sample Groups:	del 13C	del 18O
BUG FIELD - Lower Desert Creek Cores Whole Rock Dolomite		
May Bug 2: 6304'A (phylloid-algal mound & marine sediment)	+4.49	-4.72
May Bug 2: 6315' B (phylloid-algal mound fabric)	+4.03	-4.42
Dolomitized Internal Sediment (cream-colored)		
May Bug 2: 6304'B	+4.30	-4.50
May Bug 2: 6315'A	+4.16	-4.15
May Bug 4: 6297.4'B	+4.52	-4.67
Dolomitized Micro-Boxwork Fabric (probably botryoidal cements)		
May Bug 2: 6304'C	+4.40	-4.56
May Bug 4: 6289.7'	+4.77	-4.58
May Bug 4: 6297.4'A	+4.76	-4.46

Carbon and Oxygen Isotopes from Lower Desert Creek Dolomites

Isotopic composition analyses for carbon and oxygen were completed for a variety of whole rock and diagenetic phases for core samples from the lower Desert Creek dolomite interval from Bug field (table 1, figure 10). Values obtained in this project were compared to stable carbon and oxygen isotopic measurements reported by Roylance (1984, 1990), and included in this report in figure 22 and table 2. A total of eight powdered samples were drilled from core samples from two Bug field wells and analyzed (table 3). The samples were selected

Table 4. New stable carbon and oxygen isotope data from upper Ismay zone Cherokee field.

Sample Groups:	del 13C	del 18O
CHEROKEE FIELD - Upper Ismay Cores		
Whole Rock		
Cherokee 22-14: 5827.7' (mostly dolomite, w/ moldic porosity)	+5.41	-2.90
Cherokee 22-14: 5836.8' (limestone; phylloid-algal mound fabric)	+5.02	-4.55
Cherokee 33-14: 5781.2'A (mostly dolomite)	+4.67	-6.08
Micro-Porous Dolomite Zones (often w/ pyrobitumen)		
Cherokee 22-14: 5768.7'	+3.57	-2.92
Cherokee 33-14: 5781.2'B	+4.85	-4.54

Table 5. New stable carbon and oxygen isotope data from upper Ismay buildup zone Samedan Bonito No. 41-6-85 core.

Sample Groups:	del 13C	del 18O
Whole Rock (dolomitized oolite)		
Bonito 41-6-85: 5544'A	+4.53	-5.10
Dolomitized Cements (in oolite)		
Bonito 41-6-85: 5544'B	+4.51	-5.15
Calcite Cements (within phylloid-algal buildup)		
Bonito 41-6-85: 5592'A (black cement)	+6.30	-5.10
Bonito 41-6-85: 5592'B (gray cement)	+5.67	-5.68
Bonito 41-6-85: 5592'C (brown cement ? w/sediment?)	+5.56	-5.87
Bonito 41-6-85: 5592'D (white cap cement; no sediment)	+5.73	-5.05
Bonito 41-6-85: 5592'E (coarse blocky cement)	+5.69	-6.41

to analyze dolomitized phylloid-algal mound fabrics and breccias, cream-colored dolomitized internal sediments, and dolomitized void-filling cements (mostly botryoids and blunt-ended fibrous fans). Annotated close-up core photos (figure 23) show the approximate locations of the drilled and powdered samples from the May Bug No. 2 and Bug No. 4 wells. A plot of carbon versus oxygen compositions for all Bug field samples obtained in this study is shown on figure 24 (see also table 3). Comparison of the new data with previously reported Bug field isotope compositions (Roylance, 1984, 1990) is shown in figure 25.

Carbon isotopic compositions for the eight Bug field dolomite samples (figure 24) all cluster very close around a mean value of +4.43‰ PDB (range of +4.03 to +4.77‰). Interestingly, the range for del ^{13}C values is slightly higher for the Bug 4 well (+4.03 to +4.77‰) for the May Bug No. 2 well (+4.52 to +4.77‰), although their means (+4.28 versus 4.68‰) may not be significantly different. The carbon isotope values for Bug field dolomites are remarkably similar for all the rock components analyzed, including "whole rock" samples from the phylloid-algal mound fabrics and associated marine sediments, internal sediments

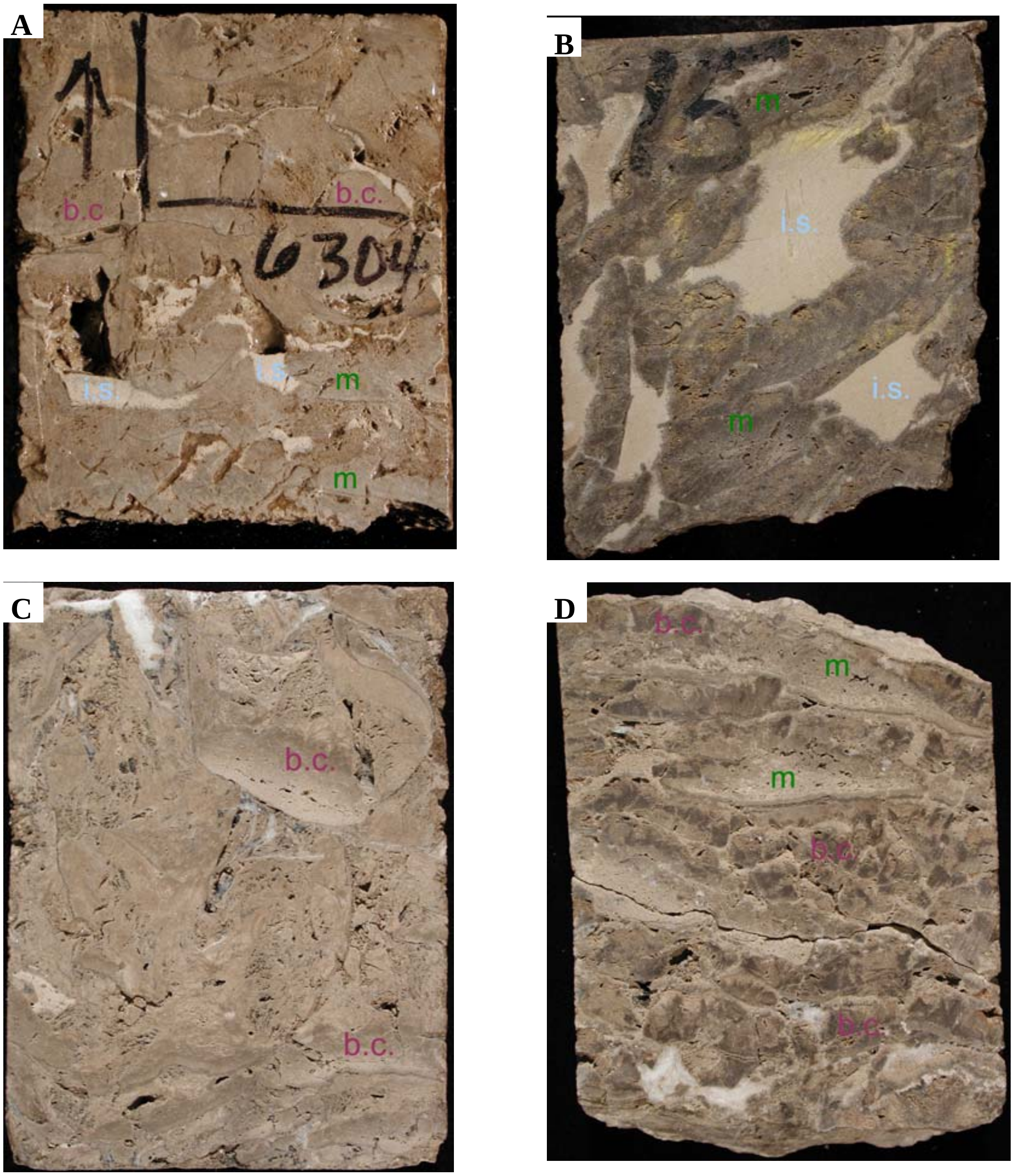

Figure 23. Core photos of typical Bug field components sampled for stable carbon and oxygen isotope analysis. (A) May Bug No. 2: 6,304 feet - the "whole rock" dolomitized phylloid-algal mound fabric (m; sample 6,304' A) in medium gray, the dolomitized cream-colored internal sediment (i.s.; sample 6,304' B), and dark gray dolomitized botryoidal cements (b.c.; sample 6,304' C) as well as associated micro-box-work fabric were sampled for isotopic analysis. (B) May Bug No. 2: 6,315 feet - both the "whole rock" dolomitized phylloid-algal mound fabric (m; sample 6,315' B) in dark gray and the dolomitized cream-colored internal sediment (i.s.; sample 6,315' A) were sampled for isotopic analysis. (C) Bug No. 4: 6,289.7 feet - dolomitized, dark gray botryoidal cements (b.c.; sample 6,289.7') displaying micro-box-work fabric were sampled for isotopic analysis. (D) Bug No. 4: 6,297.5 feet - "whole rock" dolomitized phylloid-algal mound fabric (m; sample 6,297.5' B) and dark gray dolomitized botryoidal cements (b.c.; sample 6,297.5' A) as well as associated micro-box-work fabric were sampled for isotopic analysis.

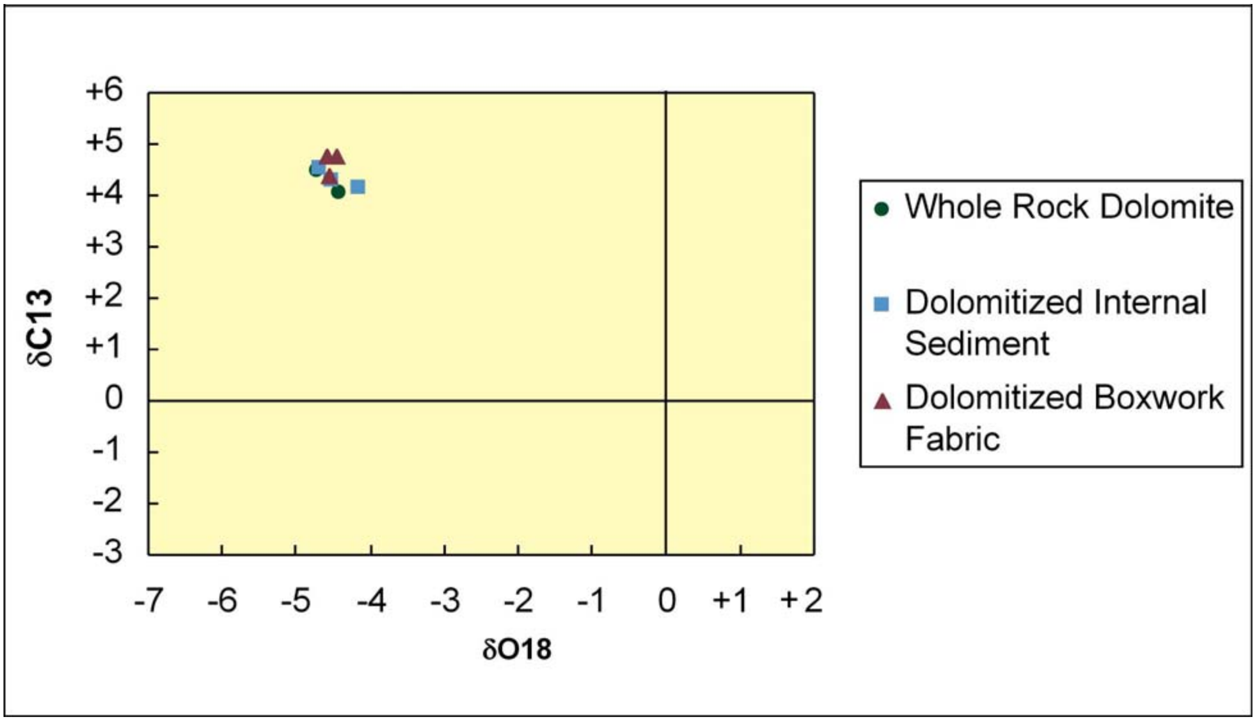

Figure 24. Graph of carbon versus oxygen compositions for Bug field dolomites completed for this study.

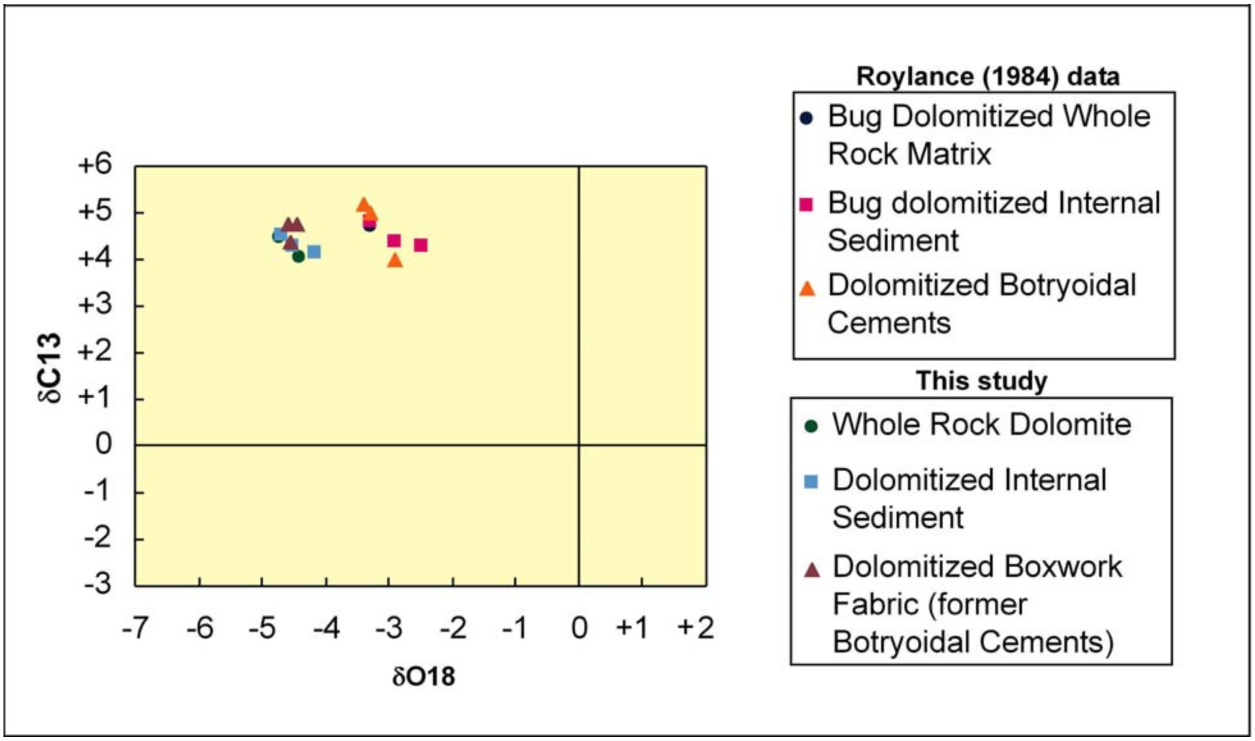

Figure 25. Graph comparing carbon versus oxygen compositions for Bug field dolomites by Roylance (1984) versus those completed for this study.

within shelter pores, and early cements lining original pores. The mean value of del ^{13}C for all Bug field samples in this study is also very close to the mean of +4.6‰ (range of +4.0 to +5.2‰) for seven samples from two other Bug field cores (Bug No. 13 and Bug No. 16) analyzed by Marathon's lab (see table 3, p. 125 in Roylance, 1984; see figure 22). Despite dolomitization, all of the lower Desert Creek samples from Bug field analyzed in this project and by Marathon show carbon isotope compositions that are very close in value to modern marine carbonates ("sediments and skeletons" on figure 21) and Holocene botryoidal marine aragonite cements (James and Ginsburg, 1979; "subsea cements" on figure 21). Furthermore, carbon isotopic compositions for former aragonite marine cements from the Late Permian Capitan Reef complex in southeastern New Mexico are calculated to be about +5.3‰ by Given and Lohmann (1985). Hence, it appears that the carbon isotope geochemistry of all of the lower Desert Creek dolomites at Bug field have retained a strong influence from Pennsylvanian marine water composition. Meteoric waters, which typically would tend to lower the carbon isotope values significantly (Hudson, 1975), do not appear to have had any effect on the composition of these lower Desert Creek dolomites.

Oxygen isotopic compositions for the eight Bug field dolomite samples (figure 24 and table 3) also cluster in a very narrow range around a mean value of -4.51‰ PDB (range of -4.15 to -4.72‰). There is no significant difference in oxygen values between the two Bug wells studied. However, the oxygen compositions in the dolomites sampled here for May Bug No. 2 and Bug No. 4 are significantly different from the values reported by Roylance (1984, 1990) for seven samples processed from the same stratigraphic interval in the Bug No. 13 and Bug No. 16 wells (figures 24 and 25, table 2). The mean oxygen isotope composition for the latter wells is -3.1‰ PDB (range of -2.5 to -3.4‰). Thus, the oxygen values in the May Bug No. 2 and Bug No. 4 cores are more negative by nearly 1.5‰. The oxygen isotope composition data from Bug No. 13 and Bug No. 16 cores, which are situated near the center of the Bug field buildup (figure 10), are rather close to the values for modern marine carbonates ("sediments and skeletons" on figure 21) and to values inferred for unaltered Pennsylvanian marine cements (Lohmann, 1983).

Oxygen isotopic compositions for former aragonite and magnesium calcite marine cements from the Late Permian Reef complex in southeastern New Mexico are calculated to be between -2.8 and -2.5‰ by Given and Lohmann (1985, 1986). The lighter oxygen values obtained from samples in the May Bug No. 2 and Bug No. 4 cores, which are located along the margins or flanks of Bug field (figure 10), may be indicative of exposure to higher temperatures, to fluids depleted in ^{18}O relative to sea water, or to hypersaline waters (Land, 1980, 1982) during burial diagenesis. It is also interesting to note that the two wells with the lightest oxygen isotope compositions in the lower Desert Creek dolomites (May Bug No. 2 and Bug No. 4) have produced significantly greater amounts of hydrocarbons. Production through May 2003 is 340,562 BO (54,149 m^3) and 0.76 BCFG (0.02 BCMG) for May Bug No. 2, and 236,248 BO (37,563 m^3) and 0.48 BCFG (0.01 BCMG) for Bug 4, while Bug No. 13 and Bug No. 16 have produced only 86,786 BO (13,799 m^3) and 0.4 BCFG (0.01 BCMG), and 24,385 BO (3,877 m^3) and 0.84 BCFG (0.02 BCMG), respectively (Utah Division of Oil, Gas and Mining, 2003). The gross productive lower Desert Creek reservoir zone within each of these wells is less than 20 feet (6 m) thick. Clearly, there are economically significant changes in the reservoir quality and the diagenetic history between these well pairs.

Two samples of regional, non-reservoir, open-marine lower Desert Creek zone from Tin Cup Mesa field were analyzed by Marathon's lab for carbon and oxygen isotope composition (MOC No. 1-25 well; figure 1, table 2). The isotopic values for these samples (a limestone and a dolomite) are significantly different from the Bug field reservoir dolomites (figure 22 and 26). The biggest difference is the much lighter (by greater than 3‰) carbon isotope compositions in the Tin Cup Mesa lower Desert Creek samples than at Bug field. For oxygen isotope composition, the limestone (calcite fraction) is significantly heavier (at -1.6‰ PDB) than either the dolomite sample in the Tin Cup Mesa sample (at –3.3‰ PDB) or the mean values in the two different Bug field dolomite data sets (-3.1‰ for the two poor wells and –4.51‰ for the two excellent wells).

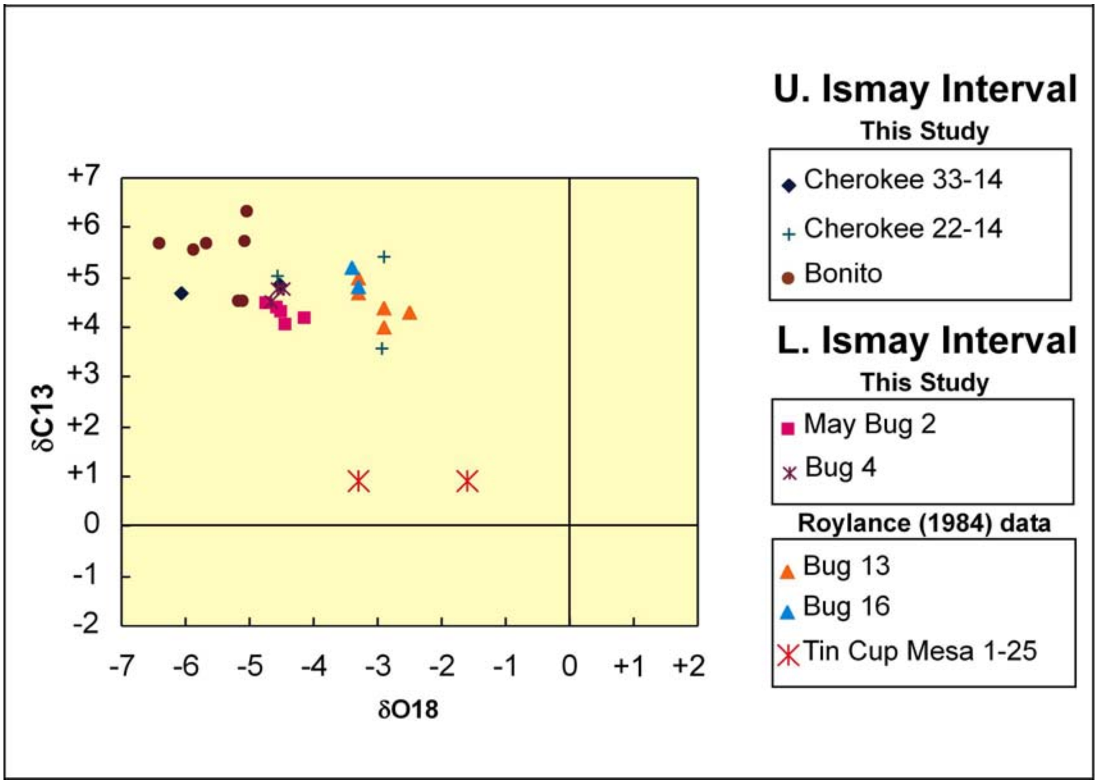

Figure 26. Summary graph of carbon versus oxygen compositions for all components sampled for this study and previously published data by Roylance (1984).

Carbon and Oxygen Isotopes from the Upper Ismay of Cherokee Field

Isotopic composition analyses for carbon and oxygen were completed for a variety of whole rock and diagenetic phases for core samples from the upper Ismay zone in Cherokee field (figures 1 and 8; table 1). A total of five powdered samples were drilled from core samples of the two cored, upper Ismay wells at Cherokee field and were analyzed (table 3). The samples were selected to analyze typical dolomitized calcarenite (bioclastic grainstone), limestone phylloid-algal fabric, dolomitized cryptalgal (stromatolitic) laminites, and microcrystalline, microporous dolomite. Annotated close-up core photos (figure 27) show the approximate locations of the drilled and powered samples from the Cherokee No. 22-14 and Cherokee No. 33-14 wells. A plot of carbon versus oxygen compositions for all Cherokee field samples obtained in this study is shown on figure 28 (see also table 4).

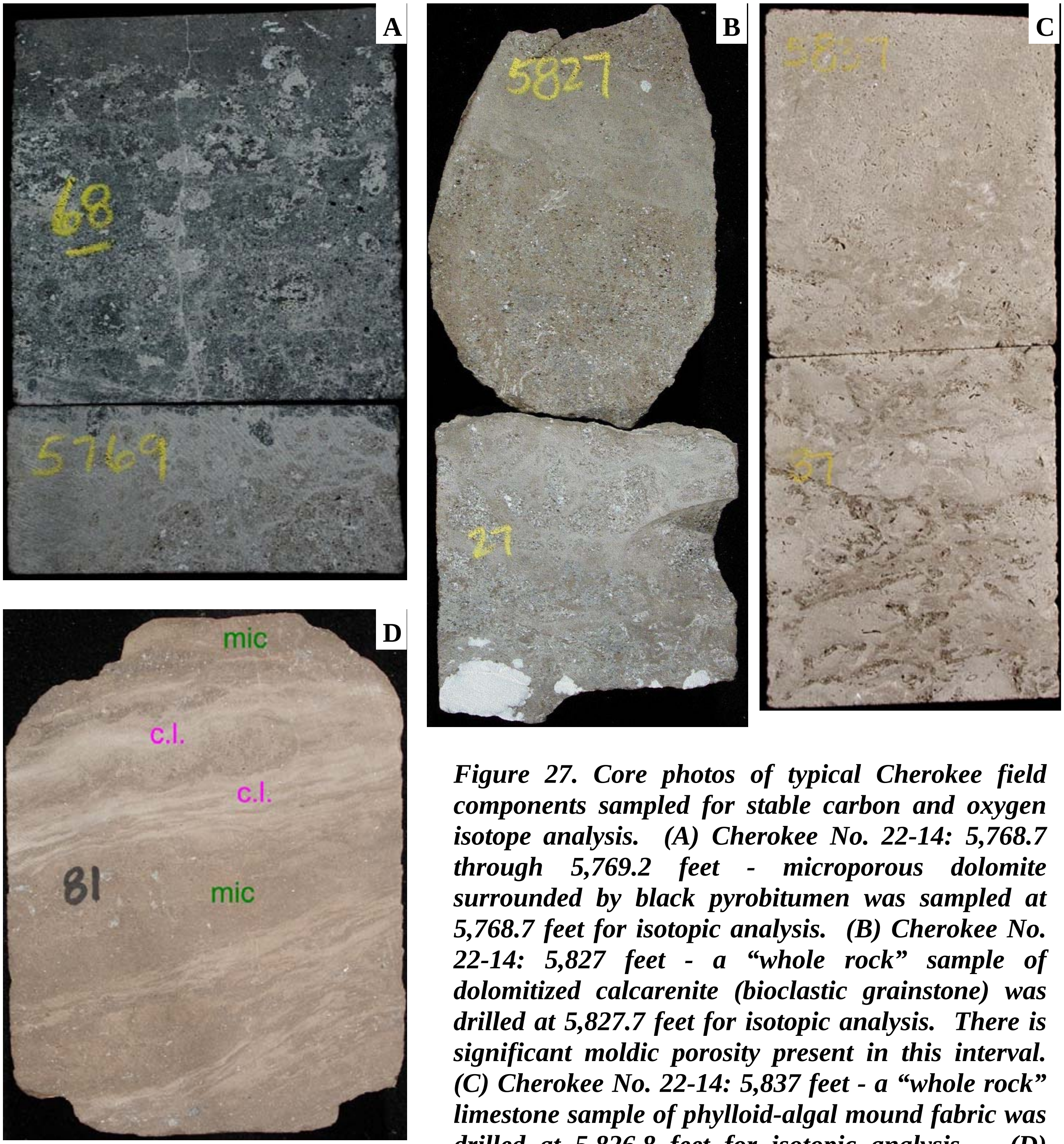

Figure 27. Core photos of typical Cherokee field components sampled for stable carbon and oxygen isotope analysis. (A) Cherokee No. 22-14: 5,768.7 through 5,769.2 feet - microporous dolomite surrounded by black pyrobitumen was sampled at 5,768.7 feet for isotopic analysis. (B) Cherokee No. 22-14: 5,827 feet - a "whole rock" sample of dolomitized calcarenite (bioclastic grainstone) was drilled at 5,827.7 feet for isotopic analysis. There is significant moldic porosity present in this interval. (C) Cherokee No. 22-14: 5,837 feet - a "whole rock" limestone sample of phylloid-algal mound fabric was drilled at 5,826.8 feet for isotopic analysis. (D) Cherokee No. 33-14: 5,781 feet - both the "whole rock" dolomitized cryptalgal laminite (c.l.; sample 5,781.2' A) and microporous dolomite (mic; sample 5,781.2' B) were sampled for isotopic analysis.

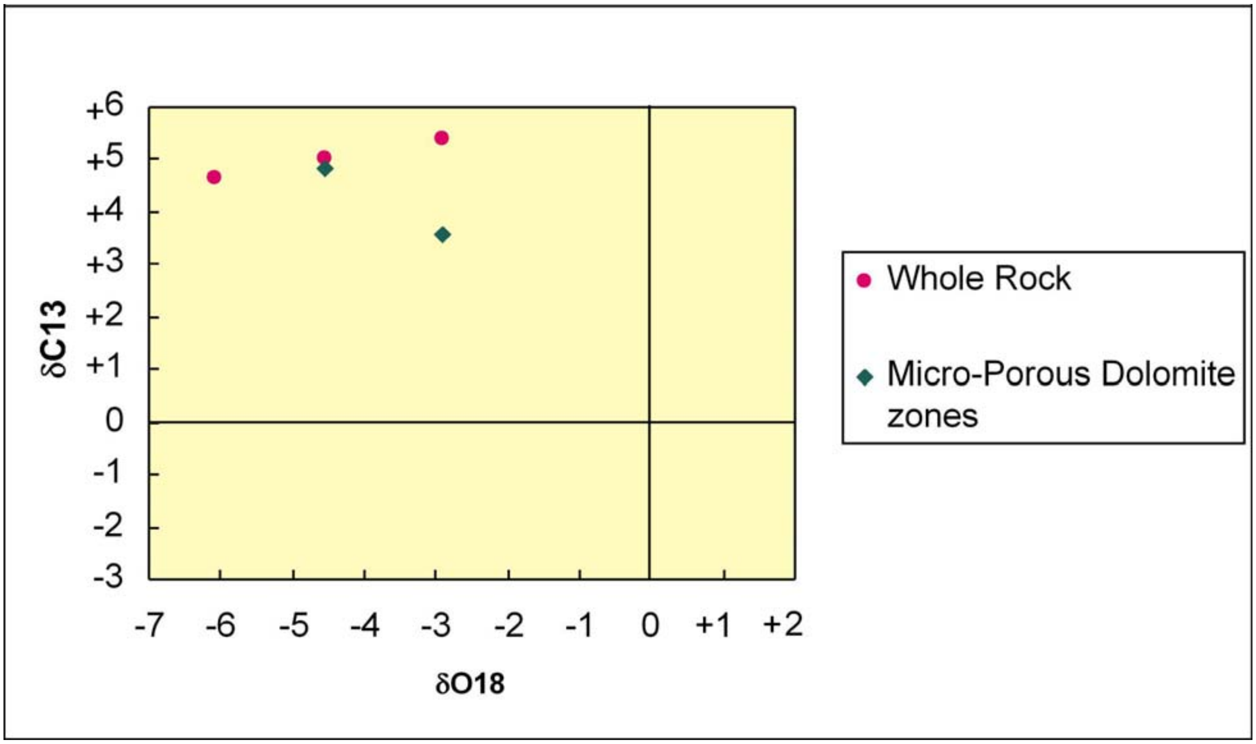

Figure 28. Graph of carbon versus oxygen compositions for Cherokee field components completed for this study.

Carbon isotopic compositions for the five upper Ismay dolomite samples from Cherokee field (figure 28) have a mean value of +4.70‰ PDB (range of +3.57 to +5.11‰). Although the mean carbon isotopic composition appears to be higher in the upper Ismay carbonate samples from Cherokee field than in the lower Desert Creek dolomites at Bug field, the values are not distinguishable at the 95 percent confidence level (t-test). In addition, the limestone (calcite) sample from representative phylloid-algal mound fabrics displays a del ^{13}C value within the same range as the dolomite samples (table 4). Brinton (l986, p. 217-218) reported a possible mean marine del ^{13}C value of +3.9‰ PDB during the time of Ismay deposition from analysis of unaltered brachiopods from Ismay field core. Carbon isotopic compositions for former aragonite marine cements from the Late Permian Capitan Reef complex in southeastern New Mexico are about +5.3‰ (Given and Lohmann, 1985). This may suggest that the fluids responsible for upper Ismay carbonates within Cherokee field have slightly heavier carbon isotope compositions than marine brachiopods at Ismay field, or slightly lighter than late Paleozoic seawater. But as with the Bug field dolomite samples, the Cherokee field carbonates fall within the same range of carbon isotope compositions as modern marine sediments, skeletons, and marine cements (see figure 21).

The del ^{13}C values of the Cherokee field upper Ismay components overlap or are slightly heavier than any of the diagenetic components reported by Dawson (1988) in Ismay field for meteoric-phreatic cements (del ^{13}C = +2.5 to +4.8‰), and are uniformly heavier than either deep burial ferroan calcite cements (del ^{13}C = +1.8 to +3.2‰) or saddle dolomites (mean del ^{13}C = +3.4‰). The range of del ^{13}C values at Cherokee field has a better overlap with values reported from marine botyroidal-fibrous (marine) cements and "neomorphosed matrix sediments" in Ismay field cores (Brinton, 1986) that range between +4.2 to +5.0‰. In addition, Brinton (1986, figure 62) shows that various forms of microcrystalline dolomite in Ismay field have isotopic values that cluster between +3.0 and +6.0‰ for del ^{13}C. As with the lower Desert

Creek dolomites in Bug field, it does not appear that meteoric waters, which typically would precipitate carbonates with more depleted carbon isotope values, have had major effects on the composition of the Ismay carbonate components in Cherokee field. Rather, it is likely that most of the carbonates present within Ismay carbonates (as well as throughout the lower Desert Creek) have retained a marine-influenced isotope geochemistry throughout marine cementation as well as through post-burial recycling of marine carbonate components during dolomitization, stylolitization, dissolution, and late cementation. Such an explanation is in agreement with the model for the positive carbon isotope values of many ancient carbonates proposed by Hudson (1975).

Oxygen isotopic compositions for the Cherokee field limestone and dolomite samples (figure 28 and table 4) form a wide range of values around a mean value of
-4.20‰ PDB (range of –2.90 to –6.08‰). As with the carbon isotope data, there is no significant difference between the oxygen isotope compositions from lower Desert Creek dolomite samples in Bug field and the upper Ismay limestones and dolomites from Cherokee field. There is no apparent pattern in the Cherokee field del ^{18}O values other than the deeper samples contain the more depleted (more negative) values. However, the range of values is probably too wide to suggest a depth-related temperature increase for the lowered del ^{18}O values. A similar range of del ^{18}O values was reported by Dawson (1988) from a variety of cement generations from Ismay field cores. Only very late ferroan calcites and baroque dolomites in Dawson's (1988) data displayed more negative oxygen isotope compositions than the Cherokee field limestones and dolomites.

Brinton (l986, p. 217-218) reported a possible mean marine del ^{18}O value of –4.7‰, during the time of Ismay deposition, from analysis of unaltered brachiopods from Ismay field core. This proposed Ismay marine value is very close to two of the Cherokee field values (see table 4), and to the mean value of all the samples. However, two of the samples (at –2.90 and –2.92‰) are significantly heavier than Brinton's marine del ^{18}O value calculated from unaltered marine fossils. They are closer to Given and Lohmann's (1985, 1986) marine diagenesis as determined from former aragonite and magnesium calcite marine cements in the Captian Reef. These heavier del ^{18}O samples (both dolomites) contain oxygen values similar to two cement-filled crinoids and many of the microcrystalline dolomites analyzed by Brinton (1986). One of the dolomitized samples in Cherokee field, from cryptalgal laminites, has a much lighter oxygen composition (-6.08‰). Only certain saddle dolomite cements, late equant calcite spars, and neomorphosed calcites commonly had such light compositions in Brinton's (1986) work on Ismay field cores. The depleted del ^{18}O value of this one dolomite sample (Cherokee No. 33-14: 5,781.2' A [1,762 m]) suggests neomorphism, cementation, and/or dolomitization from warm or isotopically light subsurface waters.

Carbon and Oxygen Isotopes from an Upper Ismay Buildup, Patterson Canyon Field

Carbon and oxygen isotopic analysis was completed on various whole rock and diagenetic cement generations from the upper Ismay oolite/phylloid-algal buildup along the southwest margin of Patterson Canyon field (figure 1, table 1). The Samedan Bonito No. 41-6-85 well cored approximately 25 feet (8 m) of very well-cemented, phylloid-algal mound limestone (a "reef wall" at the margin of the Patterson Canyon phylloid-algal reservoir) and 31 feet (10 m) of overlying tight oolitic and pelloidal calcarenites. Two samples were drilled from core near the top of the oolitic grainstone section, and five samples were drilled from the cements near the base of the well-cemented mound section. Annotated close-up core photos (figure 29) show the approximate locations of the drilled and powdered samples from the oolite and “reef cementstone” interval selected in the Bonito No. 41-6-85 well. This particular core was analyzed, despite its location outside of either of the two project fields (Bug and Cherokee) because of the spectacular development of cements that display visual characteristics suggesting different generations of development, most of which appear to have been early, or prior to significant burial. A plot of carbon versus oxygen compositions for all Samedan Bonito No. 41-6-85 limestone samples obtained in this study is shown on figure 30 (see also table 5).

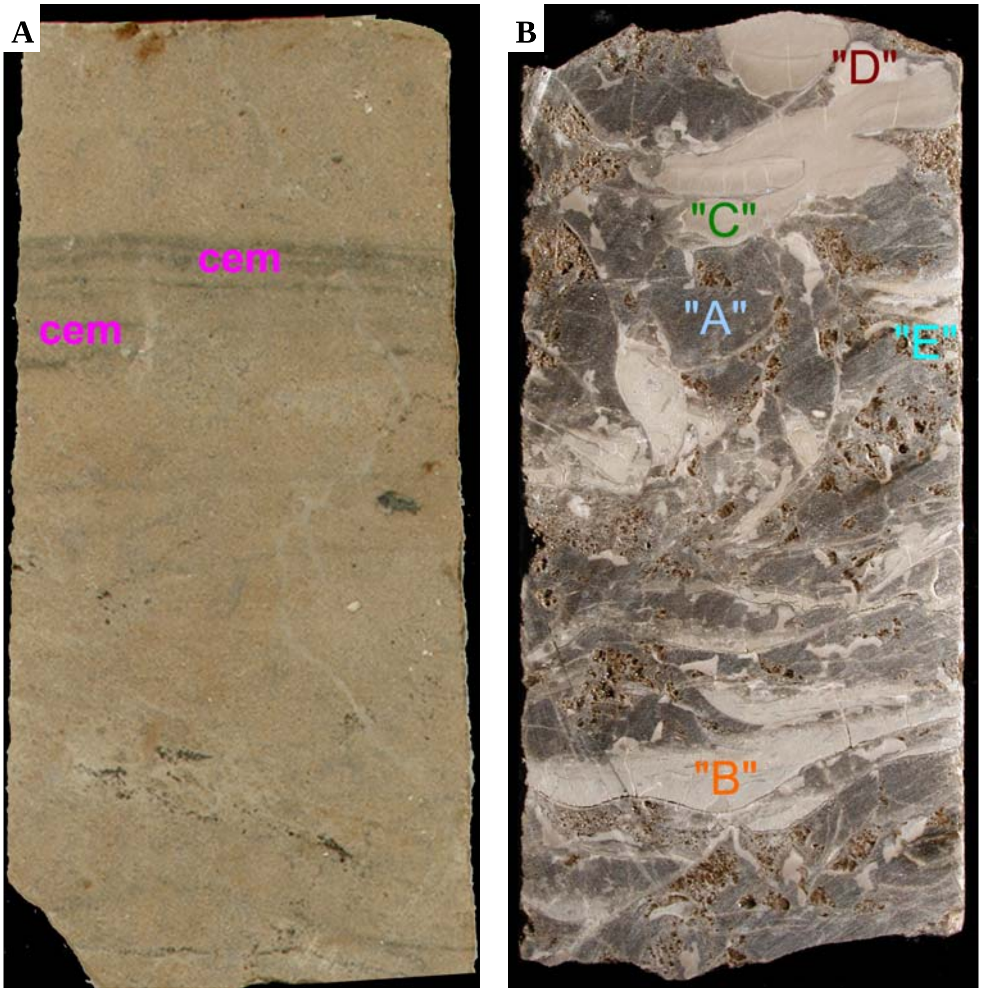

Figure 29. Core photos of whole rock and cement components sampled for stable carbon and oxygen isotope analysis in the upper Ismay buildup of the Samedan Bonito No. 41-6-85 well. (A) Bonito No. 41-6-85: 5,544 feet - both the “whole rock” limestone (an oolitic grainstone; sample 5,544’ A) and calcite cement bands (cem; sample 5,544’ B) along bedding were sampled for isotopic analysis. (B) Bonito No. 41-6-85: 5,592 feet – five calcite cement generations were sampled for isotopic analysis. Sample 5,492’ A – black cements that appear to have originally been botryoidal cement fans. Sample 5,492’ B – gray marine cements. Sample 5,492’ C – brown cements containing sediments at the bottoms of pores, often display geopetal relationships. Sample 5,492’ D – white cements that fill the tops of geopetal cores. Sample 5,492’ E – coarse, blocky calcite spar cements.

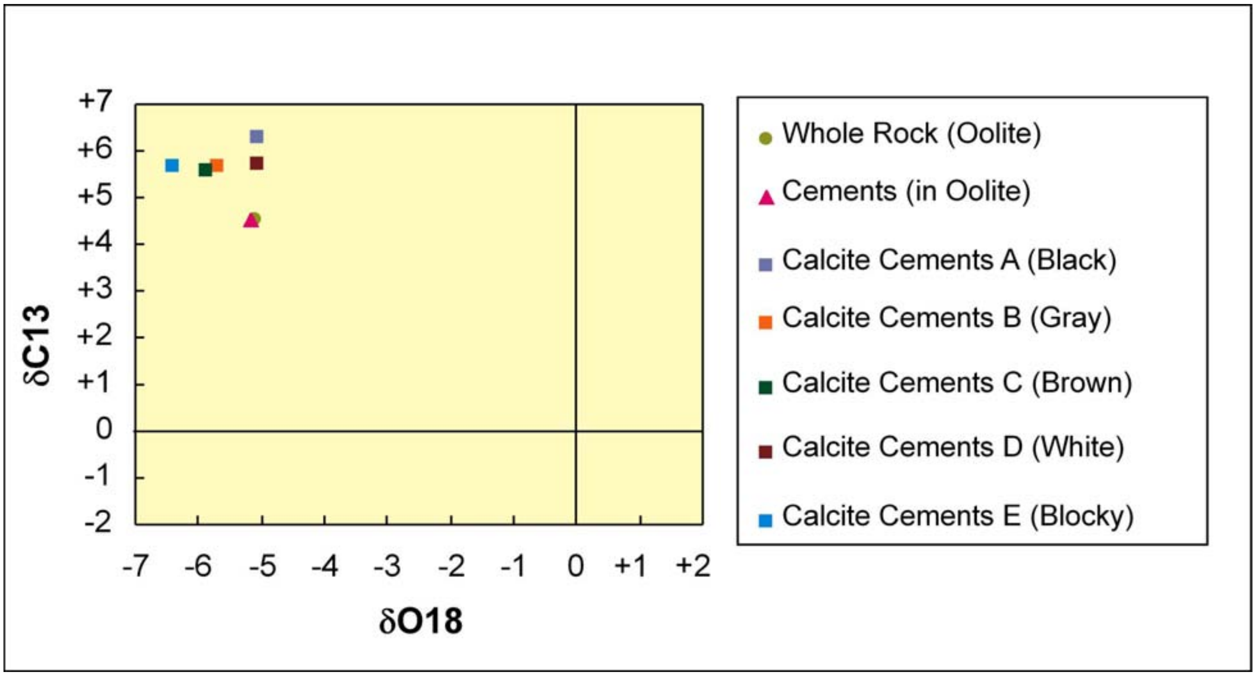

Figure 30. Graph of carbon versus oxygen compositions for whole rock and cement components in an upper Ismay buildup, Samedan Bonito No. 41-6-85 well, completed for this study.

Carbon isotopic compositions for the seven upper Ismay limestone samples in the core from the cemented buildup in Patterson Canyon field have a mean value of +5.43‰ PDB (range of +4.51 to +6.30‰). These values are distinguishable at the 95 percent confidence level (t-test) from the Cherokee field carbonate samples and at the 90 percent level from the Bug field dolomites, but like the Bug and Cherokee values of del ^{13}C, they are much heavier than the mean value of +0.56‰ (standard deviation of 1.55) for a large sampling (n = 272) of Phanerozoic marine limestones (Hudson, 1975). However, the samples can really be divided into two populations with regard to carbon isotopic composition. The five calcite samples from the deeper cemented phylloid-algal buildup have a mean value of +5.79 ‰ PDB (range of +5.56 to +6.30‰) while the oolite and cement samples from the capping grainstone have a mean value of +4.52‰ PDB (range of +4.51 to +4.53‰). Since both of these carbon isotope populations are significantly heavier than Brinton's (1986) value for unaltered brachiopods from Ismay field, it is likely that an isotopically heavier fluid, possibly from concentrated (higher salinity) or closed-system sea water, is recorded in both populations.

Interestingly, Given and Lohmann's (l985) calculated value (+5.3‰ PDB) from Late Paleozoic marine cements from the Permian Basin reef front falls between the two Bonito No. 41-6-85 well populations. It does not appear that meteoric waters, which typically would precipitate calcites with more depleted carbon isotope values, were involved in the diagenesis of the tight Patterson Canyon well buildup. But why the significant difference in del ^{13}C values between the well-cemented oolite samples and the cements present in the underlying reef? Clearly the waters were somehow different in composition between the phylloid-algal mound cements and the lithified oolites. One possible scenario is that the waters responsible for the several generations ("A" through "E") of mound cement were confined to a "closed hydrologic system" that allowed a fluid with heavier carbon to evolve. The oolite and cement bands therein may have been in a more open system allowing water exchange such that waters with a composition slightly lighter than Brinton's proposed Ismay marine value (derived from unaltered brachiopods) were involved in the lithification and diagenesis of the capping oolite.

Oxygen isotopic compositions for the seven upper Ismay limestone samples of the cemented buildup in Patterson Canyon field form a moderate range of values around a mean value of –5.48‰ PDB (range of –5.05 to –6.41‰). As with the carbon isotope data, there is a significant difference (at the 95 percent confidence level) between the Bonito No. 41-6-85 oxygen isotope compositions and those from both the lower Desert Creek dolomites and the upper Ismay at Cherokee field. There is no significant difference in the del ^{18}O values between the deeper mound, early cement samples (mean value of -5.62‰ PDB) and the overlying lithified oolite (mean of -5.58‰ PDB). All seven of the Bonito No. 41-6-85 limestone samples, regardless of component or cement type, are lighter on average by about 1.0‰ PDB than the Bug and Cherokee field samples. These Patterson Canyon samples' del ^{18}O values from diagenetic components are also lighter than either Brinton's marine del ^{18}O value calculated from unaltered marine fossils or Given and Lohmann's (1985, 1986) values of –2.8 to -2.5‰ for former aragonite and magnesium calcite marine cements from the Late Permian Reef complex in southeastern New Mexico. The reasons for these significant differences are not immediately clear. It is possible that the oxygen isotope signatures indicate waters with depleted ^{18}O characteristics evolved in the mound cavities and ooid grainstone pores, without any influence by hypersaline waters. Alternatively, the limestones in this sample set may have all been modified via neomorphism by isotopically light subsurface waters.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for three government-industry cooperative petroleum-research projects, including two in the Paradox Basin. 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 two Class II Oil (this report covers the Class II Revisit project) projects include practical oil-field demonstrations of selected technologies in the Paradox Basin. The third project involves establishing a log-based correlation scheme for the Tertiary Green River Formation in the southwestern Uinta Basin to help identify new plays and improve the understanding of producing intervals. The DOE and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and state agencies are co-funding the three projects. The UGS is also the Principal Investigator and prime contractor for the DOE Preferred Upstream Management (PUMP II) project titled *Major Oil Plays in Utah and Vicinity* which will describe and delineate oil plays in the Thrust Belt, Uinta Basin, and Paradox Basin. Finally, the UGS is just beginning a new project that will evaluate exploration methods and map regional facies trends for independents interested in the Mississippian Leadville Limestone play of the Paradox Basin.

The UGS intends to release selected products of the Paradox Basin project in a series of formal publications. These publications may include 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 periodical *Survey Notes* and be posted on the UGS Paradox Basin project Internet web page.

The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of 13 field operators from the Paradox Basin (Seeley Oil Co., Legacy Energy Corp., Pioneer Oil & Gas, Hallwood Petroleum Inc., Dolar Oil Properties, Cochrane Resources Inc., Wexpro Co., Samedan Oil Corp., Questar Exploration, Tom Brown Inc., PetroCorp Inc., Stone Energy LLC., and Sinclair Oil Corp.). This board ensures direct communication of the study methods and results to the Paradox Basin operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the Utah and Colorado state governments (Utah School and Institutional Trust Lands Administration, Utah Division of Oil, Gas and Mining, and Colorado Oil and Gas Conservation Commission), Federal Government (U.S. Bureau of Land Management and U.S. Bureau of Indian Affairs), and the Ute Mountain Ute Indian Tribe. The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports and copies of all publications, and other material resulting from the study.

Project plans, objectives, and results were through a PowerPoint™ display at the UGS booth during the AAPG annual national convention, May 11-14, 2003, in Salt Lake City, Utah. Four UGS scientists staffed the display booth at this event. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

Utah Geological Survey *Survey Notes* and Internet Web Site

The purpose of *Survey Notes* is to provide non-technical 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. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals (more than 300 as of April 2003) specifically interested in the Paradox Basin project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Economic Geology Program*, which describes the UGS/DOE cooperative studies (Paradox Basin, Ferron Sandstone, Bluebell field, Green River Formation, PUMP II), and has a link to the DOE web site. Each UGS/DOE cooperative study also has its own separate page on the UGS web site. The Paradox Basin project page http://geology.utah.gov/emp/Paradox2/index.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) a reference list of all publications that are a direct result of the project, and (5) semi-annual technical progress reports.

Technical Presentations

The following technical presentations were made during the first six months of the fourth project year as part of the technology transfer activities.

Poster Presentation: “Regional Facies Trends in the Upper Ismay Zone of the Blanding Sub-basin of the Paradox Basin, Utah – Aids for Identifying Possible Targets for Horizontal Drilling” by David E. Eby, Thomas C. Chidsey, Jr., Craig D. Morgan, and Kevin McClure, at the AAPG annual convention, Salt Lake City, Utah, May 13, 2003. Core photographs of facies types, regional facies maps, and horizontal drilling recommendations were part of the presentation.

Short Course/Core Workshop: “Pennsylvanian Heterogeneous Shallow-Shelf Buildups of the Paradox Basin: A Core Workshop,” instructed by David E. Eby, Thomas C. Chidsey, Jr., and Laura L. Wray, at the UGS Core Research Center, May 10, 2003, as part of the AAPG annual convention in Salt Lake City. The short course was co-sponsored by the DOE. Core from representative Ismay and Desert Creek fields was examined. All core displayed was placed into regional paleogeographic settings. The core workshop was organized into topical modules with participants performing a series of exercises using core, geophysical well logs, and photomicrographs from thin sections. These modules included: describing reservoir versus non-reservoir facies, determining diagenesis and porosity from core, recognizing barriers and baffles to fluid flow, correlating core to geophysical well logs, and identifying potential completion zones and candidates for horizontal drilling. There were 25 participants from oil companies around the world.

Project Publications

Chidsey, T.C., Jr., 2003, An up close and personal view of Cherokee oil field, San Juan County, Utah: Utah Geological Survey, Survey Notes, v. 35, no. 2, p. 1-3.

Eby, D.E., Chidsey, T.C., Jr., McClure, Kevin, and Morgan, C.D., 2003, Heterogeneous shallow-shelf carbonate buildups in the Paradox Basin, Utah and Colorado: targets for increased oil production and reserves using horizontal drilling techniques – semi-annual technical progress report for the period October 6, 2002 to April 5, 2003: U.S. Department of Energy, DOE/BC15128-6, 29 p.

Eby, D.E., Chidsey, T.C., Jr., Morgan, C.D., and McClure, Kevin, 2003, Regional facies trends in the upper Ismay zone of the Blanding sub-basin of the Paradox Basin, Utah – aids for identifying possible targets for horizontal drilling [abs.]: American Association of Petroleum Geologists Annual Convention, Official Program with Abstracts, v. 12, p. A48.

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 Desert Creek zone is dominantly dolomite comprising regional nearshore-shoreline trends with highly aligned, linear facies tracts. This study was undertaken to provide a useful database and methodology for identifying potential horizontal drilling targets within heterogeneous carbonate rocks containing porous phylloid-algal buildups and associated facies.

Production "sweet spots" and potential horizontal drilling candidates were identified for Cherokee and Bug fields. In Cherokee field, the highest IPFs as well as the largest volumes of oil and gas produced are from wells located on the crest of the structural nose where the upper Ismay zone buildup developed and in the thickest part of the mound facies. These wells penetrated both the phylloid-algal mound and the crinoid/fusulinid-bearing, carbonate sand facies of the carbonate buildup where there may be a thick section of microporosity. This unique pore type represents the greatest hydrocarbon storage capacity and potential horizontal drilling target in the field. In Bug field, the highest IPFs and largest volumes of oil were recorded from wells located structurally downdip from the updip porosity pinch out that forms the trap, and in the main part of the lower Desert Creek zone carbonate buildup. These wells penetrated both the phylloid-algal mound and the shoreline carbonate island facies where significant micro-box-work porosity has likely developed - the diagenetic pore type with the greatest hydrocarbon storage and flow capacity in this dolomitized reservoir.

Diagenesis is the main control on the quality of Ismay and Desert Creek reservoirs. Much of the porosity development occurred in a mesogenetic (burial) setting, mostly post-dating stylolitization. Maximum porosity is developed as dissolution adjacent to stylolites, especially in phylloid-algal mounds. It is likely that most of the carbonates present within the Ismay zone (as well as throughout the lower Desert Creek) have retained a marine-influenced isotope geochemistry through marine cementation as well as post-burial recycling of marine carbonate components during dolomitization, stylolitization, dissolution, and late cements. Such an explanation is in agreement with the model for the positive carbon isotope values of many ancient carbonates proposed by Hudson (1975).

Specific conclusions of the isotopic analyses conducted for the project are as follows:

1. Carbon isotopic compositions for Bug field dolomite samples have a mean value of +4.43‰ PDB. Despite dolomitization, all of the lower Desert Creek samples from Bug field show carbon isotope compositions that are very close in value to modern marine carbonates and Holocene botryoidal marine aragonite cements.

2. The carbon isotope geochemistry of all of the lower Desert Creek dolomites at Bug field has retained a strong influence from Pennsylvanian marine water composition. Meteoric waters do not appear to have had any effect on the composition of these lower Desert Creek dolomites.

3. Oxygen isotopic compositions for the Bug field dolomite samples have a mean value of -4.51‰ PDB. The lighter oxygen values obtained from wells located along the margins or flanks of Bug field may be indicative of exposure to higher temperatures, to fluids depleted in ^{18}O relative to sea water, or to hypersaline waters during burial diagenesis.

4. The wells in Bug field with the lightest oxygen isotope compositions in the lower Desert Creek dolomites have produced significantly greater amounts of hydrocarbons.

5. Carbon isotopic compositions for the upper Ismay dolomite samples at Cherokee field have a mean value of +4.70‰ PDB. As with the Bug field dolomite samples, the Cherokee field carbonates fall within the same range of carbon isotope compositions as modern marine sediments, skeletons, and marine cements. It does not appear that meteoric waters, which typically would precipitate carbonates with more depleted carbon isotope values, have had major effects on the composition of the Ismay carbonate components.

6. Most of the Ismay carbonates (as well as those throughout the lower Desert Creek) have retained a marine-influenced carbon isotope geochemistry throughout marine cementation as well as post-burial recycling of marine carbonate components during dolomitization, stylolitization, dissolution, and late cementation.

7. Oxygen isotopic compositions for the Cherokee field limestone and dolomite samples form a wide range of values around a mean value of -4.20‰ PDB. There is no significant difference between the oxygen isotope compositions from lower Desert Creek dolomite samples in Bug field and the upper Ismay limestones and dolomites from Cherokee field.

8. One of the dolomitized samples in Cherokee field, from cryptalgal laminites, has a much lighter oxygen composition. The depleted del ^{18}O value of this one dolomite sample suggests neomorphism, cementation, and/or dolomitization from warm or isotopically light subsurface waters.

9. Carbon isotopic compositions for upper Ismay limestone samples in the cemented buildup of Patterson Canyon field have a mean value of +5.43‰ PDB. However, the samples can be divided into two populations with regard to carbon isotopic composition: isotopically heavier mound cemented and isotopically lighter oolite and cement bands.

10. Mound cements were confined to a “closed hydrologic system” that allowed a fluid with heavier carbon to evolve. The oolite and cement bands therein may have been in a more open system allowing water exchange such that waters with a composition slightly lighter were involved in the lithification and diagenesis of the capping oolite.

11. Oxygen isotopic compositions for upper Ismay limestone samples of the cemented buildup in Patterson Canyon field have a mean value of –5.48‰ PDB, lighter than Bug and Cherokee samples.

12. The oxygen isotope signatures indicate waters with depleted ^{18}O characteristics evolved in the mound cavities and ooid grainstone pores, without any influence by hypersaline waters. Alternatively, the limestones in this sample set may have all been modified via neomorphism by isotopically light subsurface waters.

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REFERENCES

Brinton, Lisë, 1986, Deposition and diagenesis of Middle Pennsylvanian (Desmoinesian) phylloid algal banks, Paradox Formation, Ismay zone, Ismay field and San Juan Canyon, Paradox Basin, Utah and Colorado: Golden, Colorado School of Mines, M.S. thesis, 315 p.

Crawley-Stewart, C.L., and Riley, K.F., 1993, Cherokee, *in* Hill, B.G., and Bereskin, S.R., editors, Oil and gas fields of Utah: Utah Geological Association Publication 22, non-paginated.

Dawson, W.C., 1988, Ismay reservoirs, Paradox Basin - diagenesis and porosity development, *in* Goolsby, S.M., and Longman, M.W., editors, Occurrence and petrophysical properties of carbonate reservoirs in the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 163-174; 442-443.

Given, R.K., and Lohmann, K.C., 1985, Derivation of the original isotopic composition of Permian marine cements: Journal of Sedimentary Petrology, v. 55, p. 430-439.

---1986, Isotopic evidence for the early meteoric diagenesis of the reef facies, Permian reef complex of West Texas and New Mexico: Journal of Sedimentary Petrology, v. 56, p. 183-193.

Hudson, J.D., 1975, Carbon isotopes and limestone cements: Geology, v. 3, p. 19-22.

James, N.P., and Ginsburg, R.N., 1979, The seaward margin of Belize barrier and atoll reefs: International Association of Sedimentologists Special Publication 3, 191 p.

Land, L.S., 1980, The isotopic and trace elements geochemistry of dolomite - the state of the art, *in* Zenger, D.H., Dunham, J.B., and Ethington, R.L., editors, Concepts and models of dolomitization: Society for Sedimentary Geology (SEPM) Special Publication 28, p. 87-110.

---1982, Dolomitization: American Association of Petroleum Geologists Short Course Note Series No. 24, 20 p.

Lohmann, K.C., 1983, Diagenetic history of carbonate reservoirs – integration of petrographic and geochemical techniques, *in* Wilson, J.L., Wilkinson, B.H., Lohmann, K.C., and Hurley, N.F., editors, New ideas and methods of exploration for carbonate reservoirs: Dallas Geological Society, unpaginated.

Martin, G.W., 1983, Bug, *in* Fassett, J.E., editor, Oil and gas fields of the Four Corners area, volume III: Four Corners Geological Society, p. 1073-1077.

Oline, W.F., 1996, Bug, *in* Hill, B.G., and Bereskin, S.R., editors, Oil and gas fields of Utah: Utah Geological Association Publication 22 Addendum, non-paginated.

Roylance, M.H., 1984, Depositional and diagenetic control of petroleum entrapment in the Desert Creek interval, Paradox Formation, southeastern Utah and southwestern Colorado: Lawrence, University of Kansas, M.S. thesis, 178 p.

---1990, Depositional and diagenetic history of a Pennsylvanian algal-mound complex - Bug and Papoose Canyon fields, Utah and Colorado: American Association of Petroleum Geologists Bulletin, v. 74, p. 1087-1099.

Utah Division of Oil, Gas and Mining, 2003, Oil and gas production report, May: non-paginated.