

**HETEROGENEOUS SHALLOW-SHELF CARBONATE
BUILDUPS IN THE PARADOX BASIN,
UTAH AND COLORADO: TARGETS FOR INCREASED
OIL PRODUCTION AND RESERVES USING
HORIZONTAL DRILLING TECHNIQUES**
(Contract No. DE-2600BC15128)

**DELIVERABLE 2.2.1
THREE-DIMENSIONAL GEOLOGIC
MODELS AND RESERVE
CALCULATIONS: CHEROKEE AND BUG
FIELDS, SAN JUAN COUNTY, UTAH**

Submitted by

Utah Geological Survey
Salt Lake City, Utah 84114
June 2004



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US/DOE Patent Clearance is not required prior to the publication of this document.

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INTRODUCTION

Over 400 million barrels (64 million m³) of oil have been produced from the shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation in the Paradox Basin, Utah and Colorado. 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 m³) 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 m³) 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.

GEOLOGIC SETTING

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with a small portion in northeastern Arizona and the northwestern most corner of 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 Uncompahgre Highlands (uplift) is bounded along the southwestern flank by a large basement-involved, high-angle reverse fault identified from geophysical 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 then 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).

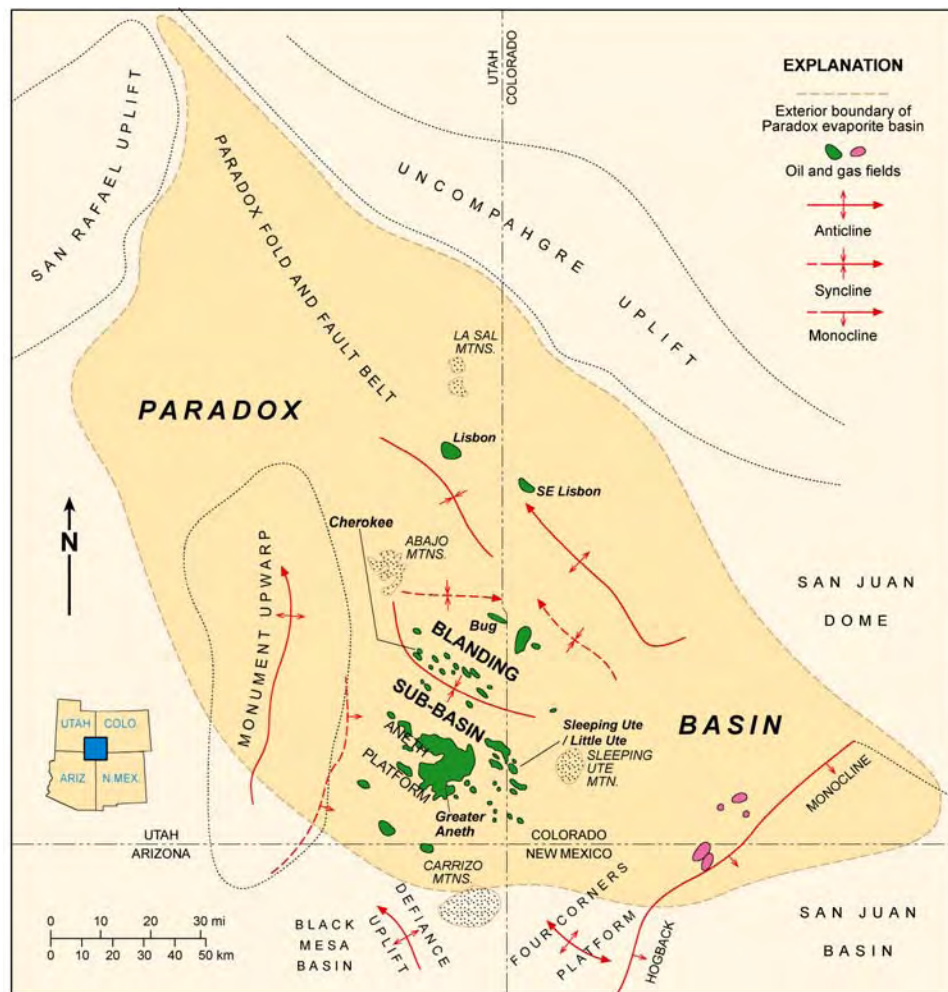


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

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.

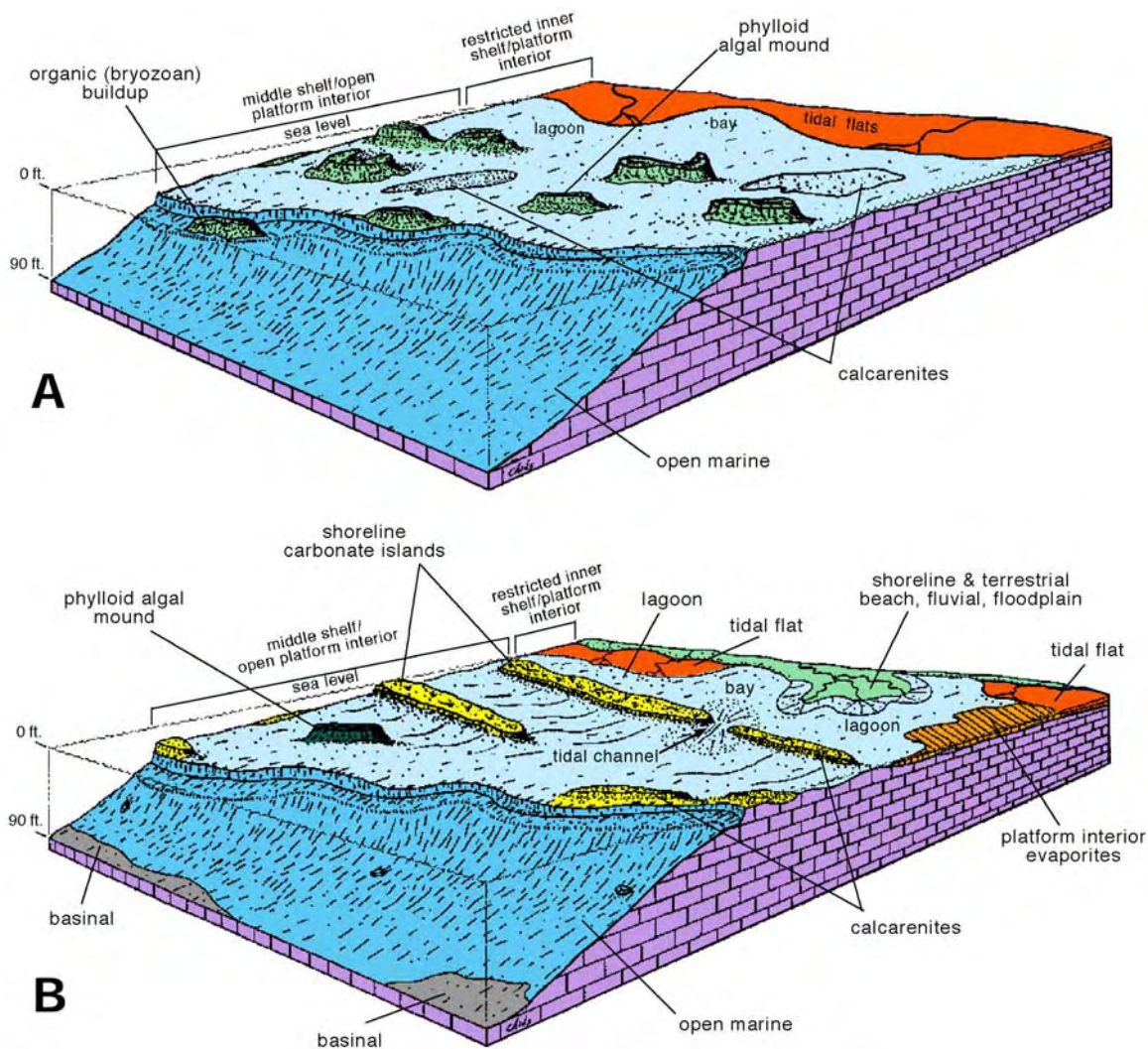
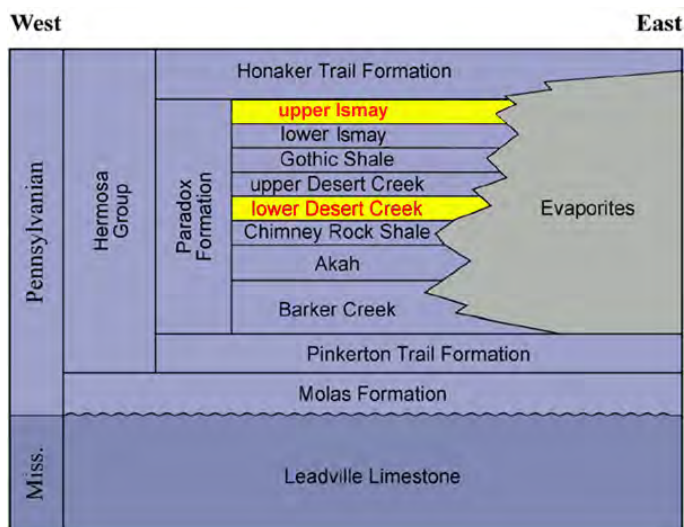


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

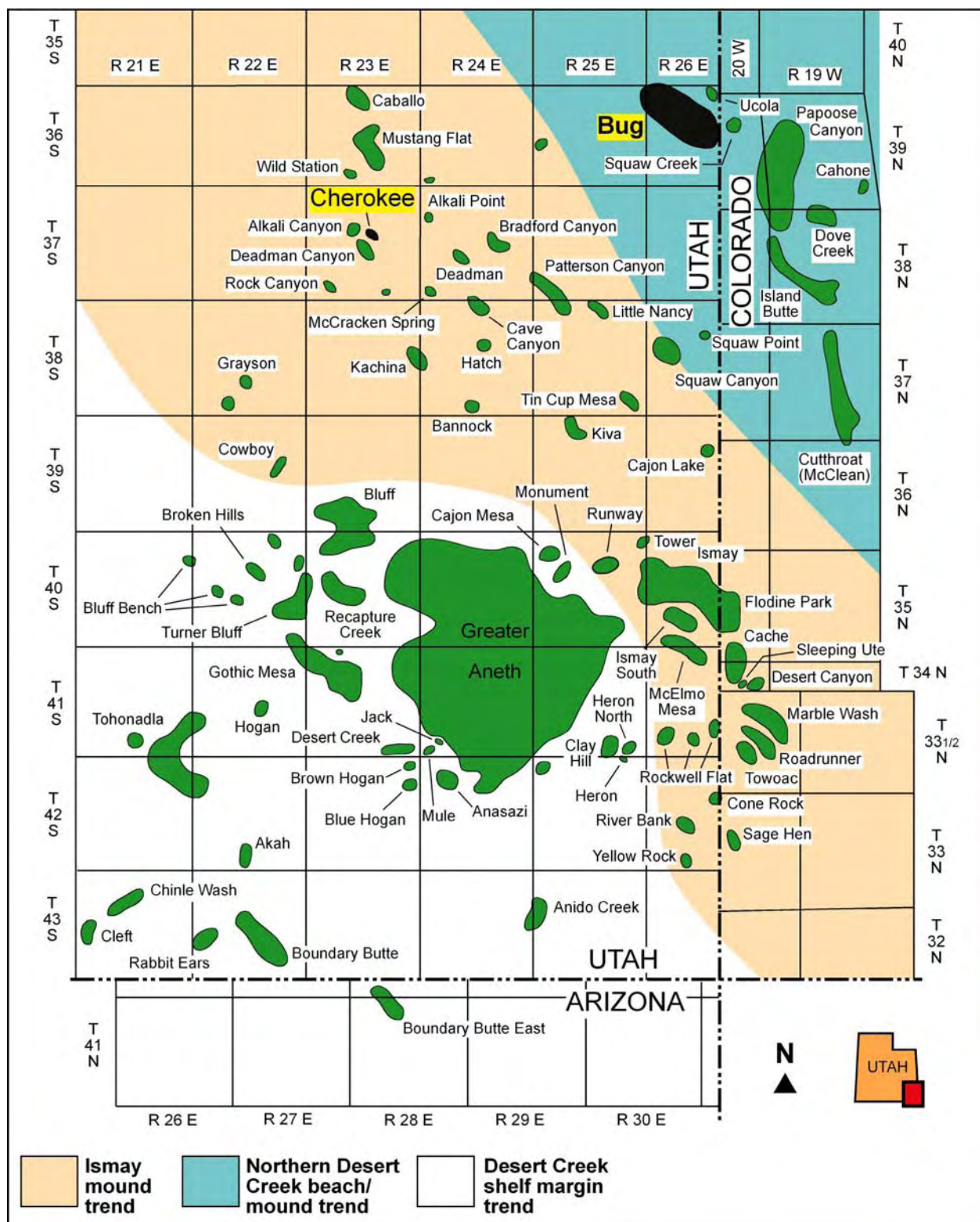


Figure 4. Project study area and fields (case-study fields in black) within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

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 4). This evaluation included data collection and reservoir mapping used to create three-dimensional (3D) models and calculate reserves of these fields, summarized in this report.

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 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 (IFP) was 53 barrels of oil per day (BOPD) (8.4 m³), 990 thousand cubic feet of gas per day (MCFGPD) (28 MCMPD), and 26 barrels of water (4.1 m³). 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 January 1, 2004, was 182,464 barrels of oil (29,012 m³), 3.67 billion cubic feet of gas (BCFG) (0.1 BCMG), and 3,358 barrels of water (534 m³) (Utah Division of Oil, Gas and Mining, 2003). The original estimated primary recovery is 172,000 barrels of oil (27,348 m³) 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, NE1/4SE1/4 section 12, T. 36 S., R. 25 E., SLBL&M, for an IFP of 608 BOPD (96.7 m³), 1,128 MCFGPD (32 MCMPD), and 180 barrels of water (28.6 m³). 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 January 1, 2004, was 1,622,455 barrels of oil (257,970 m³), 4.48

BCFG (0.13 BCMG), and 3,181,467 barrels of water (505,850 m³) (Utah Division of Oil, Gas and Mining, 2003). Estimated primary recovery is 1,600,000 bbls (254,400 m³) 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.

CORRELATION SCHEME USED IN MAPPING

The structure and isochore maps used to generate 3-D models employed a correlation scheme developed early in the project. This correlation scheme tied the core-derived, typical, vertical sequence or cycle of depositional facies from the Cherokee and Bug case-study fields to the corresponding gamma-ray and neutron-density curves from geophysical well logs. The correlation scheme identified major zone contacts, seals or barriers, baffles, producing or potential reservoirs, and depositional facies (figures 5 through 7, and table 1).

Depositionally, rock units are divided into seals or barriers (anhydrites and shales), mound (carbonate buildup [bafflestone, bindstone, grainstone, and packstone]), and off mound (mudstone and wackestone). Porosity units, and reservoir or potential reservoir layers, are identified within the mound and off-mound intervals. The mound, and some of the off-mound units, are part of the “clean carbonate” packages - intervals containing all of the productive reservoir facies, and where carbonate mudstone and shale are generally absent. The clean carbonate packages abruptly change laterally into thick anhydrite packages, particularly in the upper Ismay zone.

The top and base of all these intervals (seals, mound, clean carbonate, as well as porosity units) were determined and coded as listed on table 1. The unlisted intervening units represent the baffles or non-reservoir rocks, such as non-porous packstone or wackestone (figures 5 through 7). 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.

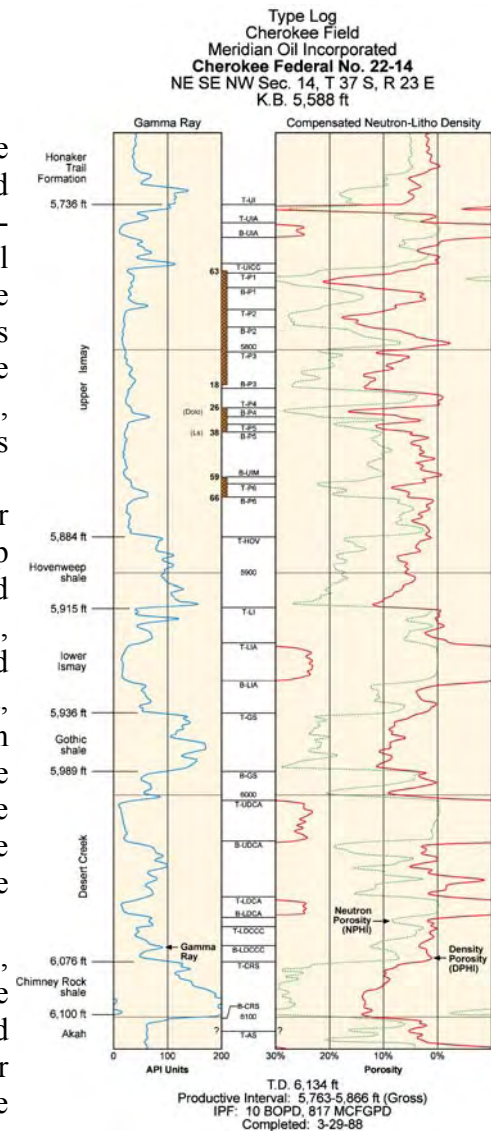
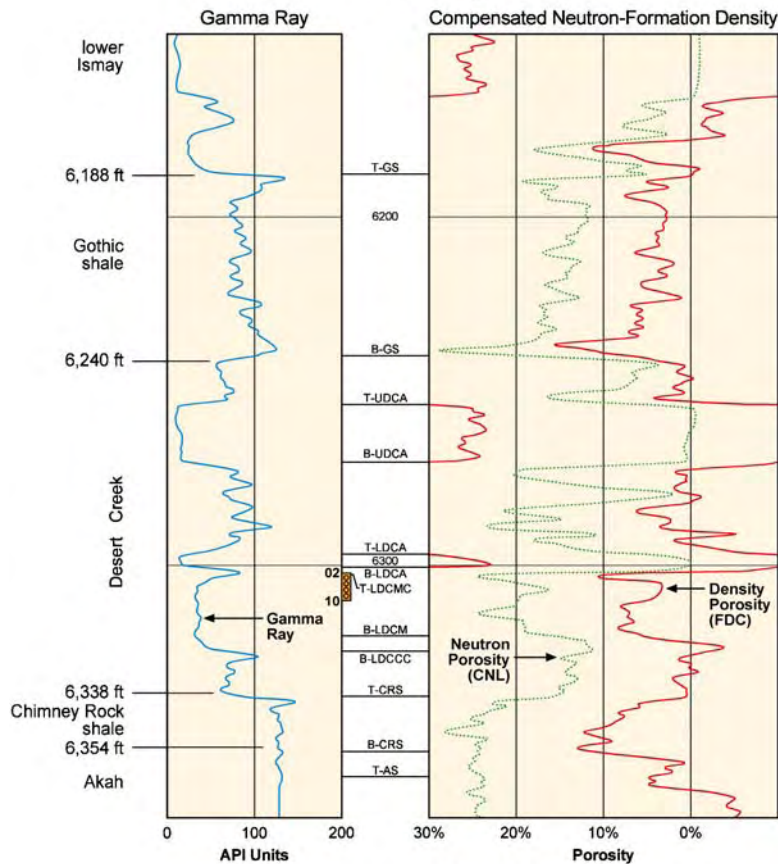


Figure 5. Type log for the Cherokee field (gamma-ray, compensated neutron-litho density) from the Cherokee Federal No. 22-14 well, showing the Ismay and Desert Creek correlation scheme, major units, and productive intervals (refer to table 1 for explanation of unit abbreviations).

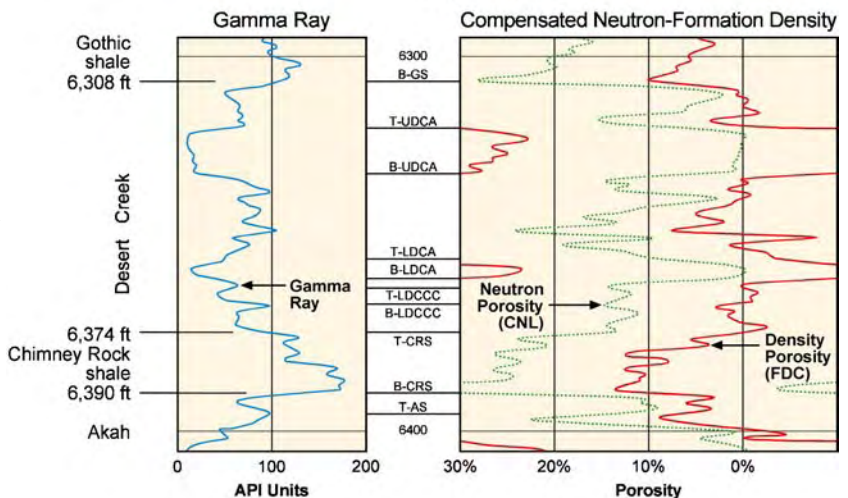
Type Log - Mound
Bug Field
Wexpro Company
Bug No. 16
NE SW Sec. 17, T 36 S, R 26 E
K.B. 6,611 ft



T.D. 6,383 ft
Productive Interval: 6,302-6,310 ft
IPF: 412 BOPD, 644 MCFGPD
Completed: 7-11-81

Figure 6. Type log for the Bug field mound (gamma-ray, compensated neutron-formation density) from the Bug No. 16 well, showing the Desert Creek correlation scheme, major units, and productive interval (refer to table 1 for explanation of unit abbreviations).

Type Log - Off Mound
Bug Field
Wexpro Company
Bug No. 7A
SW NE Sec. 7, T 36 S, R 26 E
K.B. 6,665 ft



T.D. 6,430 ft
Drilled and Abandoned
Completed: 1-11-82

Figure 7. Type log for the Bug field off-mound area (gamma-ray, compensated neutron-formation density) from the Bug No. 7A well, showing the Desert Creek correlation scheme and major units (refer to table 1 for explanation of unit abbreviations).

Table 1. Correlation scheme used for Ismay and Desert Creek zones of the Paradox Formation in Cherokee and Bug fields, Blanding sub-basin, Utah.

Unit Code	Description
T-UI	Top – upper Ismay zone
T-UIA	Top – upper Ismay anhydrite
B-UIA	Base - upper Ismay anhydrite
T-UIA2	Top – upper Ismay anhydrite 2
B-UIA2	Base – upper Ismay anhydrite 2
T-UICC	Top – upper Ismay clean carbonate
T-P1	Top – porosity unit #1
B-P1	Base – porosity unit #1
T-P2	Top – porosity unit #2
B-P2	Base – porosity unit #2
T-P3	Top – porosity unit #3
B-P3	Base – porosity unit #3
T-P4	Top – porosity unit #4
B-P4	Base – porosity unit #4
T-P5	Top – porosity unit #5
B-P5	Base – porosity unit #5
B-UIM	Base – upper Ismay mound
B-UICC	Base upper Ismay clean carbonate
T-P6	Top – porosity unit #6
B-P6	Base – porosity unit #6
T-HOV	Top – Hovenweap shale
T-LI	Top – lower Ismay zone
T-LIA	Top – lower Ismay anhydrite
B-LIA	Base – lower Ismay anhydrite
T-GS	Top – Gothic shale
B-GS	Base – Gothic shale
T-UDCA	Top – upper Desert Creek anhydrite
B-UDCA	Base – upper Desert Creek anhydrite
T-LDCA	Top – lower Desert Creek anhydrite
B-LDCA	Base – lower Desert Creek anhydrite
T-LDCMC	Top – lower Desert Creek mound cap
B-LDCM	Base – lower Desert Creek mound

THREE-DIMENSIONAL MODELING – RESULTS AND DISCUSSION

Methods

The 3-D models were created in Environmental Systems Research Institute, Inc. (ESRI) ArcView® 3D Analyst. Structure, isochore, and other reservoir property contour maps (see Deliverable 1.41 and 1.4.2 – Cross Sections and Field Maps: Cherokee and Bug Fields, San Juan County, Utah) were digitized using AutoCad®, then brought into ArcView®. These AutoCad® files were first converted to shape files and then to grids. Next, Triangulated Irregular Network (TIN) files were created. A TIN is an object used to represent a surface. It partitions a surface into a set of contiguous, non-overlapping triangles. Attribute and geometry information was stored for the points, lines, and faces that comprise each triangle. This information was used for display, query, and analysis purposes. A height value was recorded for each triangle node. Heights between nodes were interpolated, thus allowing for the definition of a continuous surface. TINs can accommodate irregularly distributed, as well as selective data sets. This made it possible to represent a complex and irregular surface with a small data set (ESRI, 1998).

The TIN was imported into a 3D Analyst scene (called a viewer) and a projection was set selected from a specific projection or coordinate system from one of the following categories: Projections of the World, Projections of a Hemisphere, Projections of the United States, State Plane – 1927, State Plane – 1983, Universal Transverse Mercator (UTM), or National Grids. Once the map projections or coordinate system categories have been selected, ArcView® displays the parameters that it uses in the projection, such as the Ellipsoid, Central Meridian, Reference Latitude and Standard Parallels. If no projection is set, TIN themes are displayed using the coordinates found in their data set. Also brought into the scene was a feature theme for the wells created from UTM coordinates. Each well has a set of coordinates. Feature themes and TIN themes had to be in the same coordinate system to display them together without a projection. To set a projection, feature themes had to be in decimal degrees and TIN themes had to be in the projection set for them (ESRI, 1998).

The scene's 3-D properties were set to control certain aspects of scene display such as sun azimuth (the compass direction of the sun), sun altitude (the height of the sun), and a vertical exaggeration factor. The vertical exaggeration factor is a multiplier used to increase or decrease the vertical dimension of data displayed in the scene's 3-D viewer (ESRI, 1998).

After the viewer scene was projected, each theme property was set. Setting the theme properties allowed us to define height, extrusion, shading, navigation simplification, and transparency properties individually. Each TIN theme had its own legend display in the view's Table of Contents. A TIN theme's legend specified what triangle points, lines, or faces were drawn and what colors were used to draw them. This controlled how the TIN theme was displayed in the view (ESRI, 1998).

The scene was shifted, rotated, panned, or zoomed to any angle without disturbing the way each theme was lined up. After all the angles were set for best viewing position, they were exported as a joint photographic expert group (.jpg) or bitmap (.bmp) image file. This image file was used to create a layout. A layout is a map used to display views and is used to prepare graphics for output from ArcView® (ESRI, 1998). Layouts were printed and exported to a number of formats. The annotations (labels, descriptions, titles, and so forth) were added at this time.

Modeling Interpretation

Cherokee Field

The relative locations of Cherokee field wells used to produce reservoir structure and isochore maps are shown on figure 8. The 3-D diagrams with structural contours on top of the upper and lower Ismay zone (figure 9), the upper Ismay clean carbonate (figure 10), and the Gothic shale (figure 11A) show the same general southwest-dipping structural nose upon which the carbonate buildup developed. This structure ends abruptly suggesting the possible presence of a northwest-southeast-trending normal fault. Intense, late-stage microporosity development along hydrothermal solution fronts in the reservoir rock likely migrated from nearby, unknown fracture and fault zones (see Deliverable 1.2.1A – Thin Section Descriptions: Cherokee and Bug Fields, San Juan County, Utah).

The 3-D models of the thickness of the Gothic (figure 11B) and Hovenweap (figure 12) shales show a general west-northwest to east-southeast linear trend. Cherokee wells align along a subtle Gothic thickness increase (figure 11B), whereas the carbonate buildup may have developed on a better-defined thick in the shallower Hovenweap (figure 12).

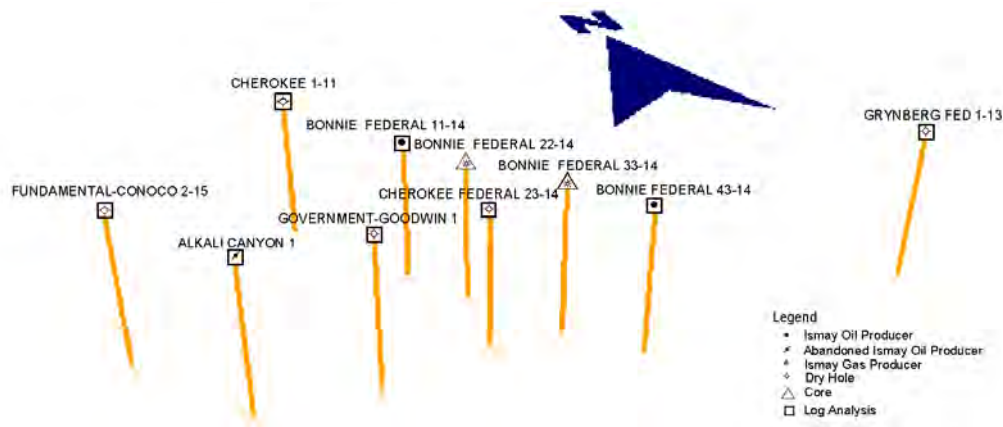


Figure 8. Relative locations and names of wells in the Cherokee field area, San Juan County, Utah.

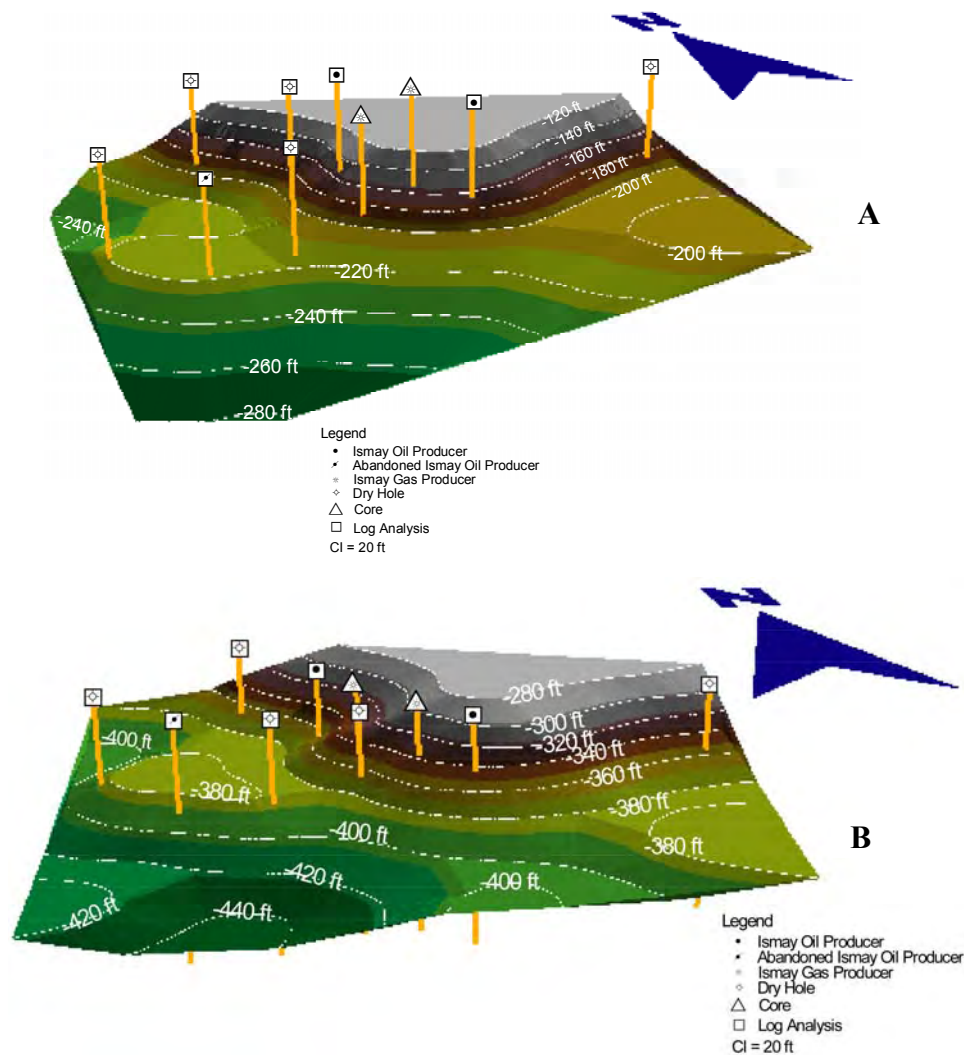


Figure 9. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Structure contours on top of upper Ismay zone. (B) Structure contours on top of lower Ismay zone.

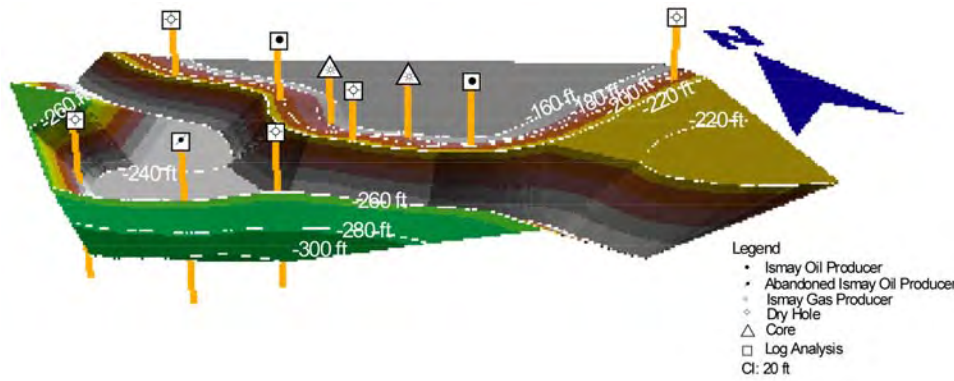
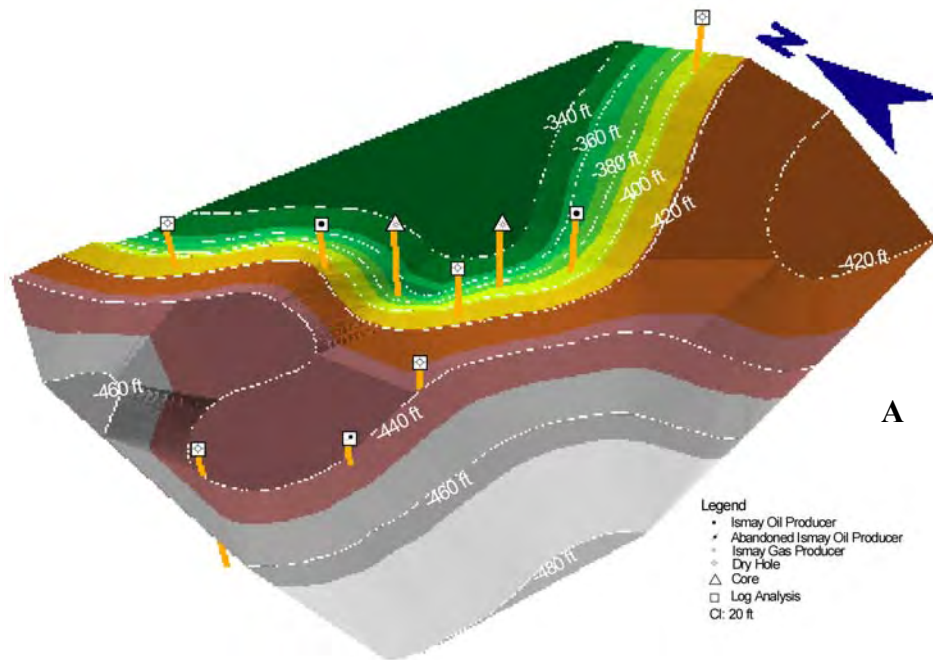
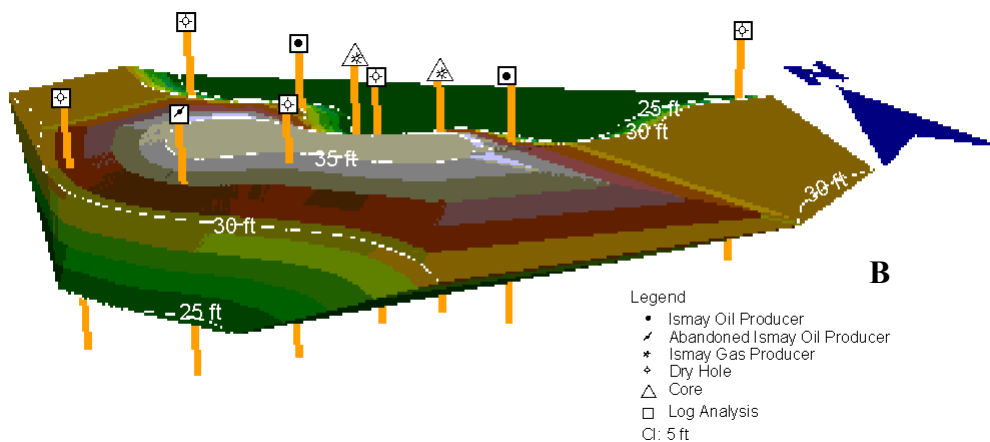


Figure 10. Three-dimensional model with structure contours on top of upper Ismay zone clean carbonate, Cherokee field, San Juan County, Utah.



A



B

Figure 11. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Structure contours on top of Gothic shale. (B) Isochore of Gothic shale.

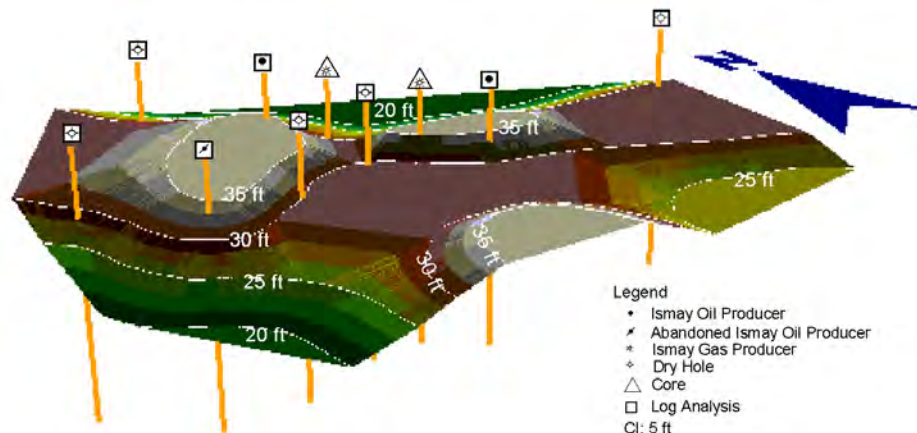


Figure 12. Three-dimensional model of the isochore of the Hovenweap shale, Ismay zone, Cherokee field, San Juan County, Utah.

There are two anhydrite units (1 and 2) in the upper Ismay zone (figure 13). They display a similar west-northwest to east-southeast linear trend as the Hovenweap and Gothic shales. Cherokee wells are located in the thickest part of the relatively thin upper Ismay anhydrite 1 (figure 13A). The upper Ismay anhydrite 2 varies in thickness from 80 feet (24 m) to 0 across the map area. This unit is 0 to 15 feet (0-5 m) thick in Cherokee wells, which lie along the edge of thick anhydrite, as seen in both isochore and inverted isochore diagrams (figures 13B and 13C). This situation is similar to the regional upper Ismay facies pattern where intrashelf basins are the locations of thick anhydrite accumulations. Phylloid-algal buildups developed on innershelf and tidal flats within curvilinear bands that rim the intrashelf basins (Eby and others, 2003a, 2003b).

Three-dimensional models of the thickness of the entire Ismay zone (figure 14A), upper Ismay (figure 14B), lower Ismay (figure 14C), and upper Ismay clean carbonate (figure 15) also display the same general west-northwest to east-southeast trend punctuated by elongate to slightly equant thicks. Cherokee field is located near thicks shown on Ismay and upper Ismay 3-D diagrams. Surprisingly, the field is located adjacent to the thickest part of the upper Ismay clean carbonate (100 feet [30 m]), although the range from that thick to the thinnest section in Cherokee wells is only 19 feet (6 m).

Five reservoir porosity units (figure 16 through 19), all having porosity greater than 6 percent, are present in the upper Ismay mound, separated by low-porosity/permeability barriers (mudstone and wackestone). These porosity units represent the phylloid-algal buildups composed primarily of bafflestone and grainstone that produce oil and gas in the field. Typical of the upper Ismay trend in the Blanding sub-basin, these units are viewed in 3-D as small, equant-shaped pods. The overall carbonate reservoir for Cherokee field is shown in a combined 3-D diagram on figure 18B, but in reality, the individual porosity units are stacked vertically, displayed diagrammatically on figure 19. Porosity unit 5 (figure 18A) is the largest and most likely the major production contributor, as well as holding the bulk of the remaining reserves. The 3-D thickness diagrams suggest all five porosity units have an untested northeastern area.

As expected, 3-D diagrams of the upper Ismay zone depicting net feet of porosity greater than 10 and 12 percent by log analysis (figure 20) show the same equant-shaped buildups as displayed by porosity units 1 through 5. At 12 percent porosity, the diagram shows a thickness pattern which is a slightly smaller match compared to the combined thickness of porosity units 1 through 5 (figure 18B).

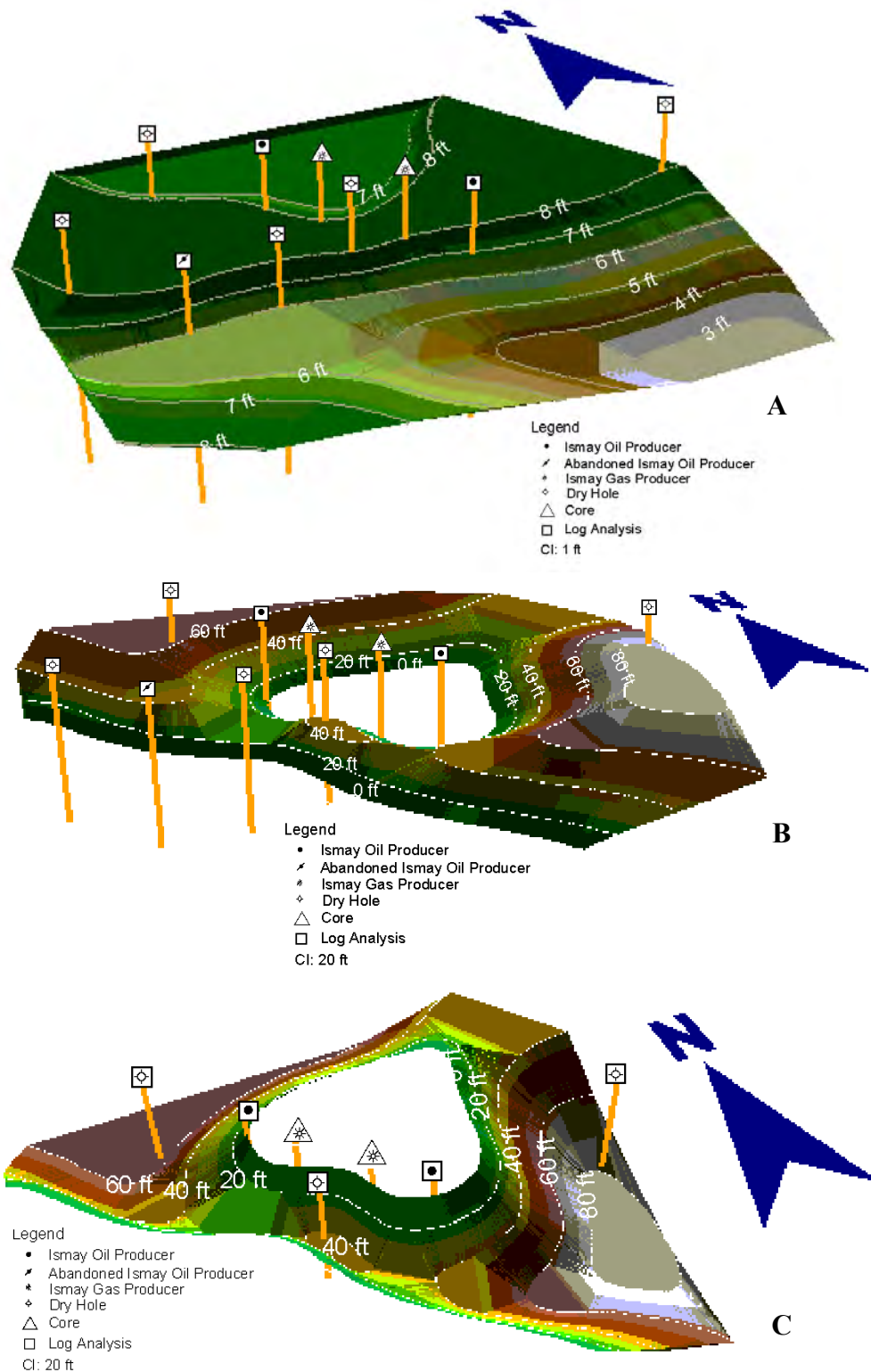


Figure 13. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Upper Ismay zone anhydrite isochore 1. (B) Upper Ismay zone anhydrite 2 isochore. (C) Upper Ismay zone anhydrite 2 inverted isochore.

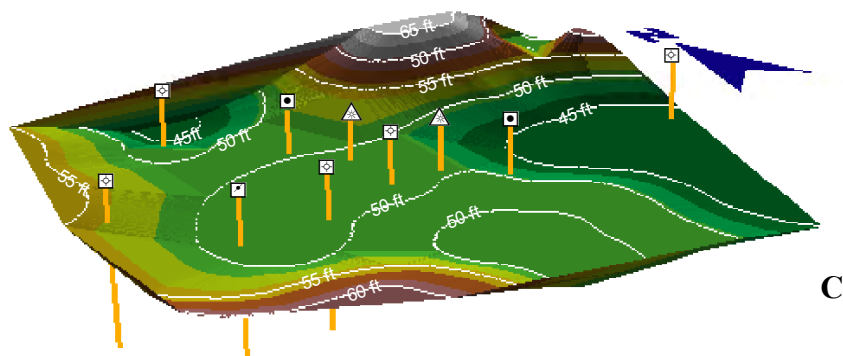
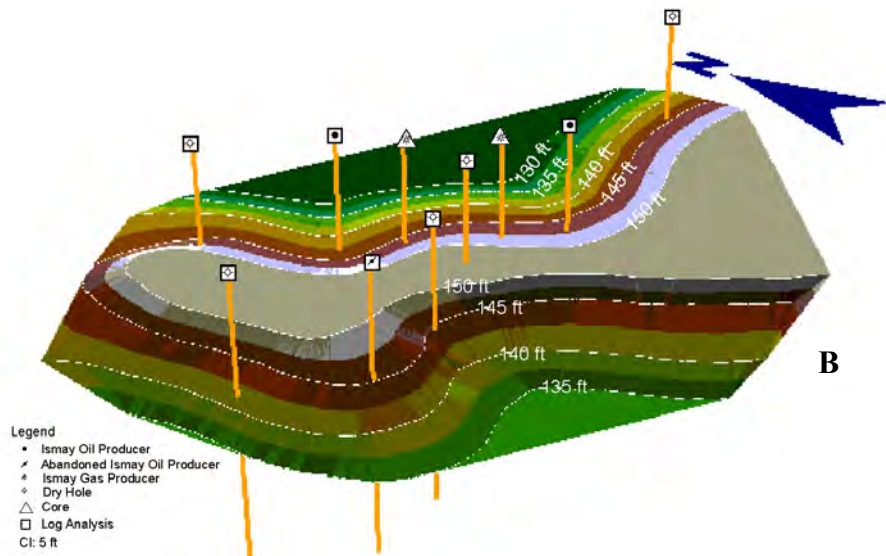
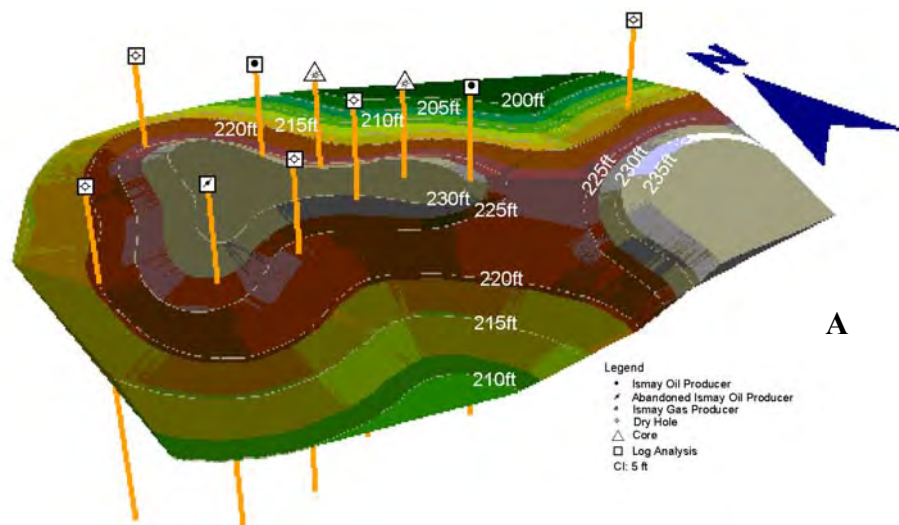
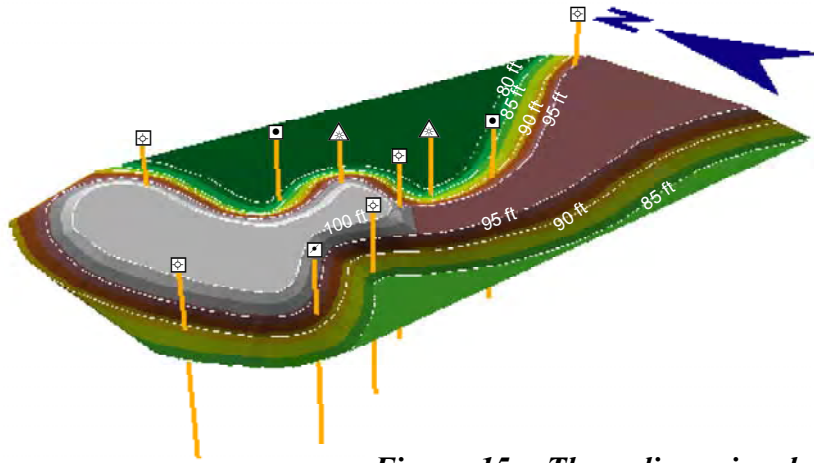
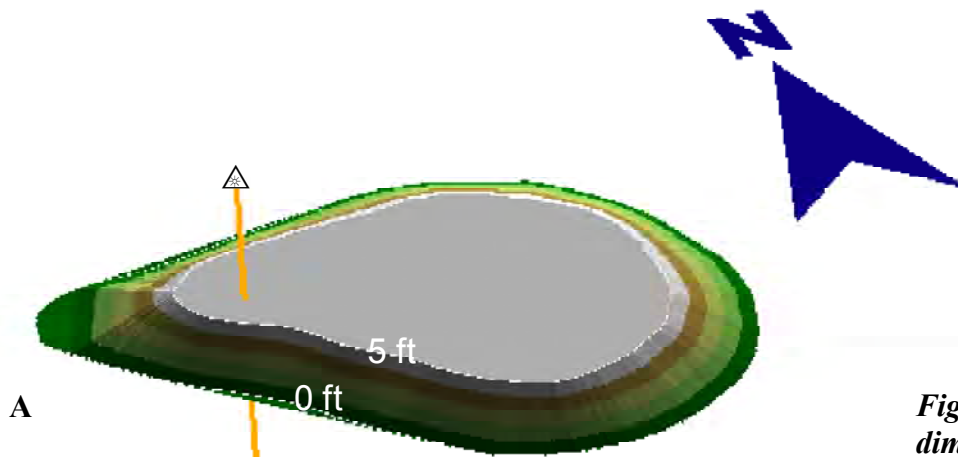


Figure 14. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Ismay zone isochore. (B) Upper Ismay zone isochore. (C) Lower Ismay zone isochore.



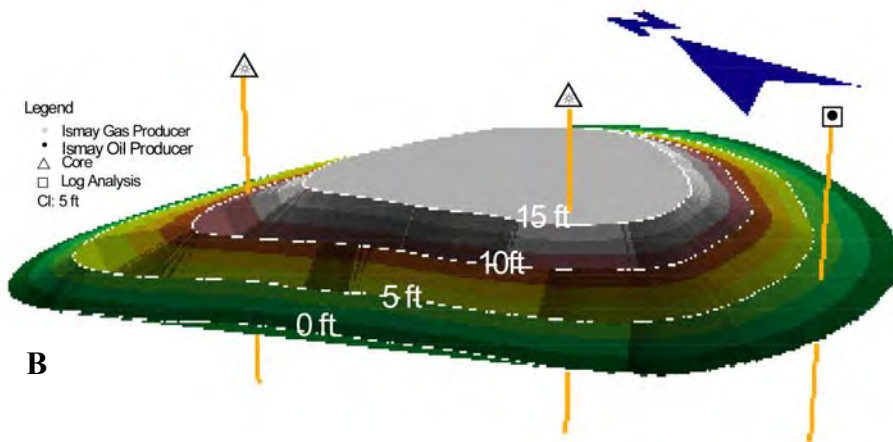
Legend
 • Ismay Oil Producer
 • Abandoned Ismay Oil Producer
 • Ismay Gas Producer
 ◊ Dry Hole
 △ Core
 □ Log Analysis
 Ct: 5 ft

Figure 15. Three-dimensional model of the isochore of the upper Ismay zone, clean carbonate, Cherokee field, San Juan County, Utah.



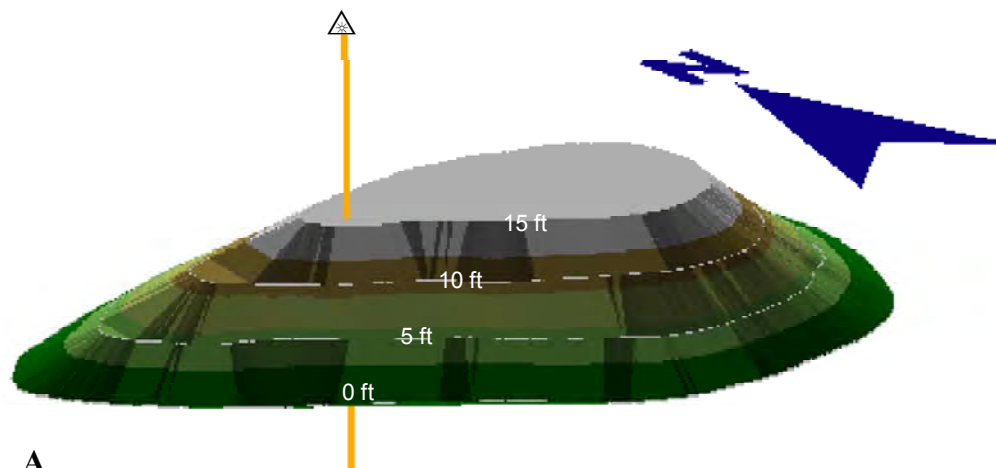
Legend
 • Ismay Gas Producer
 △ Core
 Ct: 5 ft

Figure 16. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah.



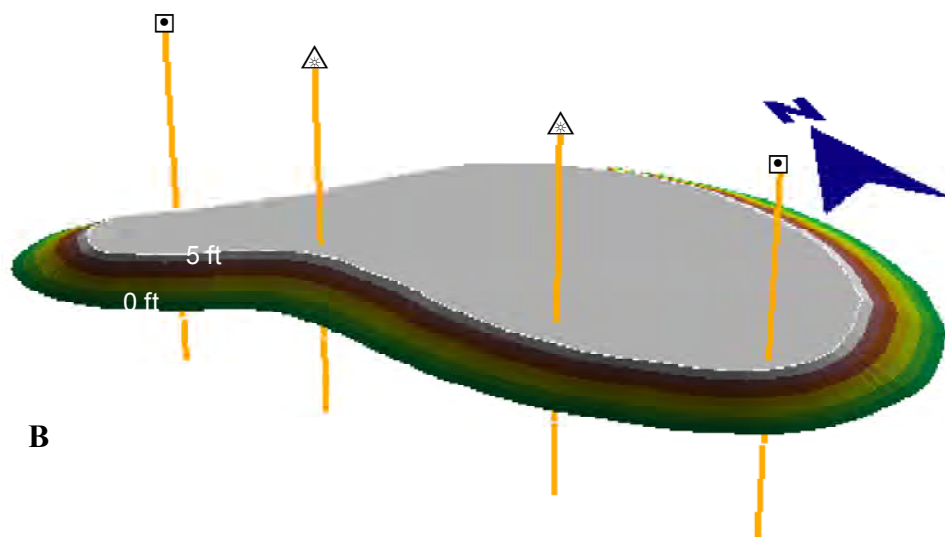
Legend
 • Ismay Gas Producer
 • Ismay Oil Producer
 △ Core
 □ Log Analysis
 Ct: 5 ft

(A) Isochore of porosity unit 1. (B) Isochore of porosity unit 2.



A

Legend
 * Ismay Gas Producer
 △ Core
 Cl: 5 ft



B

Legend
 • Ismay Oil Producer
 * Ismay Gas Producer
 △ Core
 □ Log Analysis
 Cl: 5 ft

Figure 17. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah. (A) Isochore of porosity unit 3. (B) Isochore of porosity unit 4.

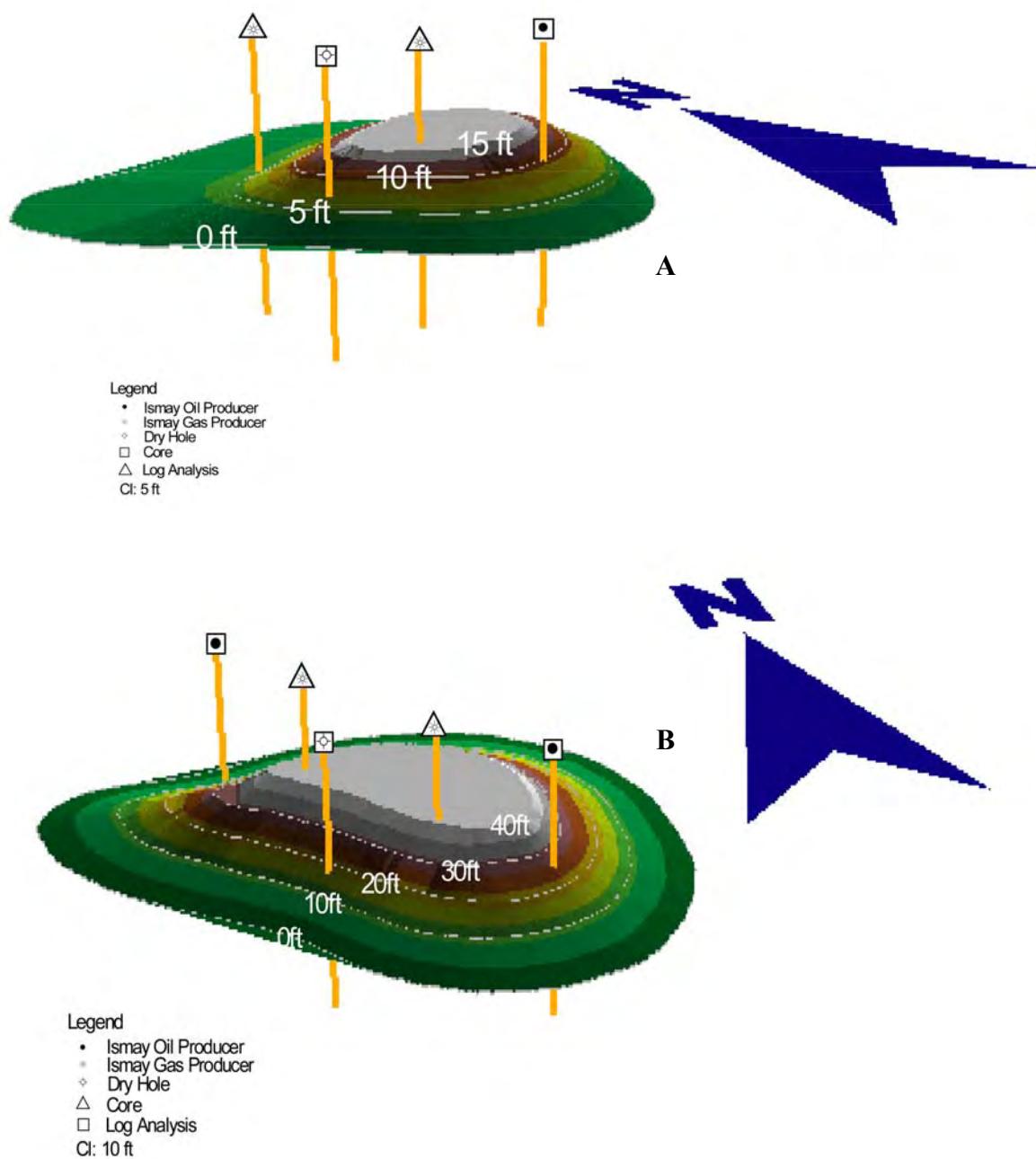


Figure 18. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah. (A) Isochore of porosity unit 5. (B) Isochore of porosity units 1 through 5 combined thickness.

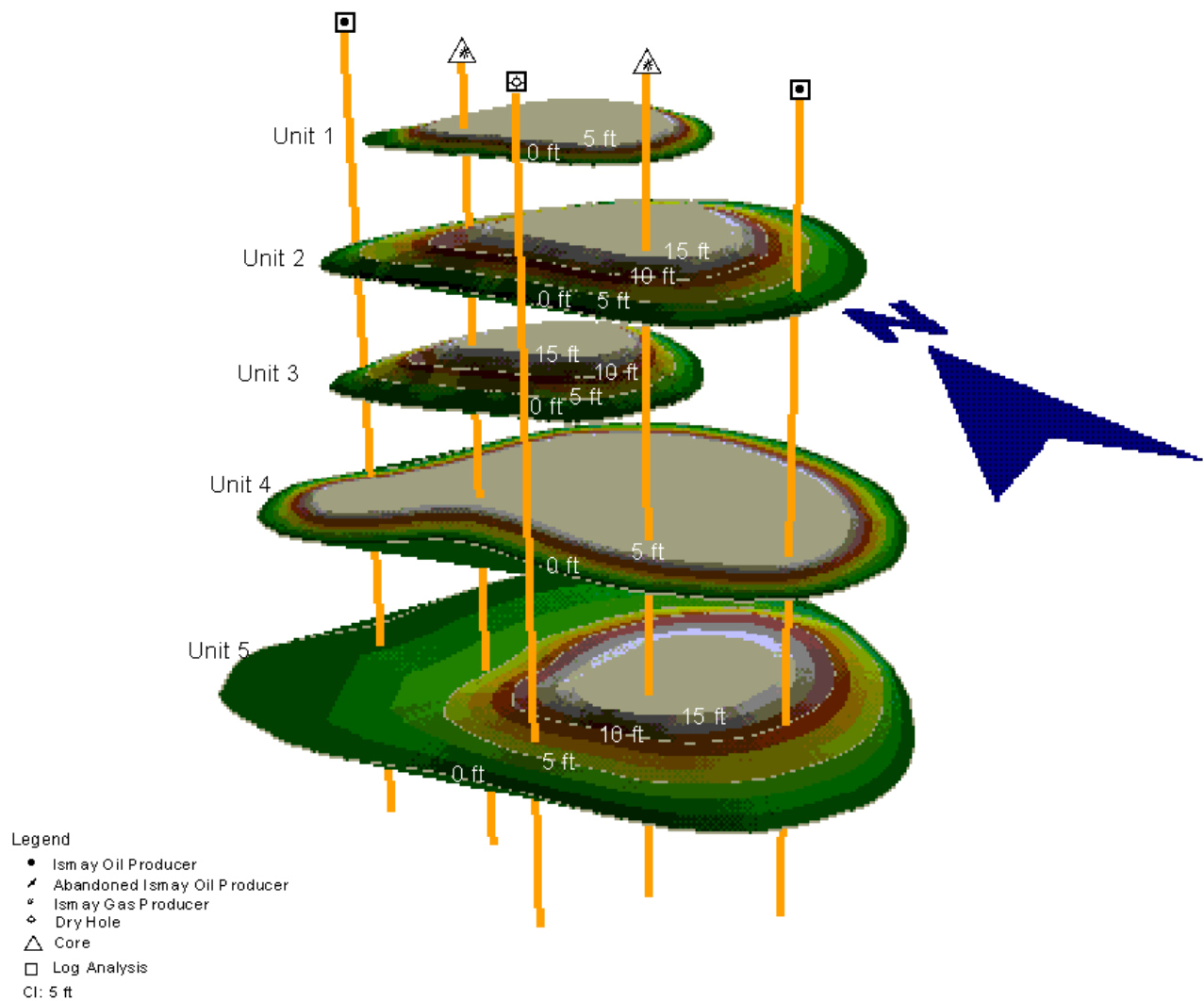
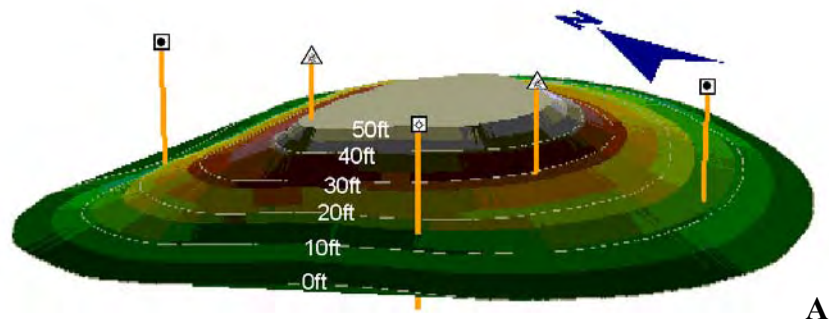


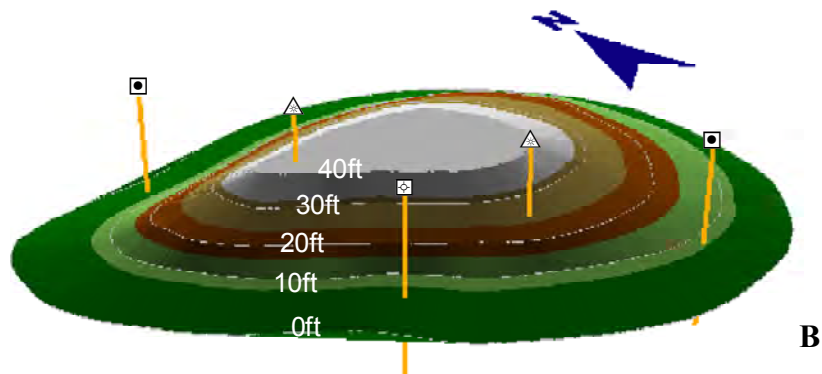
Figure 19. Three-dimensional model of porosity units 1 through 5 isochores vertically stacked (no vertical scale), upper Ismay zone, Cherokee field, San Juan County, Utah.



Legend

- Ismay Oil Producer
- / Abandoned Ismay Oil Producer
- * Ismay Gas Producer
- ◇ Dry Hole
- △ Core
- Log Analysis

Cl: 10 ft



Legend

- Ismay Oil Producer
- * Ismay Gas Producer
- ◇ Dry Hole
- △ Core
- Log Analysis

Cl: 10 ft

Figure 20. Three-dimensional models, upper Ismay zone net feet of porosity, as determined by geophysical log analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Cherokee field, San Juan County, Utah.

Upper Ismay zone net-feet of limestone (figure 21A) and dolomite (figure 21B) were determined by log analysis. The extent of the 3-D diagrams is limited due to the lack of neutron/density logs from older wells in the area. Characteristic of the Ismay zone in the Blanding sub-basin, limestone is the dominant lithology. However, there is an unusual amount of dolomite present. The 3-D thickness diagrams show a large buildup of limestone adjacent to (figure 21A), and dolomite within (figure 21B), Cherokee field. In both cases, a carbonate buildup continues northeast of the field wells.

Bug Field

The relative locations of Bug field wells used to produce reservoir structure and isochore maps are shown on figure 22. The 3-D diagram with structural contours on top of the Gothic shale (figure 23A) shows a general regional dip to the southwest and a subtle, elongate, northwest-southeast-trending anticline. The 3-D model of the thickness of the Gothic shale (figure 23B) shows a similar northwest-southeast trend. Bug wells align along, or adjacent to, a subtle Gothic thickness increase.

The 3-D diagrams with structural contours on top of the Desert Creek zone (figure 24A), lower Desert Creek mound (figure 24B), lower Desert Creek clean carbonate (figure 24A), and Chimney Rock shale (figure 24D) also each show a southwest regional dip. The top of the Desert Creek zone, which is just slightly deeper than the Gothic shale, displays the same subtle, elongate, northwest-southeast-trending anticline. The anticline broadens in the lower Desert Creek mound and clean carbonate, likely representing the buildup itself. At the Chimney Rock shale top, the anticline may depict the topographic high upon which the Bug carbonate buildup developed.

Likewise, a 3-D model of the entire thickness of the Desert Creek zone (figure 25) also displays the same general northwest to southeast trend as does the structural diagram, with elongate thins and thicks. Bug field is located adjacent to one of the thin areas (70 feet [23 m]), but is not situated entirely on a thick. However, the Bug No. 6 well does contain the thickest section of Desert Creek in the mapped area at 138 feet (46 m).

There is one anhydrite unit in the lower Desert Creek zone (figure 26). It displays the general northwest-southeast linear trend corresponding to the trend of the Gothic shale and entire Desert Creek. The unit is a thin, widespread anhydrite of relatively uniform thickness that averages about 5 feet (1.5 m) over most of the area. Bug producing wells are located in a thicker part (up to 9 feet [3 m]) as seen in both isochore and inverted isochore diagrams (figures 26A and 26B), and the Southeast Bug 1-21 well contains an exceptionally thick section of anhydrite at 18 feet (6 m). Unlike the Ismay zone, there are no intrashelf basins that we have identified in the Desert Creek (Eby and others, 2003a, 2003b).

The 3-D models of the thickness of the lower Desert Creek clean carbonate (figure 27) and mound core (figure 28) display an elongate, northwest-southeast-trending carbonate buildup depicting the typical, nearshore, shoreline-linear facies tracts of the Desert Creek zone in the northern Blanding sub-basin. Both diagrams appear similar as they represent nearly the same interval of the lower Desert Creek – the producing reservoir. The slightly thicker clean carbonate displays a small saddle between two subsidiary buildups, whereas the mound core is represented by one uniformly thick buildup.

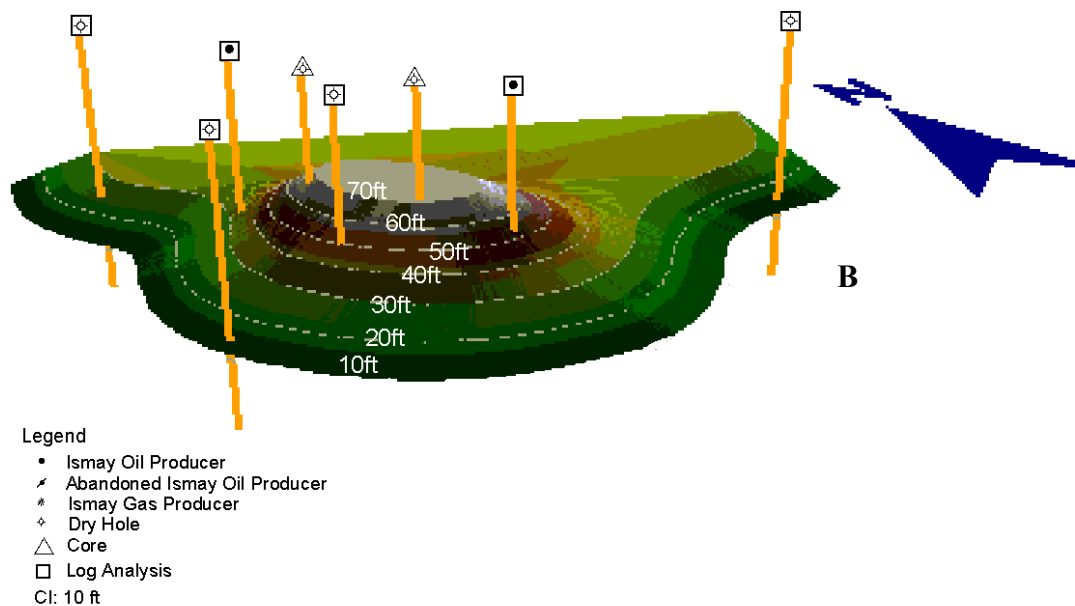
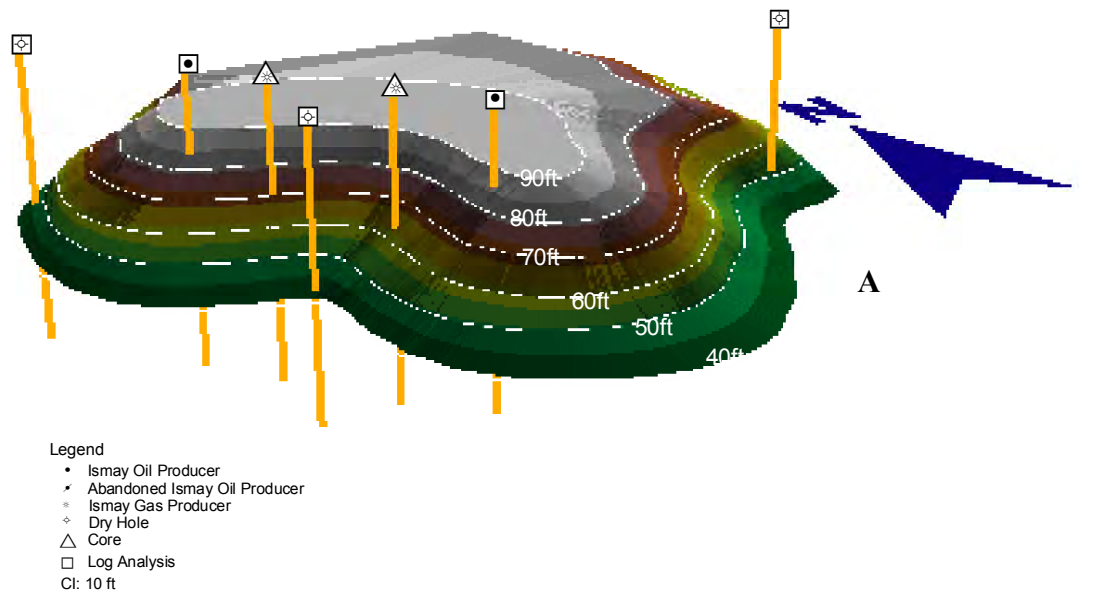


Figure 21. Three-dimensional models, upper Ismay zone net feet of limestone (A) and dolomite (B) as determined by geophysical log analysis, Cherokee field, San Juan County, Utah.

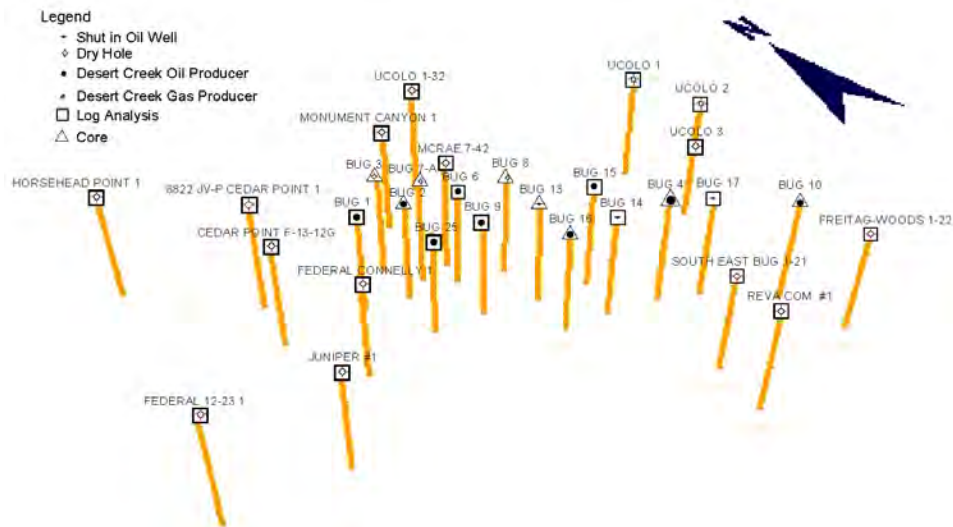


Figure 22. Relative locations and names of wells in the Bug field area, San Juan County, Utah.

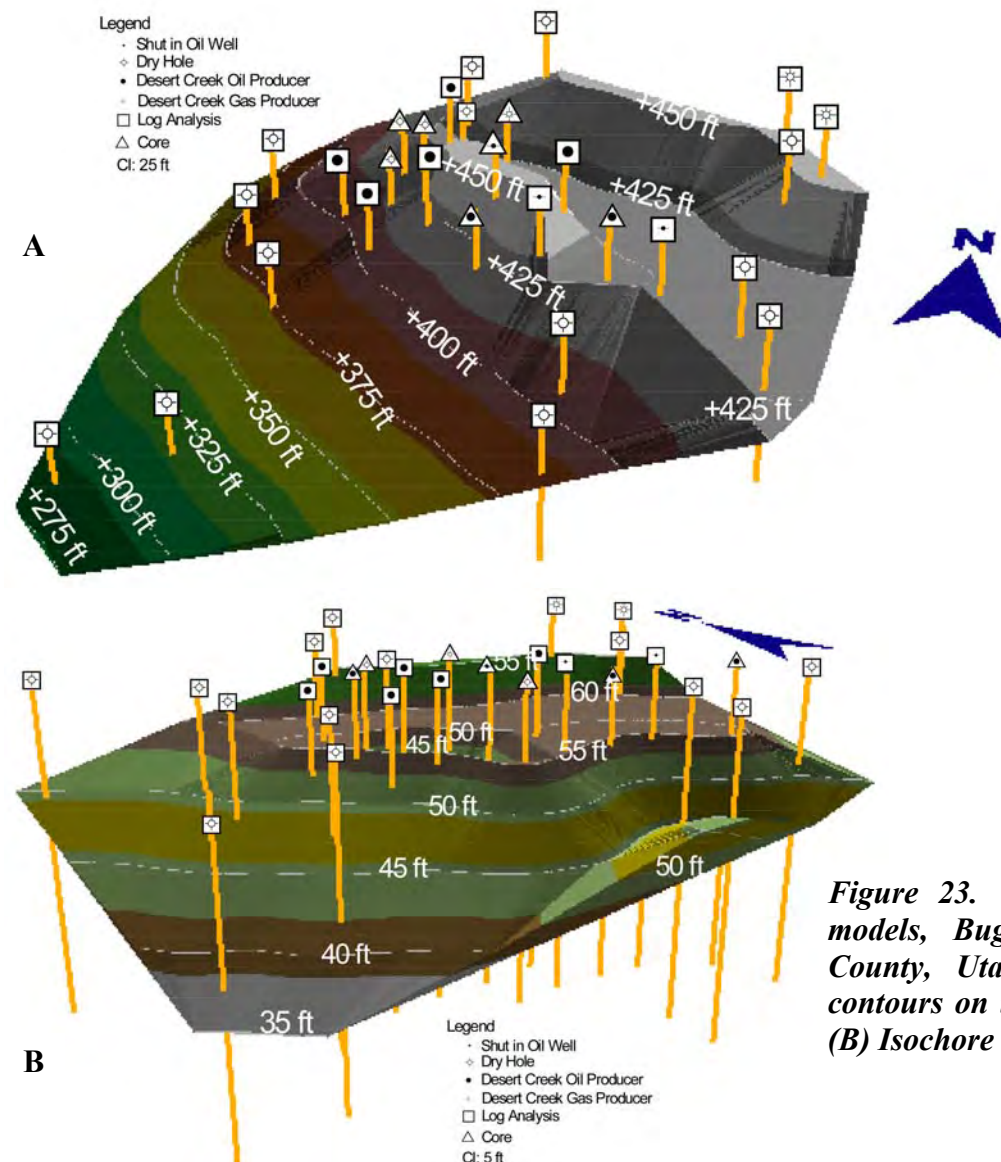


Figure 23. Three-dimensional models, Bug field, San Juan County, Utah. (A) Structure contours on top of Gothic shale. (B) Isochore of Gothic shale.

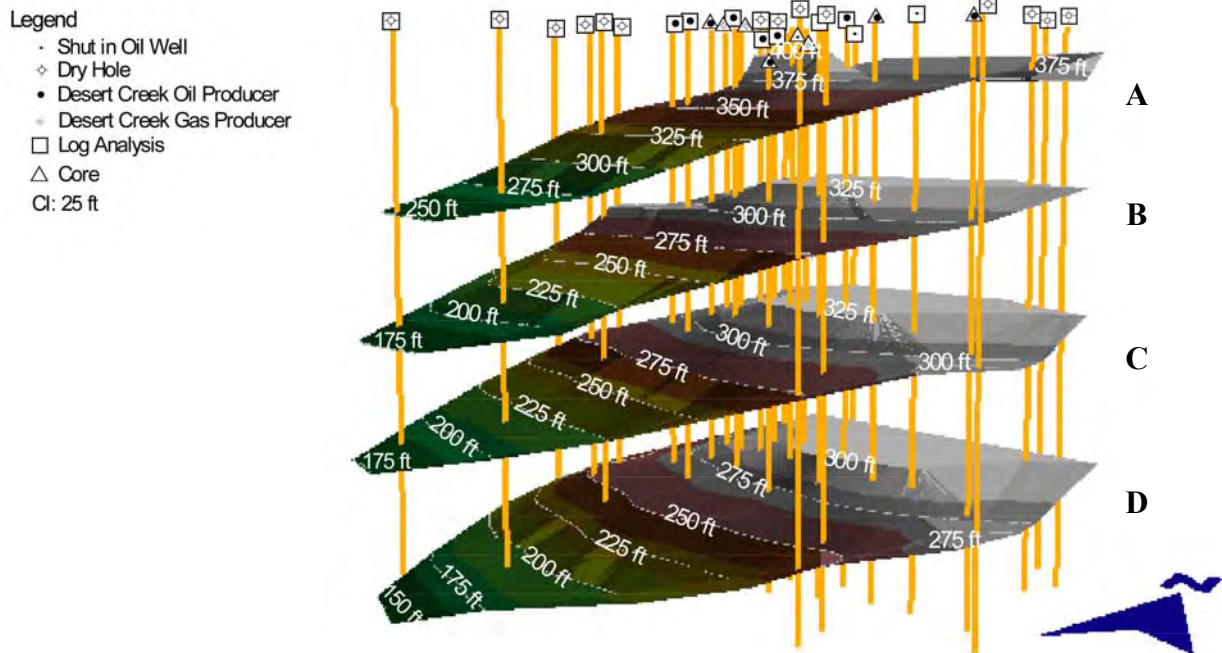


Figure 24. Three-dimensional models vertically stacked (no scale) with structural contours on tops of the Desert Creek zone (A), lower Desert Creek mound (B), lower Desert Creek clean carbonate (C), and Chimney Rock shale (D), Bug field, San Juan County, Utah.

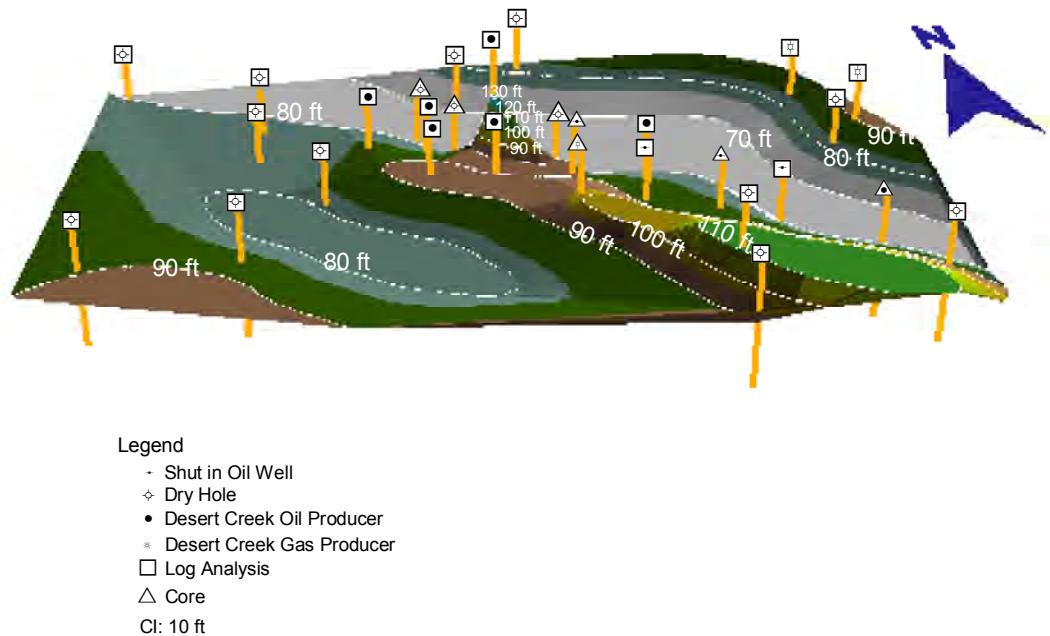


Figure 25. Three-dimensional model of the isochore of the Desert Creek zone, Bug field, San Juan County, Utah.

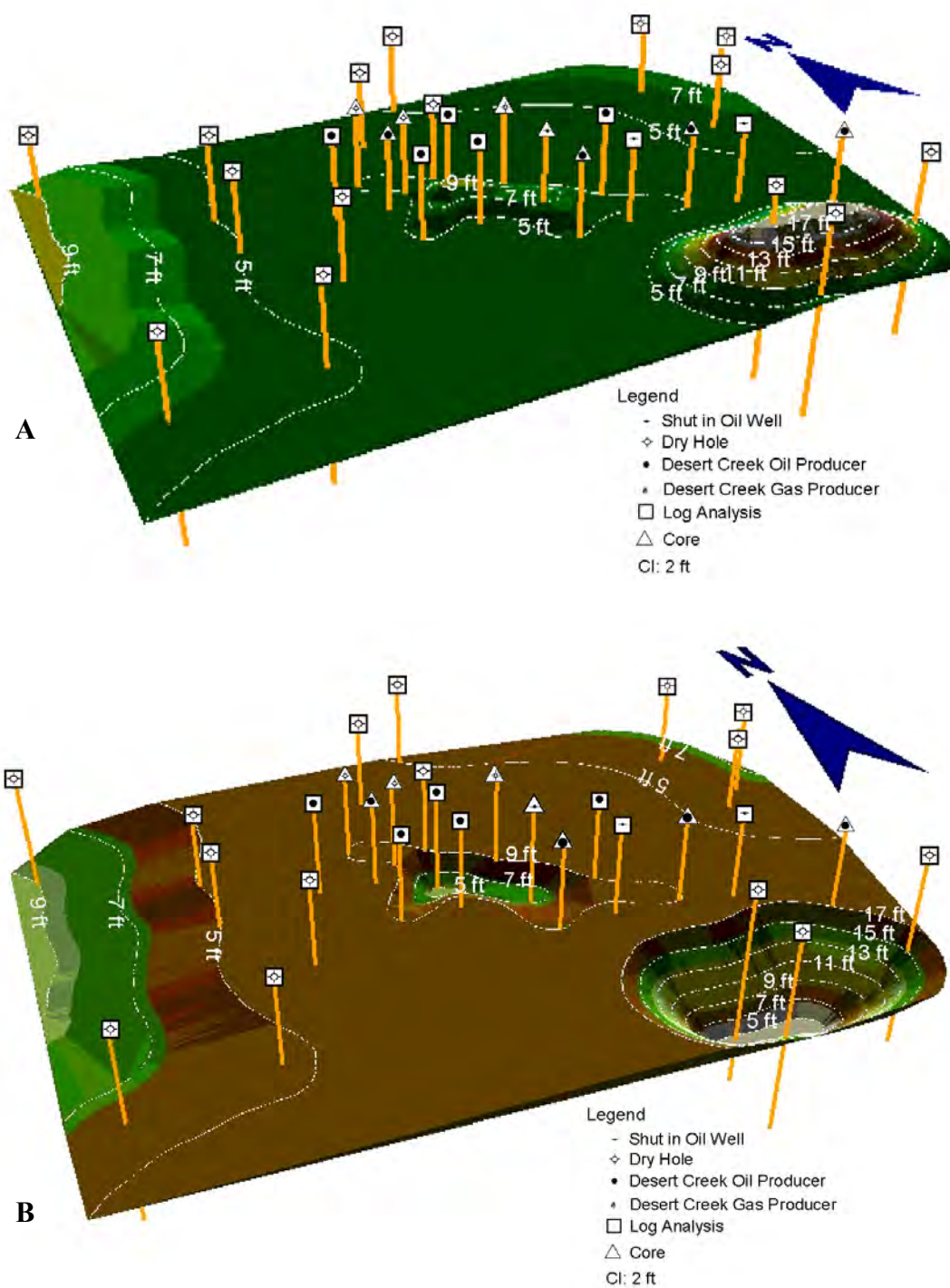


Figure 26. Three-dimensional models, Bug field, San Juan County, Utah. Lower Desert Creek zone anhydrite isochore (A) and inverted isochore (B).

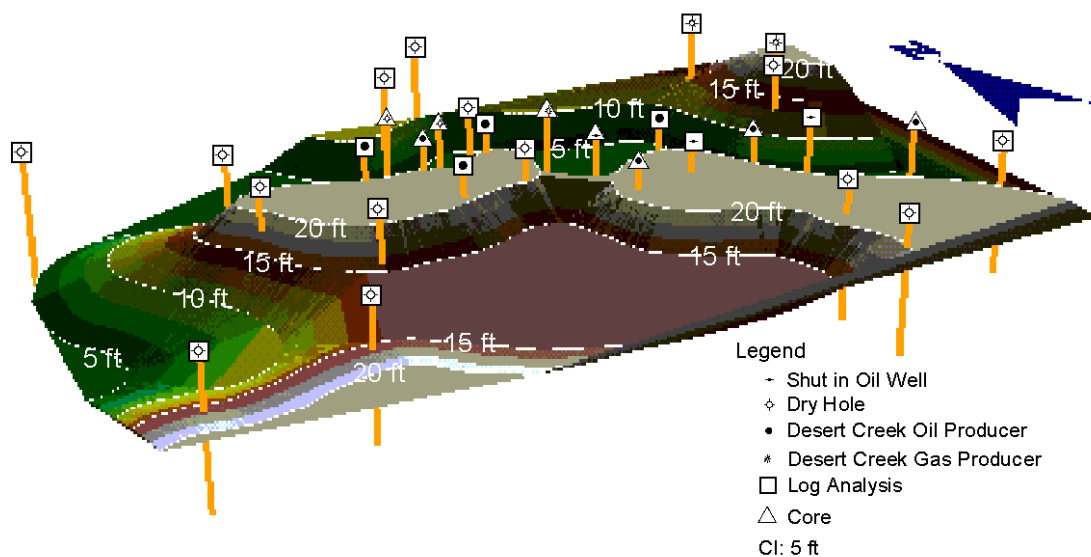


Figure 27. *Three-dimensional model of the isochore of the lower Desert Creek zone clean carbonate, Bug field, San Juan County, Utah.*

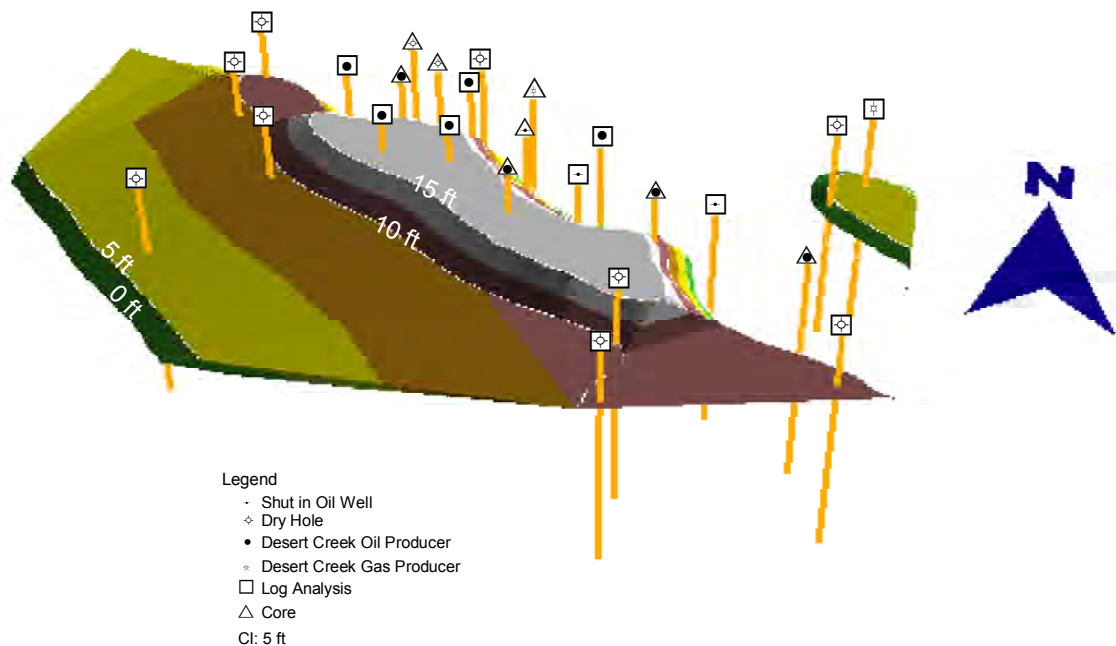


Figure 28. *Three-dimensional model of the isochore of the lower Desert Creek zone mound core, Bug field, San Juan County, Utah.*

The 3-D model of the thickness of the Chimney Rock shale (figure 29) shows a slightly east-west trend. The Chimney Rock varies in thickness only slightly over the area from 14 to 18 feet (5-6 m). Some Bug wells align along a subtle Chimney Rock thickness increase, but in general no particular pattern can be discerned.

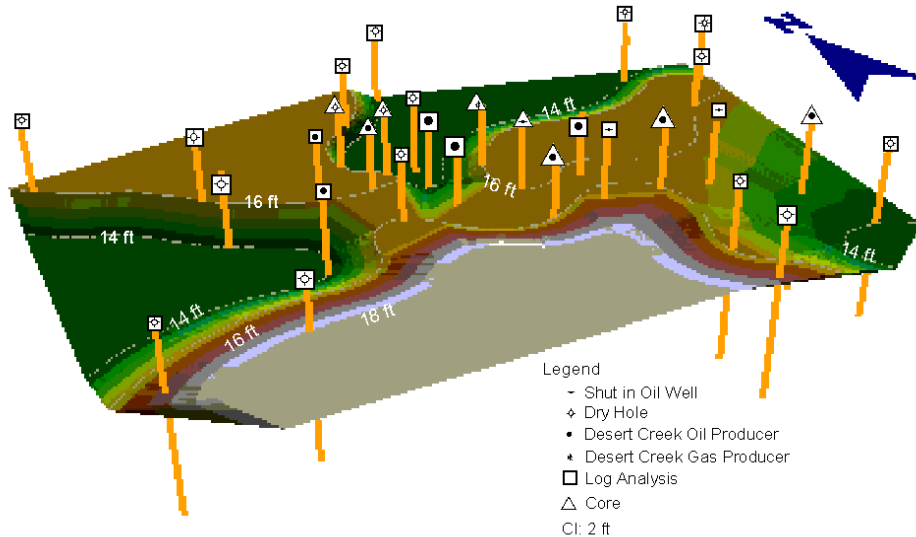


Figure 29. Three-dimensional model of the isochore of the Chimney Rock shale, Bug field, San Juan County, Utah.

The 3-D diagrams of the lower Desert Creek clean carbonate with the net feet of log-derived porosity greater than 10 and 12 percent (determined by geophysical log analysis; figures 30A and 30B) show an elongate reservoir buildup with two subsidiary thickets separated by a slightly thinner saddle that may represent an intermound trough. The northern thick trends generally east-west while the southern thick trends northwest-southeast. At 12 percent porosity, as expected the buildup is thinner and smaller in overall areal extent, but still mimics the general characteristics of the buildup at 10 percent porosity. In both diagrams the porosity pinches out along the northeast flank of the buildup, which when combined with a coincident anticline in the top of the lower Desert Creek zone clean carbonate (figure 24) provides a combination stratigraphic/structural trap. The 3-D diagrams of the lower Desert Creek clean carbonate with the net feet of core-derived porosity greater than 10 and 12 percent (determined by core analysis; figures 31A and 31B) also show an elongate reservoir buildup, but one that is narrower and thinner than its counterpart based on geophysical log analysis. No subsidiary buildups or saddles are present; the top of the buildup is flat. The buildup trends west-northwest to east-southeast. In both diagrams the entire carbonate buildup is bounded by a porosity pinchout and represents a stratigraphic trap.

The 3-D models of the lower Desert Creek clean carbonate with the net feet of core-derived permeability greater than 2 mD (figure 32A), greater than 10 mD (figure 32B), and greater than 50 mD (figure 32C), portray a buildup very similar to that constructed for net feet of porosity greater than 10 and 12 percent by core analysis (figures 31A and 31B). In both diagrams the entire carbonate buildup is defined by a permeability pinchout and trends west-northwest to east-southeast. At permeability greater than 2 mD (figure 32A), there is a subsidiary buildup in the northwestern part of the reservoir. At permeability greater than 10 and 50 mD (figures 32B and 32C), the thinner buildups depict two subsidiary thickets divided by an even thinner saddle.

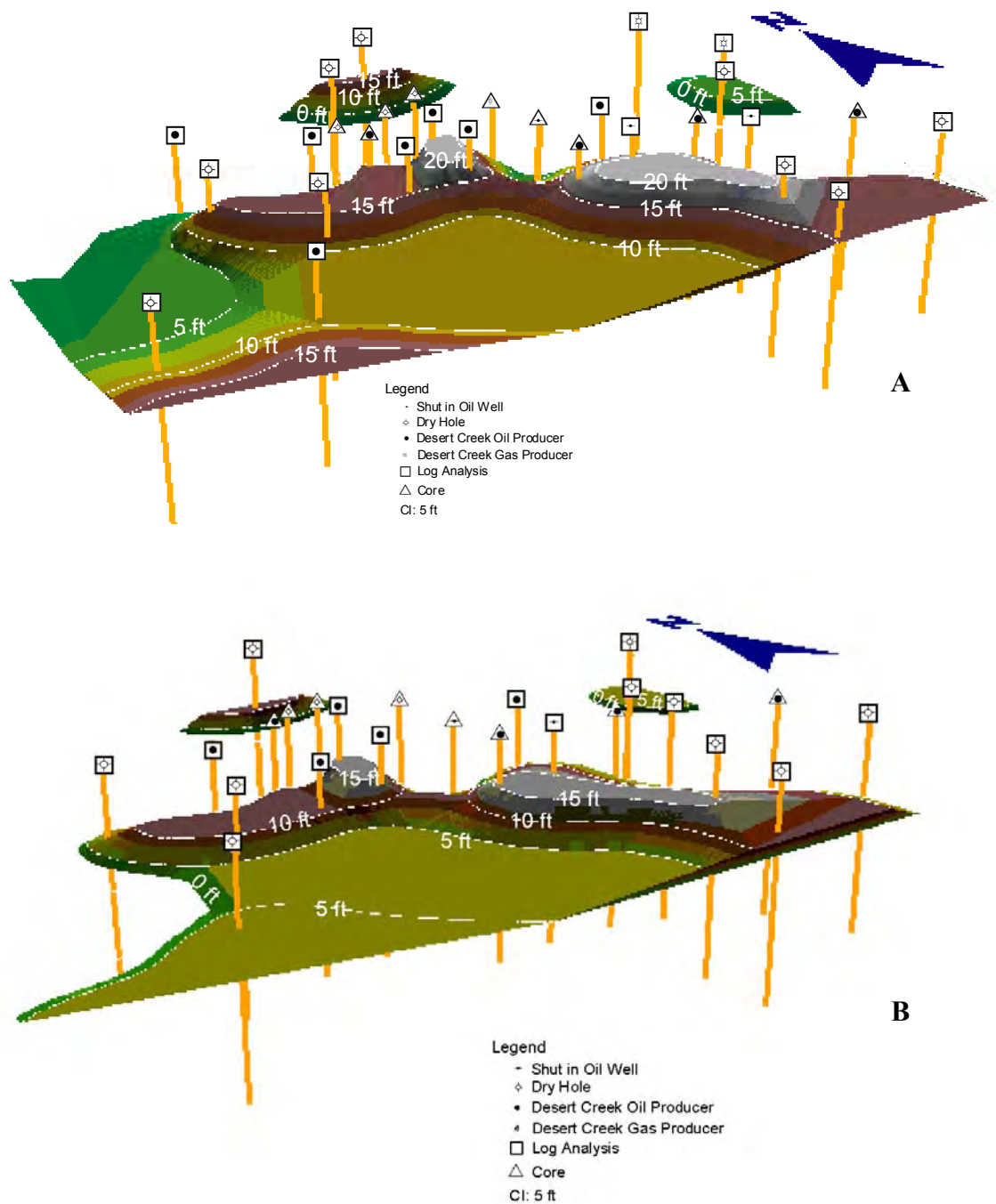


Figure 30. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of porosity, as determined by geophysical log analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Bug field, San Juan County, Utah.

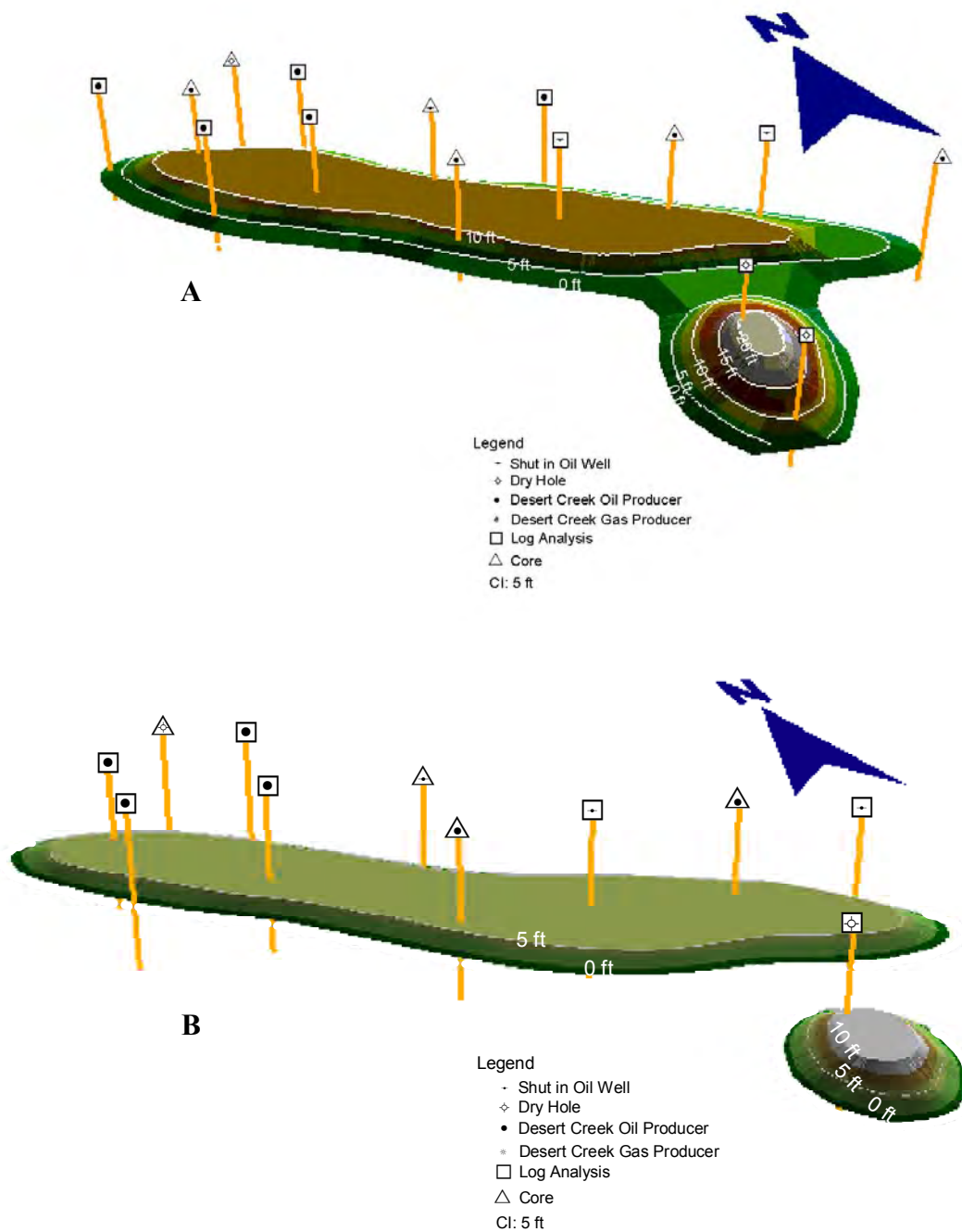


Figure 31. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of porosity, as determined by core analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Bug field, San Juan County, Utah.

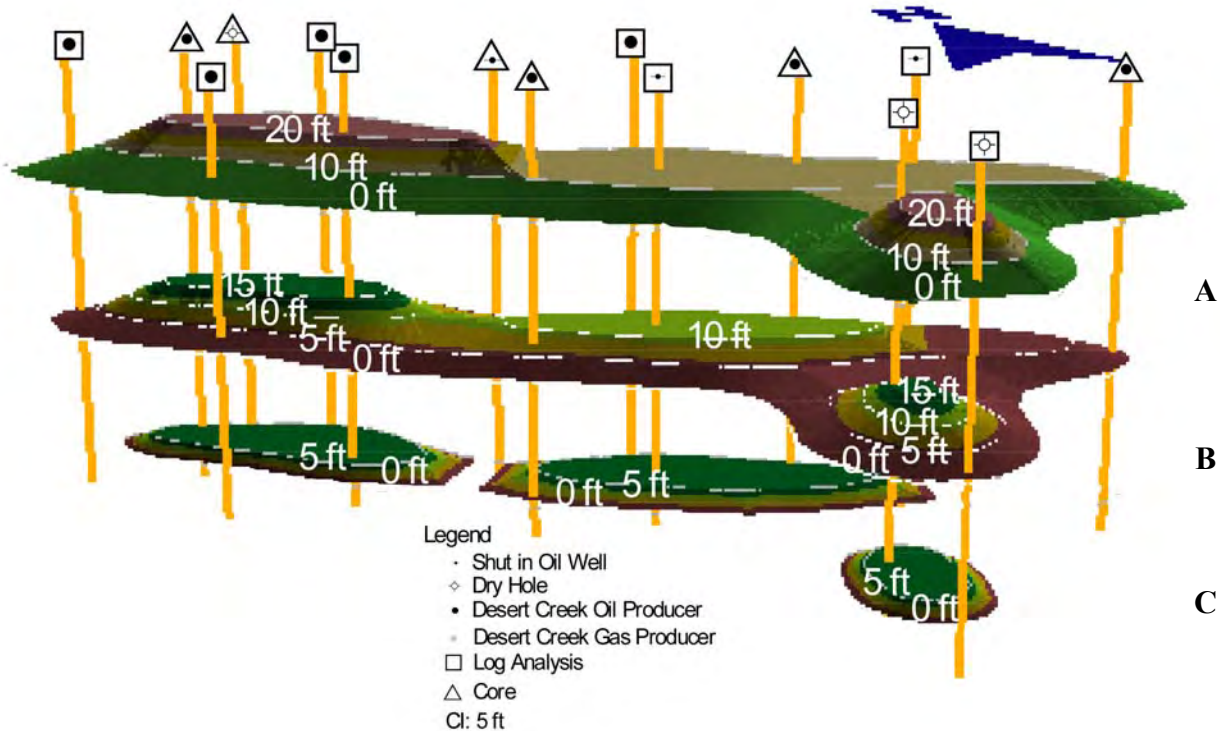


Figure 32. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of permeability, as determined by core analysis, for greater than 2 mD (A), greater than 10 mD (B), and greater than 50 mD (C), Bug field, San Juan County, Utah.

Lower Desert Creek clean carbonate with net feet of dolomite (figure 33) was determined by core analysis. The extent of the 3-D diagram is limited due to the lack available cores in the area. Characteristic of the Desert Creek zone in the Blanding sub-basin, dolomite is the dominant lithology. The 3-D thickness diagram shows a large, northwest-southeast-trending buildup of dolomite within Bug field (figure 33). Not surprisingly, the buildup is divided into two subsidiary 30-foot- (10 m) thick areas separated by a saddle of 20 feet (7 m) thick.

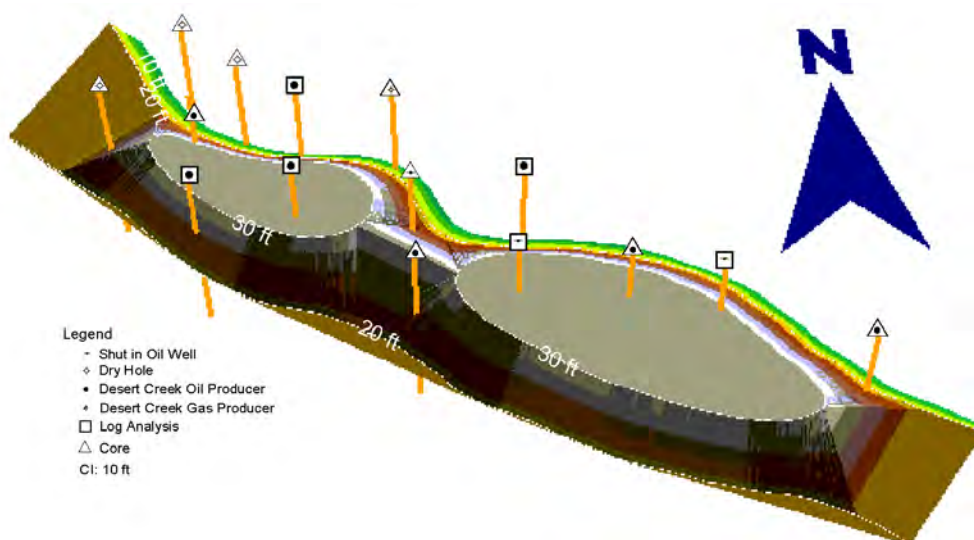


Figure 33. Three-dimensional model, lower Desert Creek zone clean carbonate net feet of dolomite, Bug field, San Juan County, Utah.

RESERVE CALCULATIONS – RESULTS AND DISCUSSION

ArcView® was also used to calculate reservoir surface areas and volumes. Surface areas were measured along the slope of a surface, taking height into consideration. The surface area (feet squared) reported was that on the surface that falls above or below the specified height and converted to acres. The volume operation calculates the cubic space between a TIN surface and the horizontal plane located at the specified height. Volumes (cubic feet) were determined either above or below the plane. In the case-study fields, reservoir volumes were determined above planes representing the oil/water or high proved water contacts. Volumes were first converted to acre-feet and then oil and gas recovery factors (in barrels and MCF per acre-foot, respectively) were applied to calculate reserves (tables 2 and 3).

Cherokee Field

Reservoir volumes (in acre-feet) (table 2) were calculated for porosity units 1 through 5 (figures 16 through 18) where the net feet of porosity was greater than 10 and 12 percent (figure 20). Recovery factors of 20 BO and 380 MCFG per acre-foot, respectively, were derived from Crawley-Stewart and Riley (1993). We applied these recovery factors to the various upper Ismay volumes to determine the primary oil and gas recovery volumes (table 2). Cumulative production as of January 1, 2004, was 182,464 BO and 3.67 BCFG (Utah Division of Oil, Gas and Mining, 2003). No single porosity unit can account for the volume of hydrocarbons produced. Therefore, all five or some combination of two or more porosity units are contributing, with porosity unit 5 being the largest followed by porosity unit 4, 2, 3, and 1 (table 2). The total volume of porosity units 1 through 5 (figure 18B) is 17,522 acre-feet, and this volume was calculated to contain over 350,000 BO and 6.6 BCFG primary recovery. Based on these calculations, the remaining recoverable oil and gas reserves are nearly 168,000 BO and 3 BCFG. Using a price of \$30/bbl and \$4/MCFG, the unrisks value of the remaining recoverable reserves is over \$5 million and \$11 million for oil and gas, respectively.

Extending the porosity cutoff down to porosity greater than 10 percent increases the combined volumes of porosity units 1 through 5 to 19,374 acre-feet, suggesting the presence of additional undrained zones (microporosity). This increase in reservoir volume amounts to an additional 37,000 BO and 0.7 BCFG that may be present in the upper Ismay zone in Cherokee field. However, our primary recovery volume for the net feet of porosity greater than 12 percent was less than the combined primary oil recovery volume of porosity units 1 through 5 as calculated earlier (table 2).

Bug Field

Reservoir volumes were calculated for the lower Desert Creek zone clean carbonate at Bug field (table 3). These include volumes for net feet of porosity greater than 10 percent both by geophysical log analysis (figure 30A) and by core analysis (figure 31A), and volumes for net feet of permeability greater than 2 mD and 10 mD (figures 32A and 32B, respectively). Recovery factors of 41 BO and 103 MCFG per acre-foot, respectively, were derived from Oline (1996). We applied these recovery factors to the various lower Desert Creek clean carbonate volumes to determine the primary oil and gas recovery volumes (table 3). Cumulative production as of January 1, 2004, was 1,622,455 BO and 4.48 BCFG (Utah Division of Oil, Gas and Mining, 2003).

Table 2. Reservoir calculations, upper Ismay zone, Cherokee field, San Juan County, Utah.

NAME	VOLUME (AC FT)	OIL RECOVERY FACTOR (BBL/AC FT)*	PRIMARY OIL VOLUME RECOVERY (BBL)	GAS RECOVERY FACTOR (MCF/AC FT)*	PRIMARY GAS VOLUME RECOVERY (MCF)	CUMULATIVE FIELD OIL PRODUCTION (BBL) AS OF 1/01/04*	REMAINING RECOVERABLE OIL (BBL)	UNRISKED OIL VALUE BASED ON \$30 PER BBL	CUMULATIVE FIELD GAS PRODUCTION (MCF) AS OF 1/01/04**	REMAINING RECOVERABLE GAS (MCF)	UNRISKED GAS VALUE BASED ON \$4 PER MCF
Porosity Unit 1	699	20	13,975	380	265,528	ND	--	--	ND	--	--
Porosity Unit 2	4060	20	81,207	380	1,542,941	ND	--	--	ND	--	--
Porosity Unit 3	2117	20	42,348	380	804,607	ND	--	--	ND	--	--
Porosity Unit 4	4123	20	82,464	380	1,566,825	ND	--	--	ND	--	--
Porosity Unit 5	6523	20	130,454	380	2,478,620	ND	--	--	ND	--	--
Total of Porosity Units 1-5	17,522	20	350,448	380	6,658,521	182,464	167,984	\$5,039,520	3,667,068	2,991,453	\$11,965,812
Net Feet of Porosity (>10% by LA)	19,374	20	387,474	380	7,362,015	182,464	205,010	\$6,150,300	3,667,068	3,694,947	\$14,779,788
Net Feet of Porosity (>12% by LA)	14,650	20	293,001	380	5,567,017	182,464	110,537	\$3,316,110	3,667,068	1,899,949	\$7,599,796

*Crawley-Stewart and Riley, 1993.

**Utah Division of Oil, Gas & Mining,

December 2003.

LA = log analysis

ND = no data

Table 3. Reservoir calculations, lower Desert Creek zone, Bug field, San Juan County, Utah.

NAME	VOLUME (AC FT)	OIL RECOVERY FACTOR (BBL/AC FT)*	PRIMARY OIL VOLUME RECOVERY (BBLs)	GAS RECOVERY FACTOR (MCF/AC FT)*	PRIMARY GAS VOLUME RECOVERY (MCF)	CUMULATIVE FIELD OIL PRODUCTION (BBLs) AS OF 1/01/04**	REMAINING RECOVERABLE OIL (BBLs)	UNRISKED OIL VALUE BASED ON \$30 PER BBL	CUMULATIVE FIELD GAS PRODUCTION (MCF) AS OF 1/01/04**	REMAINING RECOVERABLE GAS (MCF)	UNRISKED GAS VALUE BASED ON \$4 PER MCF
Clean Carbonate Net Feet of Porosity (>10% by LA)	99,057	41	4,061,352	103	10,202,909	1,622,455	2,438,897	\$73,166,910	4,483,368	5,719,541	\$22,878,164
Clean Carbonate – Porosity Thickness (>10% by core analysis)	42,621	41	1,747,465	103	4,389,974	1,622,455	125,010	\$3,750,300	4,483,368	0	0
Clean Carbonate Net Feet of Permeability (kh>2 mD)	64,027	41	2,625,105	103	6,594,775	1,622,455	1,002,650	\$30,079,500	4,483,368	2,111,407	\$8,445,628
Clean Carbonate Net Feet of Permeability (kh>10 mD)	41,746	41	1,711,568	103	4,299,794	1,622,455	89,113	\$2,673,390	4,483,368	0	0

* Oline, 1996.

**Utah Division of Oil, Gas & Mining, December
2003.

LA = log analysis

The volume calculated for net feet porosity greater than 10 percent by log analysis (99,057 acre-feet) is over twice that by core analysis (42,621 acre-feet). This may be a function of more data provided by well logs than by core, or that porosity determined from geophysical well logs is considerably optimistic. This suggests the presence of additional undrained zones (micro-box-work porosity). The bottom line is that from log analysis, the lower Desert Creek clean carbonate may contain recoverable oil and gas reserves of nearly 2,440,000 BO and 5.7 BCFG. Again, using prices of \$30/BO and \$4/MCFG, the unrisks value of the remaining reserves is over \$73 million and \$22 million for oil and gas, respectively. However, for the porosity volume calculated from core analysis, only about 125,000 BO remain having an unrisks value of \$3.75 million. Theoretically, there are no remaining gas reserves using the calculated volume.

The volumes calculated for net feet of permeability also show significant differences (table 3). As expected, the net feet greater than 2 mD yielded an optimistically high volume (64,027 acre-feet) with remaining recoverable reserves of 1,000,000 BO and 2.1 BCFG, at an unrisks value of \$30 million and \$8.4 million, respectively. At 10 mD, the clean carbonate volume was a third lower (41,746 acre-feet) than at 2 mD, with about 89,000 BO at an unrisks value of \$2.7 million. Again, theoretically, there are no remaining gas reserves using the calculated volume.

ACKNOWLEDGEMENTS

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