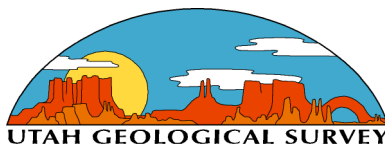


**HETEROGENEOUS SHALLOW-SHELF CARBONATE
BUILDUPS IN THE PARADOX BASIN,
UTAH AND COLORADO: TARGETS FOR INCREASED
OIL PRODUCTION AND RESERVES USING
HORIZONTAL DRILLING TECHNIQUES**
(Contract No. DE-2600BC15128)

**DELIVERABLE 1.2.3
SCANNING ELECTRON MICROSCOPY
AND PORE CASTING:
CHEROKEE AND BUG FIELDS,
SAN JUAN COUNTY, UTAH**

Submitted by

Utah Geological Survey
Salt Lake City, Utah 84114
December 2003



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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).

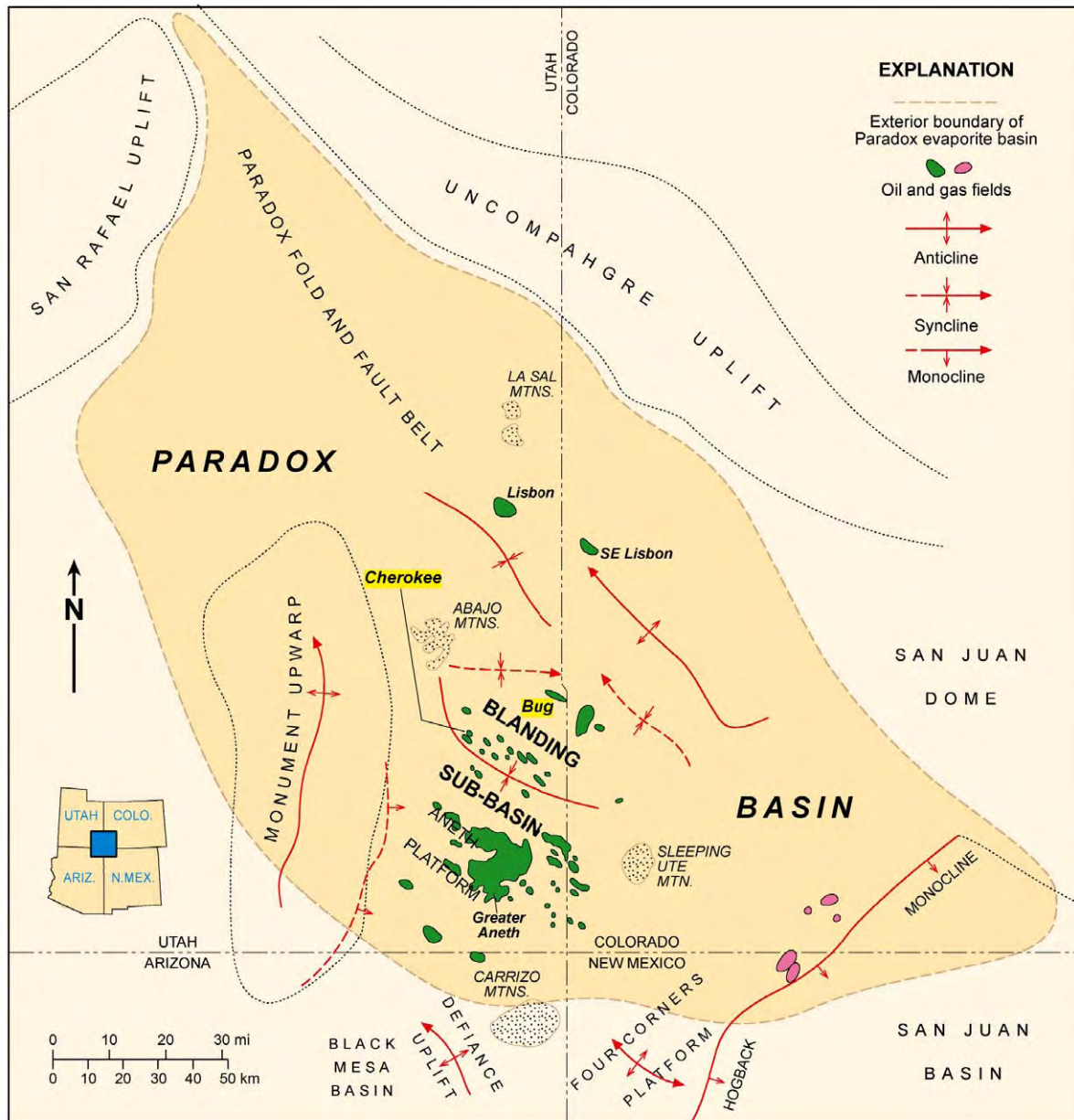
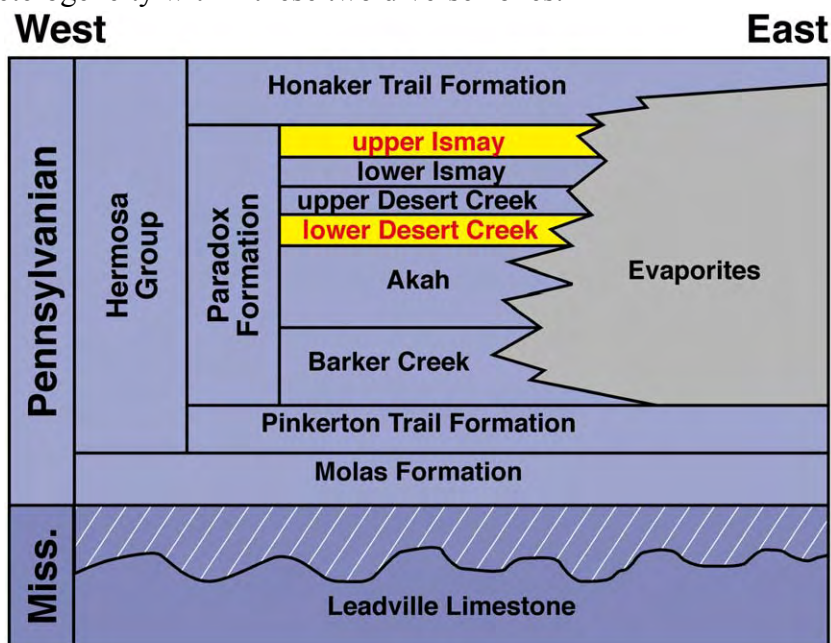


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

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; the Ismay and Desert Creek zones productive in the case-study fields described in this report are highlighted.



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 scanning electron microscopy (SEM) and pore casting from selected samples in these fields as 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).

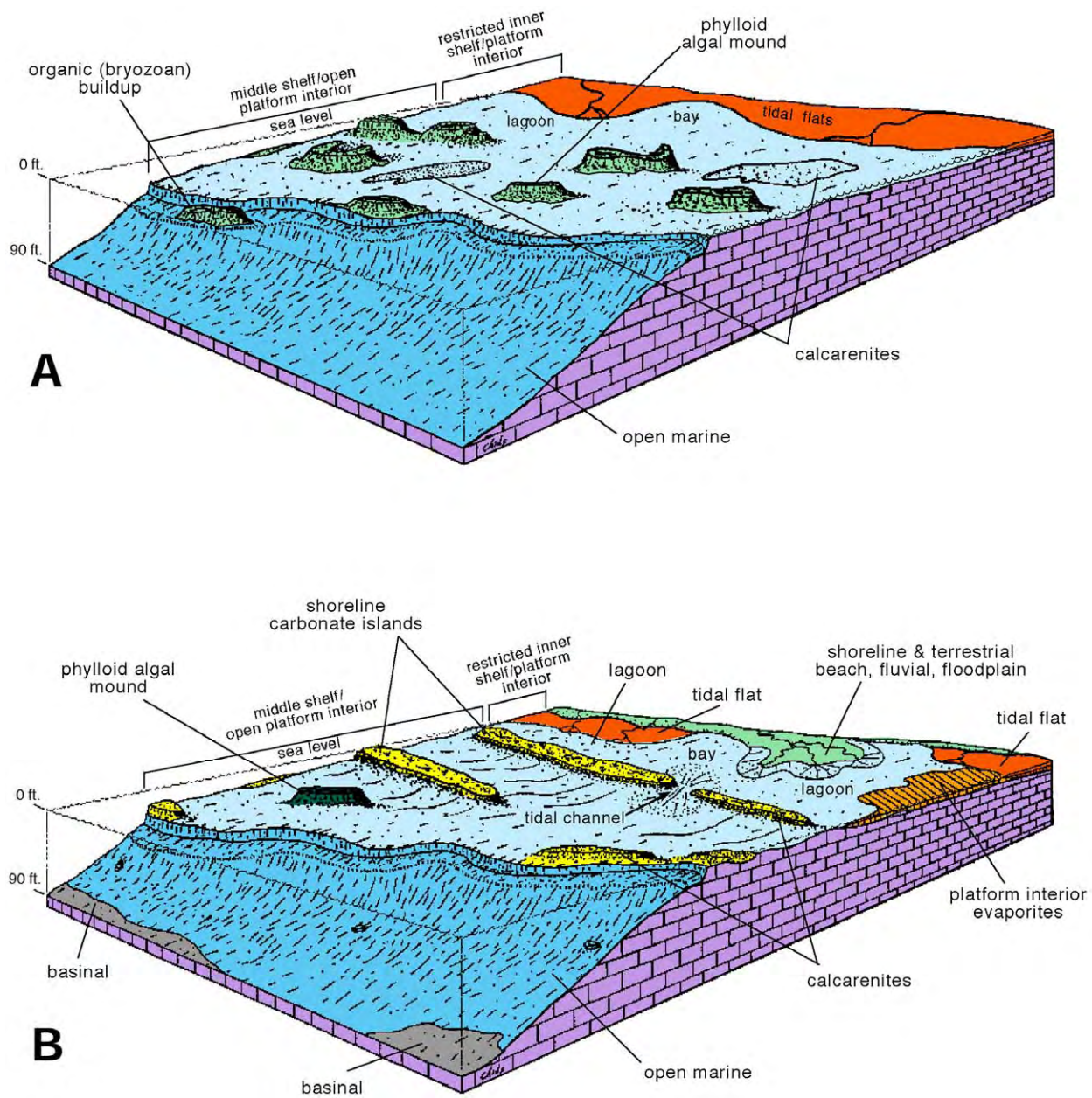


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

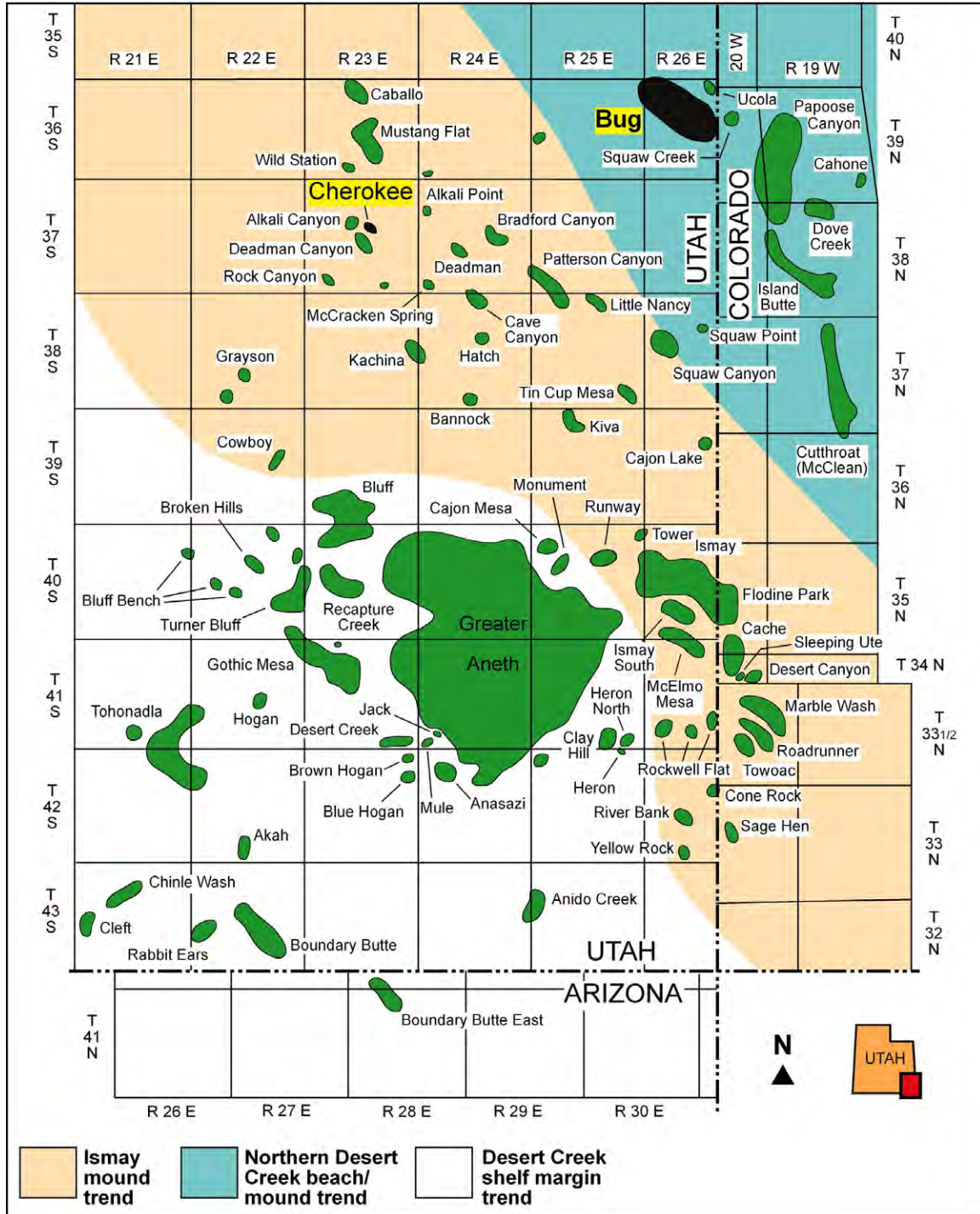


Figure 4. Map showing the project study area and fields (case-study fields in black) within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

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 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 June 1, 2003, was 182,071 barrels of oil ($28,949 \text{ m}^3$), 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 ($27,348 \text{ m}^3$) and 3.28 BCFG (0.09 BCMG) (Crawley-Stewart and Riley, 1993). The fact that both these estimates have been surpassed suggests significant additional reserves could remain.

Bug Field

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

Bug field was discovered in 1980 with the completion of the Wexpro Bug No. 1, NE1/SE1/4 section 12, T. 36 S., R. 25 E., SLBL&M, for an 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 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 June 1, 2003, was 1,622,202 barrels of oil ($257,901 \text{ m}^3$), 4.47 BCFG (0.13 BCMG), and 3,181,448 barrels of water ($505,850 \text{ m}^3$) (Utah Division of Oil, Gas and Mining, 2003). Estimated primary recovery is 1,600,000 bbls ($254,400 \text{ m}^3$) 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.

SCANNING ELECTRON MICROSCOPY AND PORE CASTING

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Cherokee and Bug fields can be indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. In order to determine the diagenetic histories of the various Ismay and Desert Creek reservoirs, representative samples were selected from the suite of 44 samples taken from conventional cores of each field, which were used for thin sections. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. A scanning electron microscope (SEM) was used to photograph: (1) typical preserved primary and secondary pore types and pore throats, (2) cements, (3) sedimentary structures, (4) fractures, and (5) pore plugging anhydrite, halite, and bitumen.

Pore casting is a special technique where the carbonate matrix of an epoxy impregnated thin section blank is dissolved by hydrochloric acid. What remains is only the epoxy that represents the entire pore system of the sample (pores and pore throats). The pore cast is then coated with gold, and studied and photographed with the SEM (the same method as if it were the actual thin section blank).

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

Scanning electron microscope and/or pore casting analyses were conducted on eight thin section blanks from core samples that displayed particular characteristics of interest (table 1 and appendix). The objectives of this study were to: (1) characterize the cements present, (2) characterize the types of porosity present, and (3) identify diagenetic events. The results are summarized in table 2. Porosity types and associated abbreviations included in this report are from Choquette and Pray (1970) (figure 5). Some porosity descriptions provided here vary from those determined by thin section analysis reported by Chidsey and others (2001) and in Deliverable 1.2.1A – Thin Section Descriptions. The descriptions presented in this report are from SEM examination and measurement only.

Table 1. List of samples examined in this study and the characteristics of interest.

Well	Depth	SEM	Pore Casting	Characteristics of Interest
Cherokee 22-14	5768.7	X	X	Microporosity dolomite with bitumen
Cherokee 22-14	5827.7	X		Moldic porosity and micro-crystalline dolomite
Cherokee 33-14	5773.9	X		Dolomite, microporosity and moldic porosity, relatively low porosity and permeability
Cherokee 33-14	5781.2	X	X	Microporosity only dolomite, high porosity and permeability
May Bug 2	6304	X	X	Micro-box-work dolomite/hollow dolomite fabric
May Bug 2	6312B	X		B - (second sample) botryoidal cement/dolomite
May Bug 2	6315A	X	X	A – yellow internal sediment/dolomite
Bug 4	6289.7	X	X	Microporosity/with bitumen and micro-box-work dolomite
TOTAL	-	8	5	-
















Porosity Types

All samples exhibit microporosity in the form of intercrystalline (BC) microporosity (figure 6) and micro-box-work porosity (figure 7). Microporosity represents an important site for untapped hydrocarbons and possible targets for horizontal drilling. Dissolution has contributed to porosity in most samples (figure 6). It has created moldic (MO), vuggy (VUG), and channel (CH) porosity. Dissolution pores are most often in the mesopore size range.

Table 2. Summary of porosity, cement, and diagenetic characters of samples examined.

WELL	Cherokee 22-14		Cherokee 33-14		May Bug 2 **			Bug 4
DEPTH (ft)	5768.7'	5826.7'	5773.9'	5781.2'	6304.0'	6312.0' B	6315.0' A	6289.7'
POROSITY								
Intergranular (Micro) (BC)	X	X	X	X	X	X	X	X
Dissolution (MO)	X	X	X			X		
Dissolution (VUG)	X				X	X		X
Dissolution (CH)	X	X	X					X
Fractures	X				X			X
CEMENTS								
Anhydrite	X	X	X			X		X
Calcite		X	X			X		
Quartz		X	X	X		X		
Dolomite					X			
Smectite	X	X	X					
Pyrobitumen	X	X	X	X				
DIAGENESIS								
Botryoidal Calcite Deposition					X	X	X	X
Dolomitization	X	X	X	X	X	X	X	X
Dissolution	X	X	X	X	X	X		X
Calcite Cementation		X	X					
Quartz Cementation		X	X	X		X		
Smectite Deposition	X	X	X	X				
Anhydrite Cementation	X	X	X			X		X
Pyrobitumen Emplacement	X	X	X	X				
Fracturing					X			

** Limited observation of the 6312-foot B specimen.

BASIC POROSITY TYPES					
FABRIC SELECTIVE			NOT FABRIC SELECTIVE		
	INTERPARTICLE	BP		FRACTURE FR	
	INTRAPARTICLE	WP		CHANNEL *	CH
	INTERCRYSTAL	BC		VUG *	VUG
	MOLDIC	MO		CAVERN *	CV
	FENESTRAL	FE	*Cavern applies to man-sized or larger pores of channel or vug shapes.		
	SHELTER	SH			
	GROWTH-FRAMEWORK	GF			
FABRIC SELECTIVE OR NOT					
	BRECCIA BR		BORING BO		BURROW BU
					SHRINKAGE SK

MODIFYING TERMS						
GENETIC MODIFIERS				SIZE * MODIFIERS		
PROCESS		DIRECTION OR STAGE		CLASSES		
SOLUTION	s	ENLARGED	x	MEGAPORE mg	mm [†]	
CEMENTATION	c	REDUCED	r		large lmg	256
INTERNAL SEDIMENT	i	FILLED	f	small smg	32	
				MESOPORE ms	large lms	4
					small sms	1/2
				MICROPORE mc		1/16
TIME OF FORMATION				Use size prefixes with basic porosity types:		
PRIMARY		P		mesovug	msVUG	
pre-depositional		Pp		small mesomold	smsMO	
depositional		Pd		microinterparticle	mcBP	
SECONDARY		S		* For regular-shaped pores smaller than cavern size.		
eogenetic		Se		† Measures refer to average pore diameter of a single pore or the range in size of a pore assemblage. For tubular pores use average cross-section. For platy pores use width and note shape.		
mesogenetic		Sm				
telogenetic		St				
Genetic modifiers are combined as follows:				ABUNDANCE MODIFIERS		
[PROCESS] + [DIRECTION] + [TIME]				percent porosity (15%)		
EXAMPLES: solution-enlarged sx				or		
cement-reduced primary crP				ratio of porosity types (1:2)		
sediment-filled eogenetic ifSe				or		
				ratio and percent (1:2) (15%)		

Figure 5. Classification of pores and pore systems in carbonate rocks (Choquette and Pray, 1970).

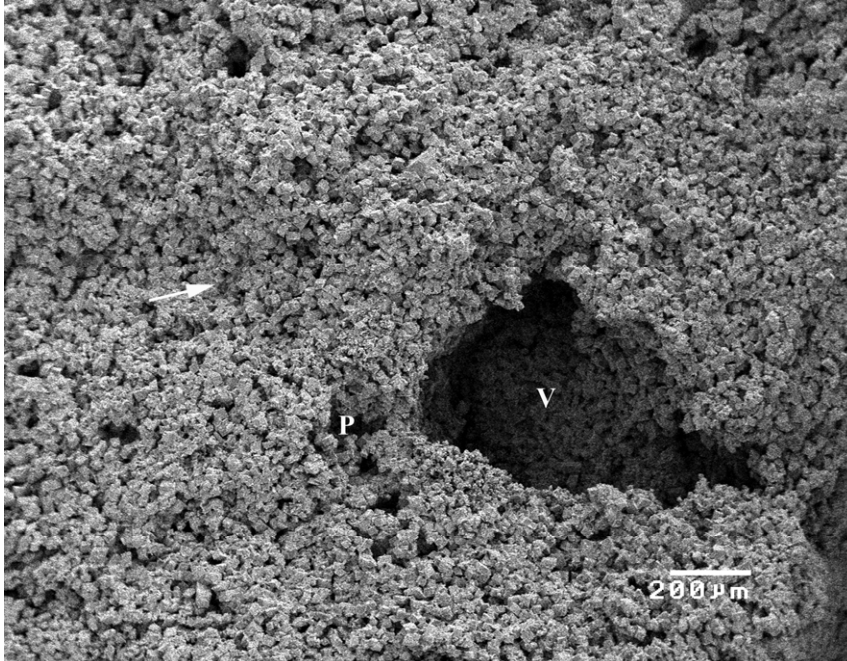


Figure 6. Scanning electron microscope photomicrograph of a core plug from 5,768.7 feet, Cherokee no. 22-14 well. Dolomite exhibits three porosity types: intercrystalline microporosity – BC (arrow); moldic microporosity – MO (P); and a large mesovug – msVUG (V). Oil drainage is mainly from macro- and mesopores, but not from micropores (BC). Scale represents 200 microns (0.2 mm). Porosity = 22.9 percent; permeability = 215 millidarcies based on core-plug analysis.

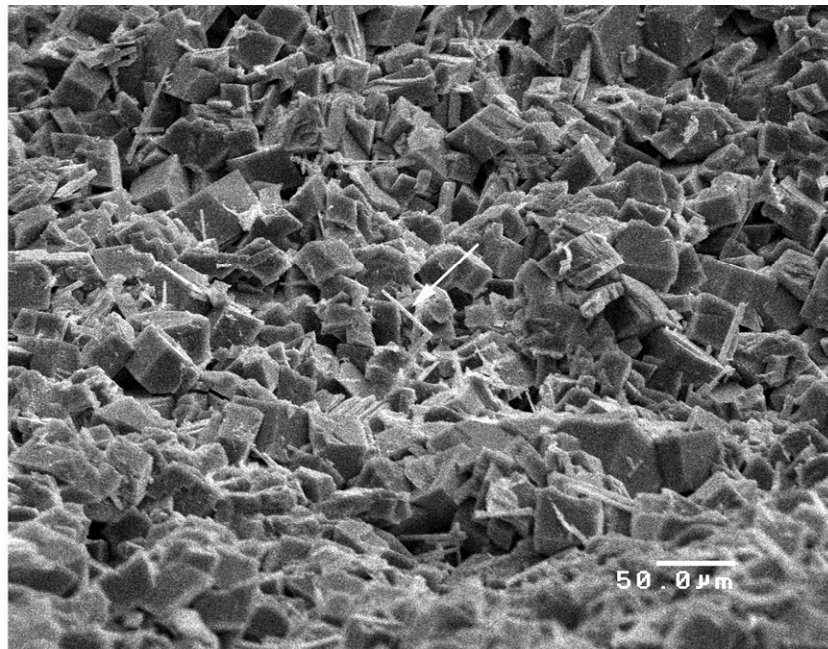


Figure 7. Scanning electron microscope photomicrograph of a core plug from 6,315 feet, May Bug no. 2 well, showing dolomite with intercrystalline microporosity – BC (black). Fragments (lathes) (arrow) of dolomite represent partially dissolved dolomite rhombs present within a yellow portion of the sample. The collapse and/or crushing of dolomite rhombs within the internal hollow dolomite sediment indicate early dolomitization and early meteoric dissolution resulting in micro-boxwork porosity. Scale represents 50 microns (0.05 mm). Porosity = 10.3 percent; permeability = 5.7 millidarcies based on core-plug analysis.

Permeability is related to the size and number of pore throats, and, particularly, to the continuity of pore throats (figures 8 and 9). Pore cast examination reveals the presence of “dead end” pore throats that undoubtedly limit permeability. In general, permeability is limited in these samples by the presence of such pore throats, as well as the presence of cements, pyrobitumen, and tight dissolution remnants.

Fractures enhance the permeability in three samples: the sample from 5,768.7-feet (1,758.2-m) in the Cherokee no. 22-14 well; the sample from 6,304-feet (1,921-m) in the May Bug no. 2 well (figure 10); and the sample from 6,289.7-feet (1,917.0-m) in the Bug no. 4 well (figure 11). The permeability of these three samples is among the highest of those examined.

Lithology, Cements, and Diagenesis

All samples contain dolomite (figure 6 and 12). Anhydrite, calcite, smectite clays, and pyrobitumen are present in some samples. The dominant cement occluding porosity and permeability in the Cherokee wells is anhydrite (figure 13). Although we did not observe anhydrite in the sample from 5,781.2-feet (1,762.0-m) in the Cherokee no. 33-14 well, thin section analyses of this interval and other samples from the well suggest that it is present.

Porosity reduction in the Bug wells is the result of tight areas that consist of former calcite cements that have been dolomitized. Anhydrite contributes to porosity and permeability reduction in these wells, too, as anhydrite is present in the sample from 6,312-feet (1,924-m) in the May Bug no. 2 well and the sample from 6,289.7-feet (1,917.0-m) in the Bug no. 4 well. Pyrobitumen is common in many samples lining pores and plugging pore throats (figure 14).

Calcite (figure 15) and quartz (figure 16) are very rare, but are present in the Cherokee wells and in one sample (6,312 feet [1,924 m]) of the May Bug no. 2 well. Smectite clay is present (figure 15), but is also extremely rare. It is visible in the Cherokee wells only. The minor constituents of calcite, quartz, and smectite contribute little to the overall lithology and are relatively insignificant to reservoir quality.

The general diagenetic sequence for these samples, based on SEM and pore casting analyses, is listed below (not all diagenetic events were identified in every sample). The various diagenetic events are included in table 2.

1. Deposition of calcite cement
2. Dissolution
3. Dolomitization
4. Dissolution
5. Fracturing
6. Calcite cementation
7. Quartz cementation
8. Clay deposition
9. Anhydrite cementation
10. Pyrobitumen emplacement

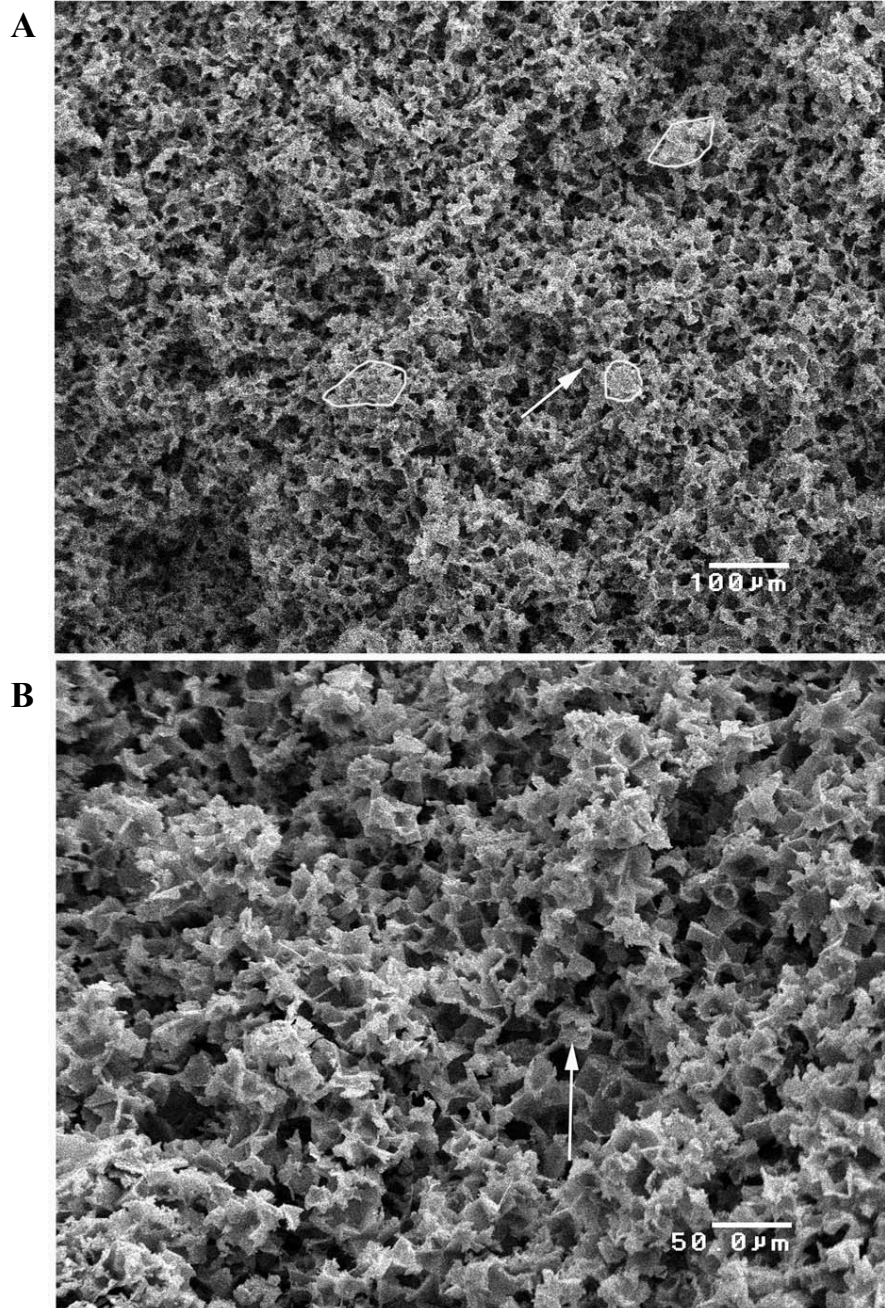


Figure 8. Scanning electron microscope photomicrograph of a pore cast from 5,768.7 feet, Cherokee no. 22-14 well. (A) The overall intercrystalline microporosity – BC (arrow) is relatively uniform. A few larger micropores are visible (outline). Note that the solid areas (light gray) represent porosity and the open areas (dark gray to black) represent matrix. Scale represents 100 microns (0.1 mm). (B) Enlargement of (A) showing microporosity. Impressions of dolomite rhombs are visible (arrow). Scale represents 50 microns (0.05 mm). Porosity = 22.9 percent; permeability = 215 millidarcies based on core-plug analysis.

Figure 9. Scanning electron microscope photomicrograph of a pore cast from 6,304 feet, May Bug no. 2 well. Sheet-like linear pores - MO - are associated with phylloid-algal fronds. Note that the solid areas represent porosity. Scale represents 333 microns (0.333 mm). Porosity = 10.9 percent; permeability = 99 millidarcies based on core-plug analysis.

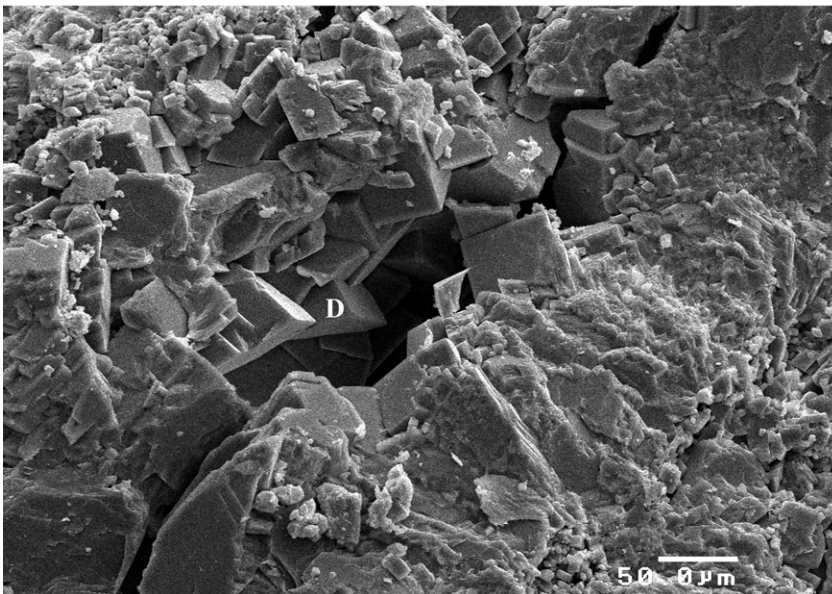
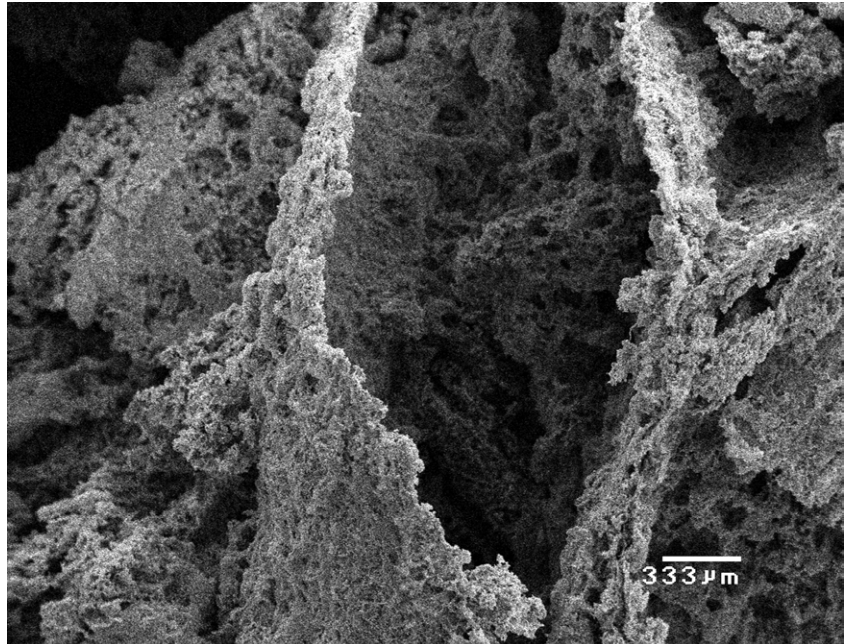


Figure 10. Scanning electron microscope photomicrograph of a core plug from 6,304 feet, May Bug no. 2 well, showing a fracture pore and dolomite (D) within it. This demonstrates that the fracture was open during dolomite deposition. Scale represents 50 microns (0.5 mm). Porosity = 10.9 percent; permeability = 99 millidarcies based on core-plug analysis.

Figure 11. Scanning electron microscope photomicrograph of a pore cast from 6,289.7 feet, Bug no. 4 well, showing pattern of intersecting fractures in a tight portion of the sample. The linear feature in the upper right may represent artificially bent fracture-filling epoxy. The circular feature is a grain. Note that the solid areas represent porosity. Scale represents 333 microns (0.333 mm). Porosity = 14.5 percent; permeability = 92 millidarcies based on core-plug analysis.

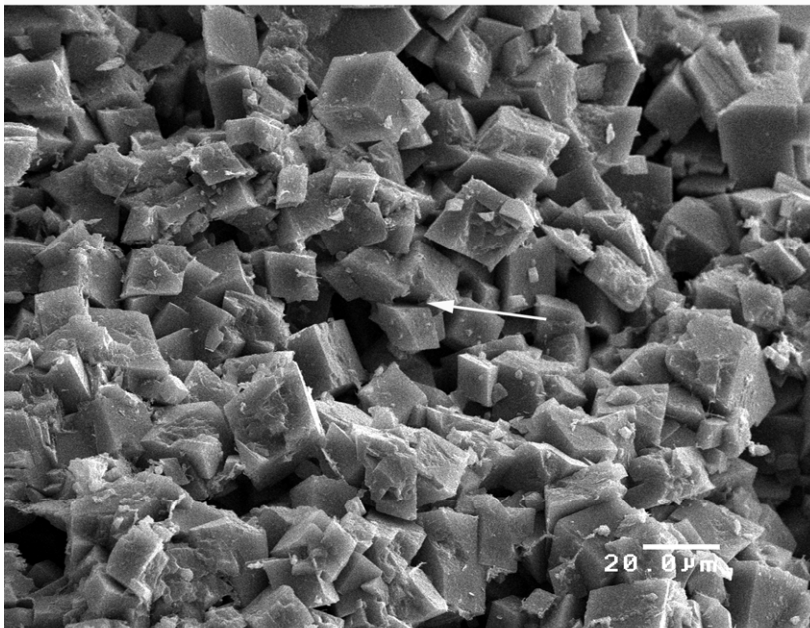
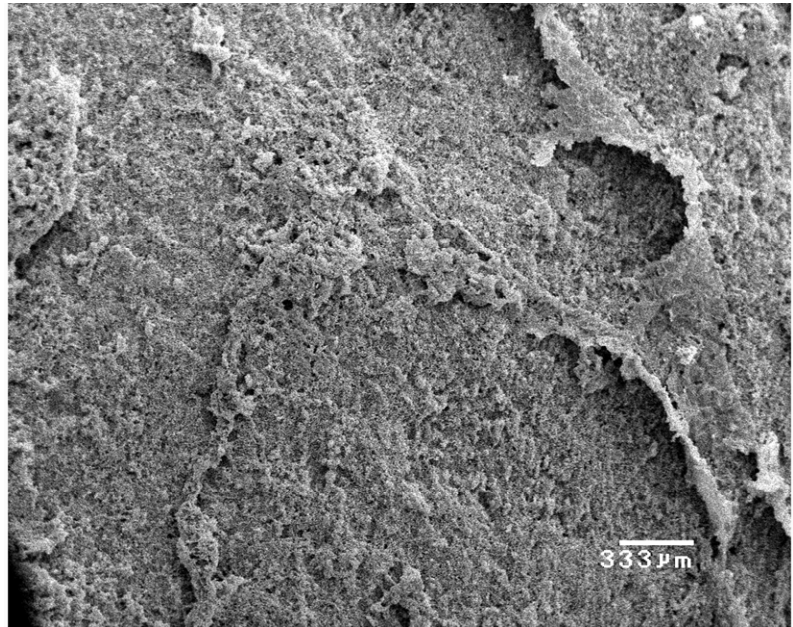


Figure 12. Scanning electron microscope photomicrograph of a core plug from 5,781.2 feet, Cherokee no. 33-14 well, showing well-developed dolomite rhombs exhibiting abundant intercrystalline microporosity – BC (arrow). Scale represents 20 microns (0.02 mm). Porosity = 23.6 percent; permeability = 103 millidarcies based on core-plug analysis.

Figure 13. Scanning electron microscope photomicrograph of a core plug from 5,827.7 feet, Cherokee no. 22-14 well, showing dolomite with a mesovug – msVUG (V) and visible anhydrite (A) cement, smaller mesopores (P), and intercrystalline micropores – BC (arrow). Scale represents 50 microns (0.05 mm). Porosity = 17.1 percent; permeability = 4.5 millidarcies based on core-plug analysis.

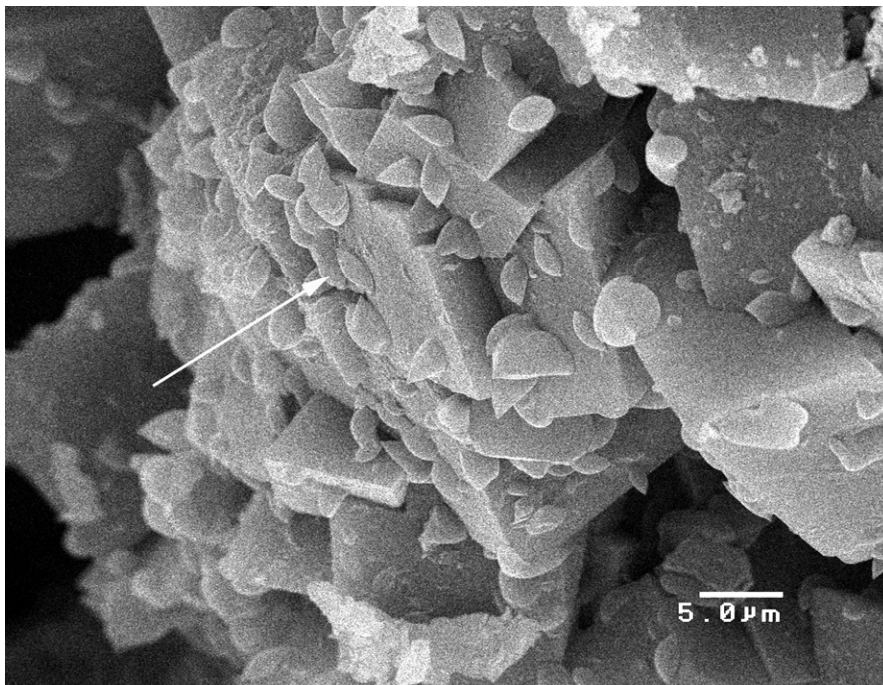
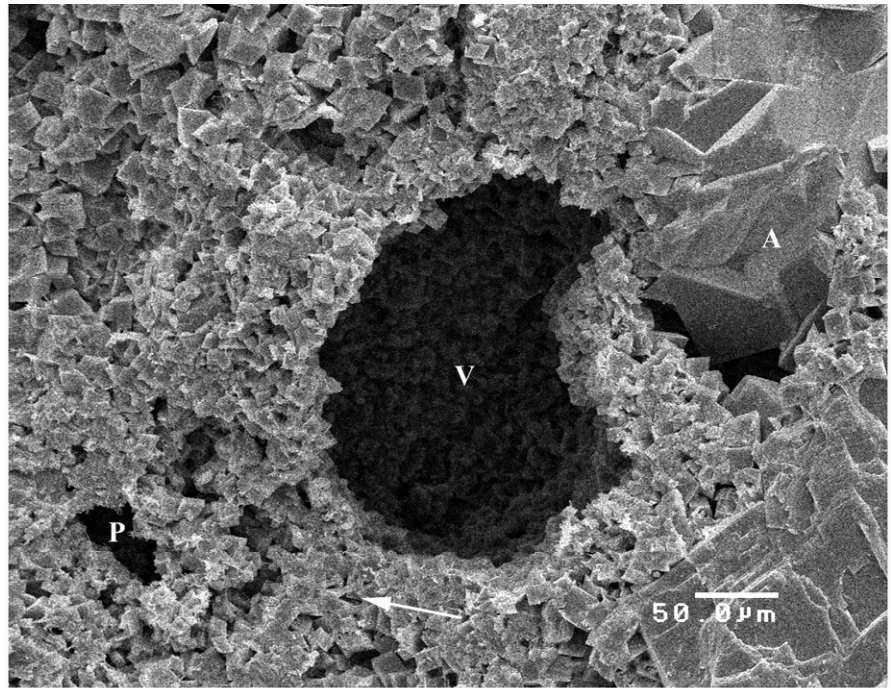


Figure 14. Scanning electron microscope photomicrograph of a core plug from 5,768.7 feet, Cherokee no. 22-14 well, showing pyrobitumen (arrow) on dolomite, within a microfracture. Micropores are black areas. Scale represents 5 microns (0.005 mm). Porosity = 22.9 percent; permeability = 215 millidarcies based on core-plug analysis.

Figure 15. Scanning electron microscope photomicrograph of a core plug from 5,827.7 feet, Cherokee no. 22-14 well, showing equant spar calcite (C), a burial cement, as well as minor smectite clay (arrow) present in a large moldic (MO) pore on the dolomite. Scale represents 20 microns (0.02 mm). Porosity = 17.1 percent; permeability = 4.5 millidarcies based on core-plug analysis.

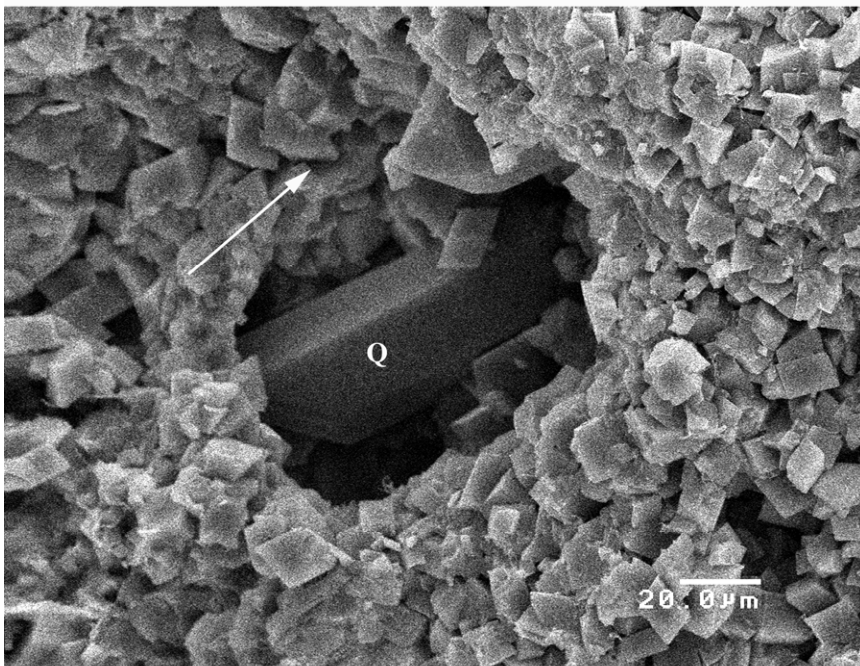
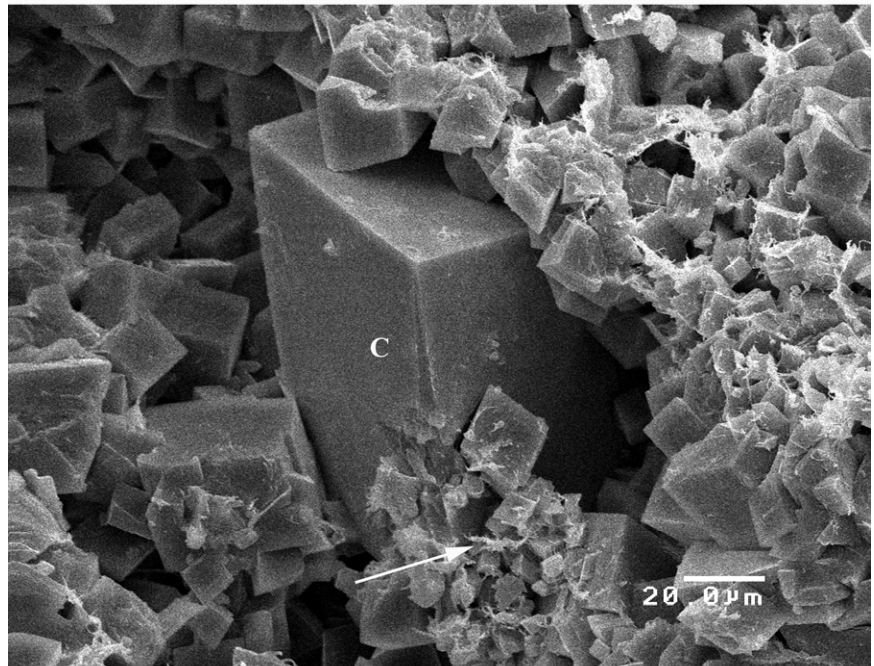


Figure 16. Scanning electron microscope photomicrograph of a core plug from 5,773.9 feet, Cherokee no. 33-14 well, showing authigenic quartz crystal (Q) within a mesovug - msVUG. Note the presence of intercrystalline microporosity - BC (arrow). Scale represents 20 microns (0.02 mm). Porosity = 19.1 percent; permeability = 11 millidarcies based on core-plug analysis.

ACKNOWLEDGEMENTS

Core and petrophysical data were provided by Burlington Resources, Seeley Oil Company, and Wexpro Company. Jim Parker and Cheryl Gustin of the Utah Geological Survey prepared the figures. The report was reviewed by David Tabet and Mike Hylland of the Utah Geological Survey. Cheryl Gustin, Utah Geological Survey, formatted the manuscript for publication.

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