MAJOR OIL PLAYS IN UTAH AND VICINITY

QUARTERLY TECHNICAL PROGRESS REPORT

Reporting Period
Start Date: January 1, 2006
End Date: March 31, 2006

by
Thomas C. Chidsey, Jr., Principal Investigator
Utah Geological Survey

UTAH GEOLOGICAL SURVEY

July 2006

Contract No. DE-FC26-02NT15133

Submitting Organization: Utah Geological Survey
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DISCLAIMER

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ABSTRACT

Utah oil fields have produced over 1.2 billion barrels (191 million m^3) of oil and hold 241 million barrels (38.3 million m^3) of proved reserves. The 13.7 million barrels (2.2 million m^3) of production in 2002 was the lowest level in over 40 years and continued the steady decline that began in the mid-1980s. However, in late 2005 production increased due to the discovery of Covenant field in the central Utah Navajo Sandstone thrust belt play. The Utah Geological Survey believes this new upward production trend can continue by providing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. Oil plays are geographic areas with petroleum potential caused by favorable combinations of source rock, migration paths, reservoir rock characteristics, and other factors. The play portfolios will include descriptions and maps of the major oil plays by reservoir; production and reservoir data; case-study field evaluations; locations of major oil pipelines; identification and discussion of land-use constraints; descriptions of reservoir outcrop analogs; and summaries of the state-of-the-art drilling, completion, and secondary/tertiary recovery techniques for each play.

This report covers research activities for the fifteenth quarter of the project (January 1 through March 31, 2006). This work included (1) describing the Blanding sub-basin Desert Creek zone, Blanding sub-basin Ismay zone, and Aneth platform Desert Creek zone subplays of the Pennsylvanian Paradox Formation Play in the Paradox Basin, and (2) technology transfer activities.

The most prolific oil and gas play in the Paradox Basin is the Pennsylvanian Paradox Formation play. The Paradox Formation has produced over 500 million barrels (80 million m^3) of sweet, paraffinic oil and 650 billion cubic feet of gas (18 billion m^3) from more than 70 fields. The main producing zones are referred to as the Desert Creek and Ismay. The Paradox Formation Play is divided into four subplays: (1) fractured shale, (2) Blanding sub-basin Desert Creek zone, (3) Blanding sub-basin Ismay zone, and (4) Aneth platform Desert Creek zone.

In Pennsylvanian time, the Paradox Basin was rapidly subsiding in a subtropical arid environment with a shallow-water carbonate shelf on the south and southwest margins of the basin that locally contained carbonate buildups, commonly phylloid-algal mounds. Traps types include stratigraphic, stratigraphic with some structural influence, combination stratigraphic/structural, and diagenetic. The Paradox Formation has heterogeneous reservoir properties because of depositional lithofacies with varying porosity and permeability, carbonate buildup (mound) relief and flooding surfaces (parasequence boundaries), and diagenetic effects.

Mapping the Ismay-zone lithofacies delineates very prospective reservoir trends that contain productive carbonate buildups around anhydrite-filled intra-shelf basins. Mapping also indicates a relatively untested lithofacies belt of calcarenite carbonate deposits south and southeast of Greater Aneth field.

Technology transfer activities during this quarter consisted of presentations on the central Utah thrust belt Navajo Sandstone oil play and a publication. An abstract on best practices in the Green River Formation play, Uinta Basin, was submitted and accepted by the American Association of Petroleum Geologists, for presentation at the 2006 Rocky Mountain Section meeting in Billings, Montana. Project team members joined Utah Stake Holders Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

Utah oil fields have produced over 1.2 billion barrels (191 million m^3) of oil and hold 241 million barrels (38.3 million m^3) of proved reserves. The 13.7 million barrels (2.2 million m^3) of production in 2002 was the lowest level in over 40 years and continued the steady decline that began in the mid-1980s. However, in late 2005 production increased due to the discovery of Covenant field in the central Utah Navajo Sandstone thrust belt play. The overall objectives of this study are to (1) continue adding new discoveries, (2) increase recoverable oil from existing field reservoirs, (3) prevent premature abandonment of numerous small fields, (4) increase deliverability through identifying the latest drilling, completion, and secondary/tertiary recovery techniques, and (5) reduce development costs and risk.

To achieve these objectives, the Utah Geological Survey is producing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. This research is partially funded by the Preferred Upstream Management Program (PUMPII) of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research activities for the fifteenth quarter of the project (January 1 through March 31, 2006). This work included (1) describing the Blanding sub-basin Desert Creek zone, Blanding sub-basin Ismay zone, and Aneth platform Desert Creek zone subplays of the Pennsylvanian Paradox Formation Play in the Paradox Basin, and (2) technology transfer activities.

A combination of depositional and structural events created the right conditions for oil generation and trapping in the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. Oil plays are specific geographic areas having petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors.

The most prolific oil and gas play in the Paradox Basin is the Pennsylvanian Paradox Formation play. The Paradox Formation has produced over 500 million barrels (80 million m^3) of sweet, paraffinic oil and 650 billion cubic feet of gas (18 billion m^3) from more than 70 fields. The main producing zones are referred to as the Desert Creek and Ismay. The Paradox Formation oil play area includes nearly the entire Paradox Basin. The Paradox Formation Play is divided into four subplays: (1) fractured shale, (2) Blanding sub-basin Desert Creek zone, (3) Blanding sub-basin Ismay zone, and (4) Aneth platform Desert Creek zone.

In Pennsylvanian time, the Paradox Basin was rapidly subsiding in a subtropical arid environment with a shallow-water carbonate shelf on the south and southwest margins of the basin that locally contained carbonate buildups. In the Blanding sub-basin, Ismay-zone reservoirs are dominantly limestones composed of small, phylloid-algal buildups; locally variable, inner-shelf, skeletal calcarenites; and rare, open-marine, bryozoan mounds. Desert Creek-zone reservoirs are dominantly dolomite comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts. On the Aneth platform, Desert Creek reservoirs include shallow-shelf buildups (phylloid algal, coralline algal, and bryozoan buildups [mounds]) and calcarenites (beach, dune, and oolite banks). Here, the Desert Creek and Ismay zones are predominately limestone, with local dolomitic units.

Phylloid-algal mound lithofacies in both the Ismay and Desert Creek zones contain large phylloid-algal plates and skeletal grains that create bafflestone or bindstone fabrics. Bryozoan buildup lithofacies are represented by bindstone, bafflestone, and packestone fabrics. Calcarenite lithofacies include grainstone and packstone fabrics containing oolites, coated grains, hard peloids, bioclastic grains, shell lags, and intraclasts.

Traps in the Blanding sub-basin and Aneth platform regions include stratigraphic, stratigraphic with some structural influence, combination stratigraphic/structural, and diagenetic. Many carbonate buildups appear to have developed on subtle anticlinal noses or structural closures. Vertical reservoir seals for the Paradox producing zones are shale, halite, and anhydrite within the formation; lateral seals are permeability barriers created by unfractured, off-mound (non-buildup) mudstone, wackestone, and anhydrite. Hydrocarbons in Paradox Formation reservoirs were generated from source rocks within the formation itself during maximum burial in the Late Cretaceous and early Tertiary. Organic-rich units, informally named the Cane Creek, Chimney Rock, and Gothic shales, are composed of black, sapropelic shale and shaley dolomite.

The Paradox Formation has heterogeneous reservoir properties because of depositional lithofacies with varying porosity and permeability, carbonate buildup (mound) relief and flooding surfaces (parasequence boundaries), and diagenetic effects. The extent of these factors, and how they are combined, affect the degree to which fluid flow barriers are created. Identification and correlation of depositional lithofacies and parasequences in individual Paradox reservoirs is critical to understanding their effect on water/carbon dioxide injection programs, production rates, and paths of petroleum movement. The typical early diagenetic events occurred in the following order: (1) early marine cementation, (2) post-burial, replacement, rhombic dolomite cementation due to seepage reflux, (3) vadose and meteoric phreatic diagenesis including leaching/dissolution, neomorphism, and fresh-water cementation, (4) mixing zone dolomitization, (5) syntaxial cementation, and (6) anhydrite cementation/ replacement. Post-burial diagenesis included additional syntaxial cementation, silicification, late coarse calcite spar, saddle dolomite cementation, stylolitization, additional anhydrite replacement, late dissolution (microporosity development), and bitumen plugging.

Mapping the Ismay zone lithofacies delineates very prospective reservoir trends that contain productive carbonate buildups around anhydrite-filled intra-shelf basins. Lithofacies and reservoir controls imposed by the anhydritic intra-shelf basins should be considered when selecting the optimal location and orientation of any horizontal drilling for undrained reserves. Projections of the inner shelf/tidal flat and mound trends around the intra-shelf basins identify potential exploration targets. Pervasive marine cement may be indicative of “wall” complexes of shallow-shelf carbonate buildups suggesting potential nearby carbonate buildups, particularly phylloid-algal mounds. Platform-margin calcarenites in the Desert Creek zone are located along the margins of the larger shallow shelf or the rims of phylloid-algal buildup complexes. Lithofacies mapping indicates a relatively untested belt of calcarenite carbonate deposits south and southeast of Greater Aneth field.

Technology transfer activities during this quarter consisted of presentations on the central Utah thrust belt Navajo Sandstone oil play to the Iron County (Utah) Comprehensive Land Use Planning Project Working Committee and the Great Basin Historical Society. Project team members joined Utah Stake Holders Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal. An abstract on best practices in the Green River Formation play, Uinta Basin, was submitted and accepted by the American Association of Petroleum Geologists for presentation at the 2006 Rocky Mountain Section meeting in Billings, Montana. The project home page was updated on the Utah Geological Survey Web site. Project team members published a Quarterly Technical Progress Report detailing project work, results, and recommendations.

INTRODUCTION

Project Overview

Utah oil fields have produced over 1.2 billion barrels (bbls) (191 million m^3) (Utah Division of Oil, Gas and Mining, 2006). The 13.7 million barrels (2.2 million m^3) of production in 2002 was the lowest level in over 40 years. However, in late 2005 production increased (figure 1), due to the discovery of Covenant field in the central Utah Navajo Sandstone thrust belt play, and reversed the decline that began in the mid-1980s (Utah Division of Oil, Gas and Mining, 2006). Proven reserves are relatively high, at 215 million bbls (34.2 million m^3) (Energy Information Administration, 2006). With higher oil prices now prevailing, secondary and tertiary recovery techniques should boost future production rates and ultimate recovery from known fields.

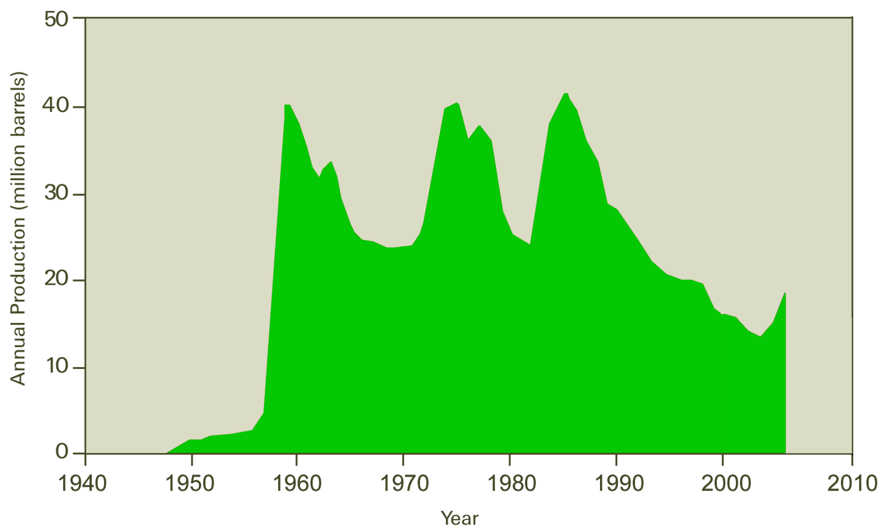


Figure 1. Oil production in Utah through 2005 showing an increase due, in part, to the discovery of Covenant field in the new central Utah thrust belt Jurassic Navajo Sandstone play. Source: Utah Division of Oil, Gas and Mining production records.

Utah's drilling history has fluctuated greatly due to discoveries, oil and gas price trends, and changing exploration targets. Utah has entered another boom period rivaling the early 1980s. In 2005, the Utah Division of Oil, Gas and Mining issued a record 1629 drilling permits and 876 wells were spudded. Sustained high petroleum prices are providing the economic climate needed to entice more high-risk exploration investments (more wildcats), resulting in new discoveries.

Utah still contains large areas that are virtually unexplored. There is also significant potential for increased recovery from existing fields by employing improved reservoir characterization and the latest drilling, completion, and secondary/tertiary recovery technologies. New exploratory targets may be identified from three-dimensional (3D) seismic surveys. Development of potential prospects is within the economic and technical capabilities of both major and independent operators.

The primary goal of this study is to increase recoverable oil reserves from existing field reservoirs and new discoveries by providing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming (figure 2). These play portfolios will include descriptions (such as stratigraphy, diagenetic analysis, tectonic setting, reservoir characteristics, trap type, seal, and hydrocarbon source) and maps of the major oil plays by reservoir; production and reservoir data; case-study field evaluations; summaries of the state-of-the-art drilling, completion, and secondary/tertiary techniques for each play; locations of major oil pipelines; and descriptions of reservoir outcrop analogs for each play. Also included will be an analysis of land-use constraints on development, such as wilderness or roadless areas, and national parks within oil plays.

This report covers research activities for the fifteenth quarter of the project (January 1 through March 31, 2006). This work included (1) describing the Blanding sub-basin Desert Creek zone, Blanding sub-basin Ismay zone, and Aneth platform Desert Creek zone subplays of the Pennsylvanian Paradox Formation Play in the Paradox Basin, and (2) technology transfer activities.

Project Benefits

The overall goal of this multi-year project is enhanced petroleum production in the Rocky Mountain region. Specific benefits expected to result from this project include the following:

(1) improved reservoir characterization to prevent premature abandonment of numerous small fields in the Paradox and Uinta Basins,

(2) identification of the type of untapped compartments created by reservoir heterogeneity (for example, diagenesis and abrupt facies changes) to increase recoverable reserves,

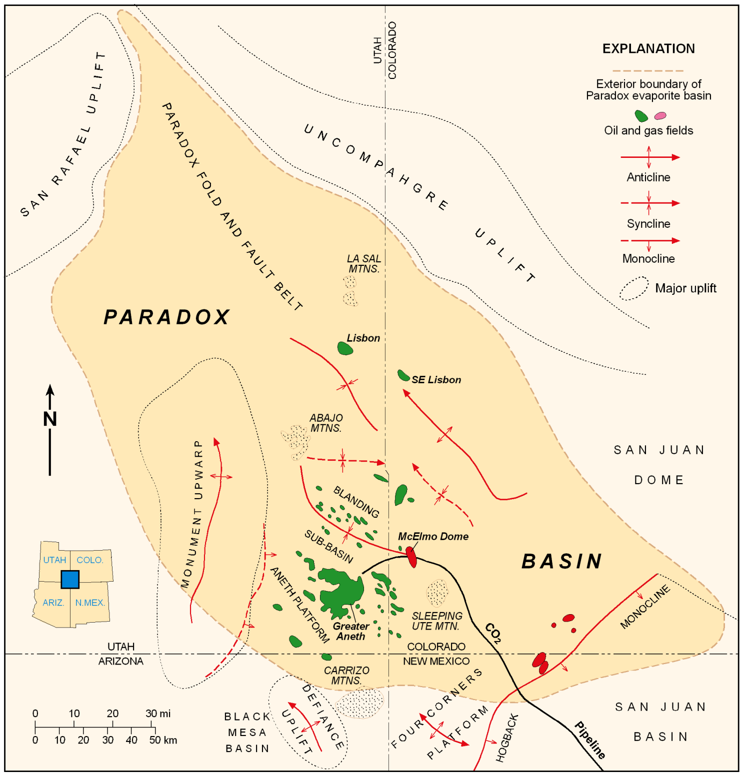
(3) identification of the latest drilling, completion, and secondary/tertiary techniques to increase deliverability,

(4) identification of reservoir trends for field extension drilling and stimulating exploration in undeveloped parts of producing fairways,

(5) identification of technology used in other basins or producing trends with similar types of reservoirs that might improve production in Utah,

(6) identification of optimal well spacing/location to reduce the number of wells needed to successfully drain a reservoir, thus reducing development costs and risk, and allowing more productive use of limited energy investment dollars, and

(7) technology transfer to encourage new development and exploration efforts, and increase royalty income to the federal, state, local, Native American, and fee owners.



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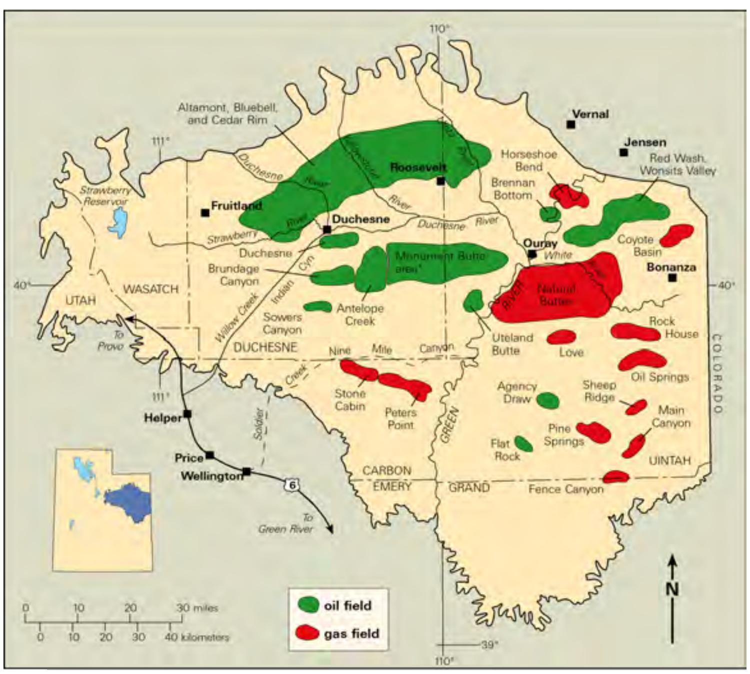

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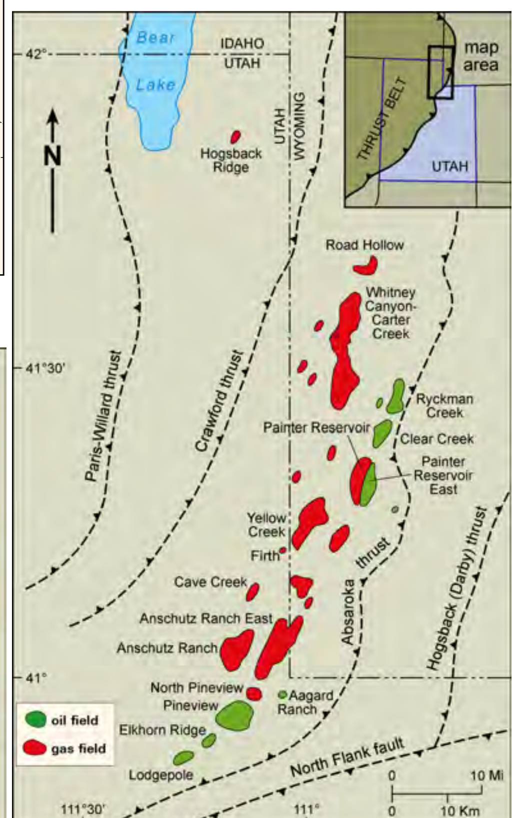


C

Figure 2. Major oil-producing provinces of Utah and vicinity. A - Oil and gas fields in the Paradox Basin of Utah and Colorado (modified from Harr, 1996). B - Oil and gas fields in the Uinta Basin of Utah. C - Oil and gas fields, uplifts, and major thrust faults in the Utah-Wyoming thrust belt.

The Utah play portfolios produced by this project will provide an easy-to-use geologic, engineering, and geographic reference to help petroleum companies plan exploration, land-acquisition strategies, and field development. These portfolios may also help pipeline companies plan future facilities and pipelines. Other users of the portfolios will include petroleum engineers, petroleum land specialists, landowners, bankers and investors, economists, utility companies, manufacturers, county planners, and numerous government agencies.

The results of this project will be transferred to industry and other interested parties through establishment of Technical Advisory and Stake Holders Boards, an industry outreach program, and technical presentations at national and regional professional society meetings. All of this information will be made public through (1) the Utah Geological Survey (UGS) Web site, (2) an interactive, menu-driven digital product on compact disc, and (3) hard-copy publications in various technical or trade journals and UGS publications.

PENNSYLVANIAN PARADOX FORMATION, PARADOX BASIN PLAY – DISCUSSION AND RESULTS

Paradox Basin Overview

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with small portions in northeastern Arizona and the northwestern corner of New Mexico (figure 2A). 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). The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1986, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian when a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a consequence 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 (uplift) 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 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. The form of the Paradox Basin was strongly influenced by rejuvenation of pre-existing (late Precambrian), northwesterly trending structures (Baars and Stevenson, 1981). 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 (figures 3 and 4) (Hintze, 1993). Deposition in the basin produced a thick cyclical sequence of carbonates, evaporates, and organic-rich shale (Peterson and Hite, 1969; Hite and others, 1984). The Paradox Basin is defined by the maximum extent of anhydrite beds in the Paradox Formation.

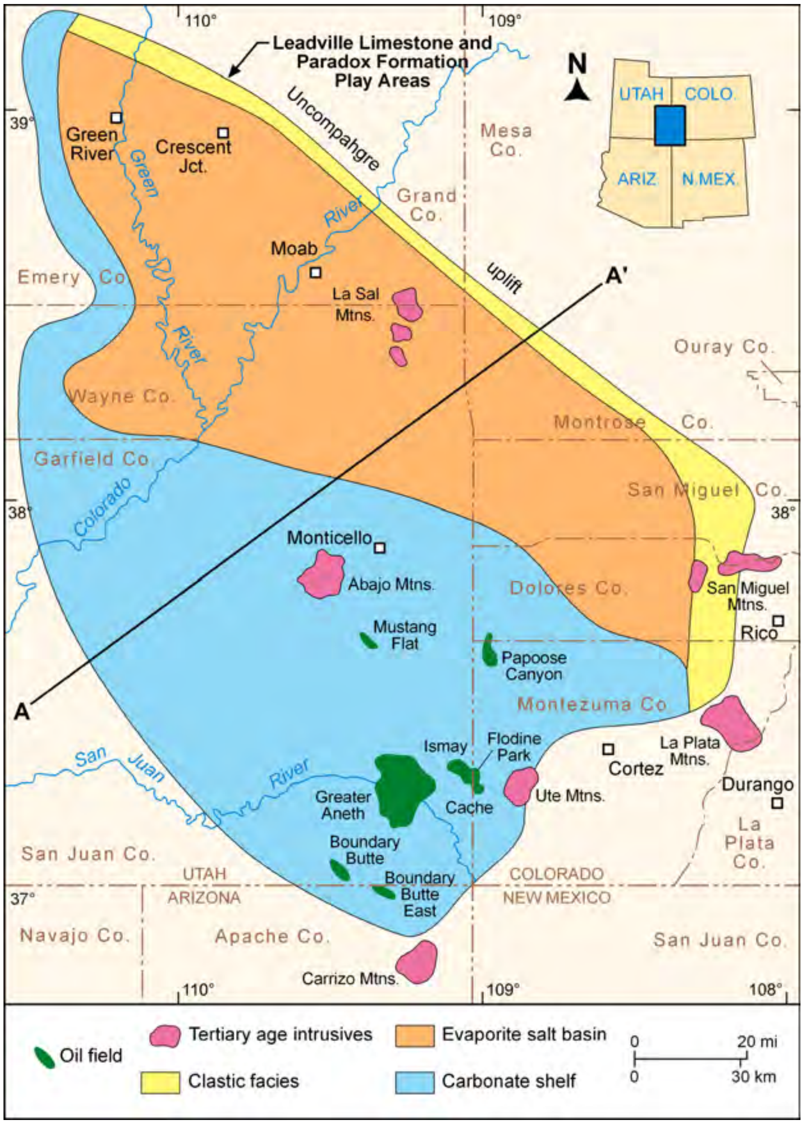


Figure 3. Generalized map of Paradox Formation facies with clastic wedge, evaporite salt basin, and carbonate shelf (modified from Wilson, 1975). Cross section A-A' shown on figure 4.

The present Paradox Basin includes or is surrounded by other uplifts that formed during the Late Cretaceous-early Tertiary Laramide orogeny such as the Monument upwarp in the west-southwest, and the Uncompahgre uplift, corresponding to earlier Uncompahgre Highlands, forming the northeast boundary (figure 2A). Oligocene-age laccolithic intrusions form the La Sal and Abajo Mountains in the north and central parts of the basin in Utah while the Carrizo Mountains in Arizona, and the Ute, La Plata, and San Miguel Mountains in Colorado are aligned along the southeastern boundary of the basin (figure 2A).

The Paradox Basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 2A). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt

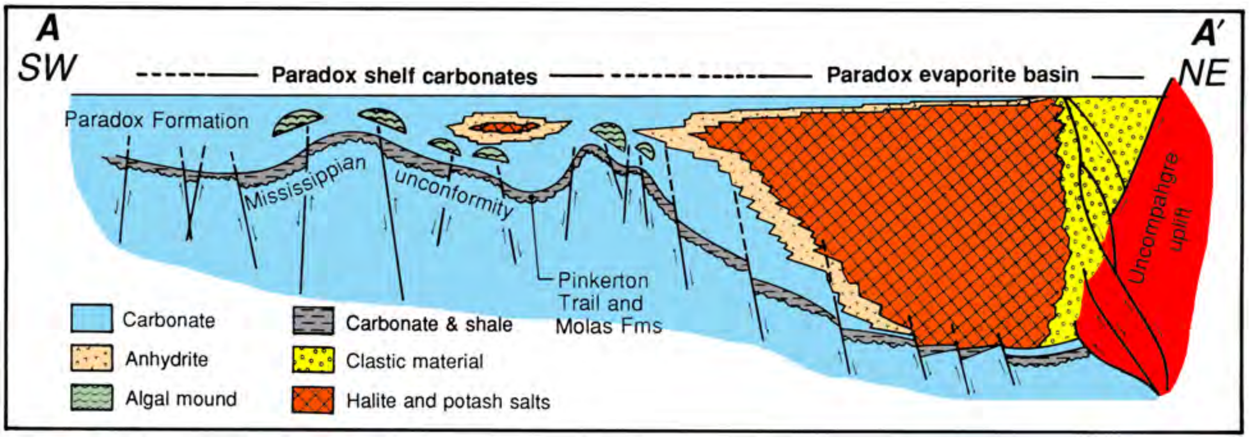


Figure 4. Generalized cross section across the Paradox Basin with gross facies relations between Middle Pennsylvanian shelf carbonates, restricted basin evaporites, and coarse clastics proximal to the Uncompahgre uplift (modified from Baars and Stevenson, 1981). Maximum extent of anhydrite beds in the Paradox Formation that define the basin is not shown. Location of cross section shown on figure 3.

flowage, dissolution, and collapse, and (3) regional uplift (Doelling, 2000). The relatively undeformed Blanding sub-basin and Aneth platform developed on a shallow-marine shelf. Each area contains oil and gas fields with structural, stratigraphic, or combination traps formed on discrete, often seismically defined, closures. Most Paradox Formation oil production comes from stratigraphic traps in the Blanding sub-basin and Aneth platform that locally contain algal-mound and other carbonate lithofacies buildups.

Paradox Formation, Paradox Basin Play Description

The most prolific oil and gas play in the Paradox Basin is the Pennsylvanian Paradox Formation play (figure 5). The Paradox has produced over 500 million barrels of oil (BO [80 million m^3]) and 650 billion cubic feet of gas (BCFG [18 billion m^3]); however, much of the gas included in the production figures is cycled gas, including carbon dioxide, for pressure maintenance (Utah Division of Oil, Gas and Mining, 2006; Colorado Oil & Gas Conservation Commission, 2006). Since the early 1920s, the Paradox Basin has been a site for oil exploration drilling. The Cane Creek anticline in the Paradox fold and fault belt was one of the most obvious structural drilling targets and first tested oil in 1924 (figure 6). However, the Cane Creek field only produced 1887 BO (300 m^3) and 25 million cubic feet of gas (MMCFG [0.7 MMCMG]), primarily from the Cane Creek shale (Stowe, 1972). The first commercial production from the Paradox Formation did not begin until the 1950s. Greater Aneth field, Utah's largest oil producer, was discovered in 1956, and it has produced over 440 million BO (70 million m^3) (Utah Division of Oil, Gas and Mining, 2006). The remaining production is from nearly 100 small fields in the basin. Using a minimum production cutoff of 500,000 BO (80,000 m^3) there are currently 24 Paradox fields in Utah, eight in Colorado, and one in Arizona. Geologic data for individual fields in the play are summarized in table 1.

The play outline represents the maximum extent of petroleum potential in the geographical area as defined by producing reservoirs, hydrocarbon shows, and untested hypotheses. The attractiveness of the Paradox Formation play (and other Paradox Basin plays)

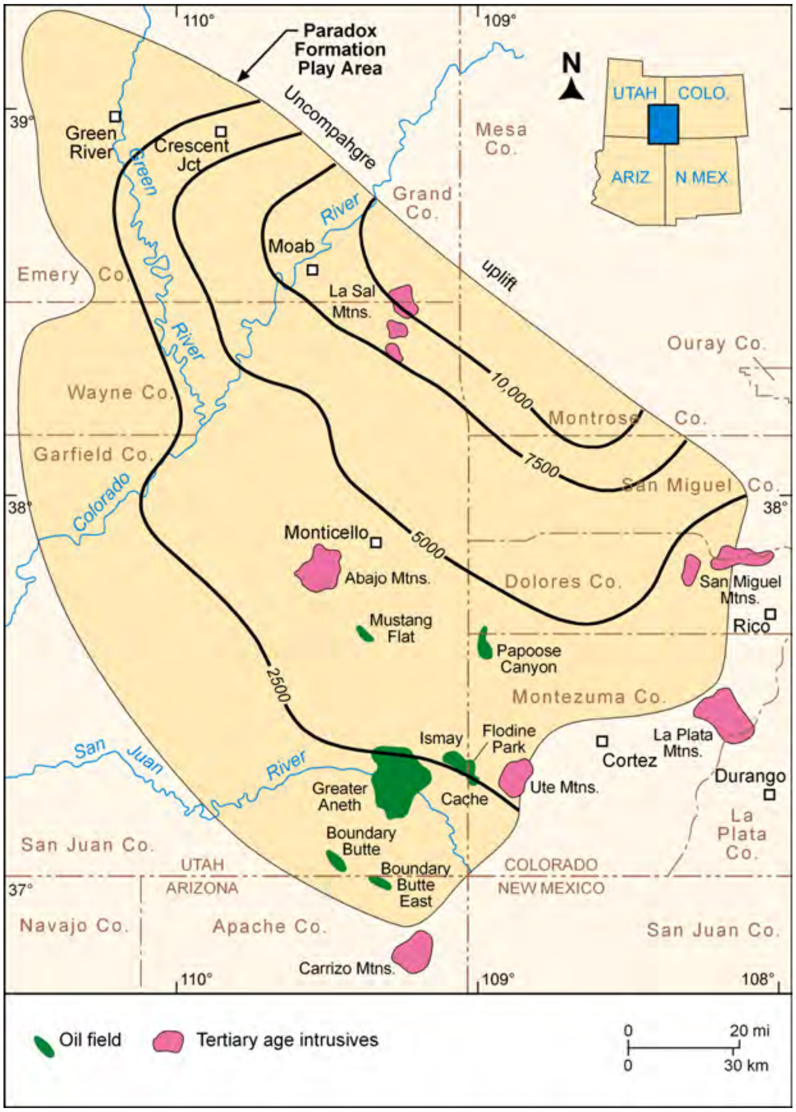


Figure 5. Pennsylvanian Paradox Formation play area and major fields, Utah, Colorado, and Arizona. Thickness of the Pennsylvanian rocks shown in feet. Modified from Choquette (1983).

Figure 6. The Midwest Exploration and Utah Southern No. 1 Shafer wildcat well, section 31, T. 26 S., R. 21 E., Salt Lake Base Line and Meridian, Grand County, Utah, drilled in 1924; view down the Colorado River to the southwest. Used by permission, Utah State Historical Society, all rights reserved.

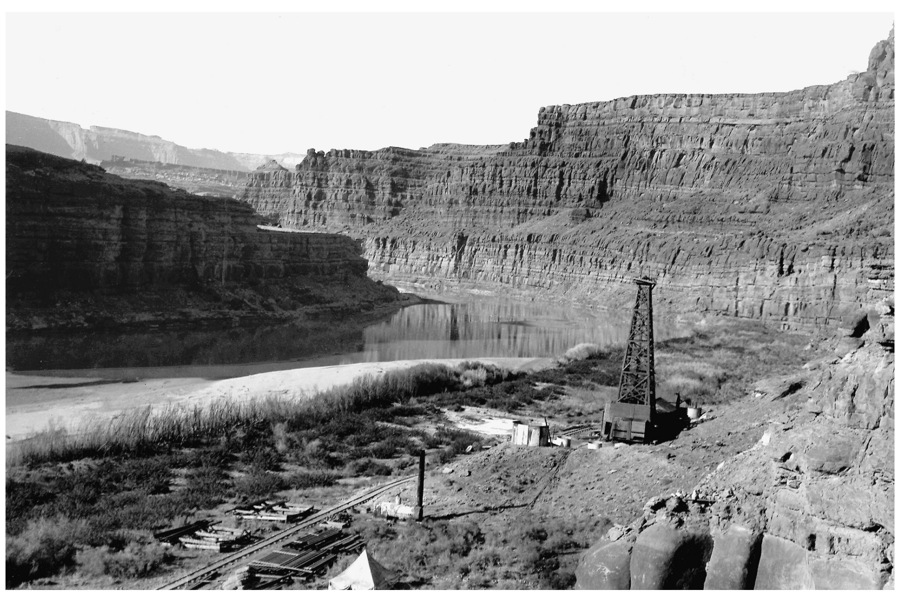


Table 1. Well and production data for fields in the Blanding sub-basin Desert Creek zone, Blanding sub-basin Ismay-zone, and Aneth platform Desert Creek-zone subplays, Pennsylvanian Paradox Formation play (data from Colorado Oil & Gas Conservation Commission, 2006; Utah Division of Oil, Gas and Mining, 2006; Steve Rauzi, Arizona Geological Survey, written communication, 2006).

State	County	Field	Zone	Discovery Date	Active Producers	Abandoned Producers	Acres	Spacing (acres)	Average Monthly Production		Cumulative Production	
									Oil (bbl)	Gas (MCF)	Oil (bbl)	Gas (BCF)
Blanding sub-basin Desert Creek zone subplay												
Colorado	Montezuma	Island Butte	Desert Creek	1991	6	2	NA	NA	837	130	2,196,781	5.9
Colorado	Montezuma	McClean	Desert Creek	1974	6	2	NA	NA	12,620	48,402	5,060,689	17.4
Colorado	Dolores/Montezuma	Papoose Canyon	Desert Creek	1970	30	13	1920	160	3690	50,409	6,507,460	36.4
Utah	San Juan	Bug	Desert Creek	1980	7	6	600	160	0	0	1,622,863	4.5
Blanding sub-basin Ismay zone subplay												
Colorado	Montezuma	Cache	Ismay	1964	10	10	1040	40	1456	19,050	4,582,519	7.6
Colorado	Montezuma	Flodine Park	Ismay	1959	7	3	1440	80	299	3414	2,580,961	9.8
Colorado	Montezuma	Marble Wash	Ismay	1958	5	3	400	80	10	222	1,013,349	1.7
Colorado	Montezuma	Roadrunner	Ismay	1984	11	3	NA	40	923	2478	2,176,601	4.5
Colorado	Montezuma	Towaoc	Ismay	1959	5	2	160	80	348	1220	802,762	1.2
Utah	San Juan	Cave Canyon	Ismay	1984	10	0	30	20	1447	2366	2,431,098	3.9
Utah	San Juan	Deadman-Ismay	Ismay	1986	4	1	120	40	435	6235	797,446	12.4
Utah	San Juan	Ismay	Ismay	1956	10	24	4370	80	2707	3604	10,822,986	17.5
Utah	San Juan	Kachina	Ismay	1986	5	0	400	80	1732	2875	2,594,130	2.3
Utah	San Juan	Kiva	Ismay	1984	5	0	350	80	856	1722	2,644,724	3.8
Utah	San Juan	McElmo Mesa	Ismay	1960	0	9	2240	80	0	0	2,219,175	2.9
Utah	San Juan	Mustang Flat	Ismay	1982	8	1	320	160	252	15,305	780,988	16.7
Utah	San Juan	Patterson Canyon	Ismay	1974	9	3	320	none	899	2281	1,093,285	2.7
Utah	San Juan	Tin Cup Mesa	Ismay	1980	10	0	880	80	682	1537	2,474,548	3.7
Aneth platform Desert Creek zone subplay												
Arizona	Apache	Boundary Butte East	Ismay-Desert Creek-Akah	1954	3	7	2800	80	199	934	885,530	9.8
Utah	San Juan	Akah	Ismay-Desert Creek-Akah	1955	2	0	240	80	200	228	531,563	0.5
Utah	San Juan	Anido Creek	Ismay-Desert Creek	1960	0	4	375	80	0	0	612,082	0.4
Utah	San Juan	Bluff	Desert Creek	1951	8	7	1040	none	218	1552	1,674,759	3.7
Utah	San Juan	Clay Hill	Desert Creek	1977	3	1	200	none	379	283	997,134	1.4
Utah	San Juan	Desert Creek	Desert Creek	1954	6	1	300	80	2864	1920	2,086,755	1.8
Utah	San Juan	Gothic Mesa	Desert Creek	1956	5	10	1520	80	329	0	1,946,420	1.3
Utah	San Juan	Greater Aneth	Desert Creek	1956	462	106	48,260	40	294,906	227,902	440,260,717	384.9
Utah	San Juan	Recapture Creek	Ismay-Desert Creek	1956	5	2	1350	80	1071	2484	2,224,172	3.8
Utah	San Juan	Runway	Desert Creek	1990	3	0	193	40	427	1414	866,568	3.0
Utah	San Juan	Tohonadla	Ismay-Desert Creek-Akah	1957	4	0	1200	80	1925	0	2,286,715	0.9
Utah	San Juan	Turner Bluff	Desert Creek	1957	7	4	720	80	202	611	927,110	0.8

NA = Not Available

to the petroleum industry depends on the likelihood of successful development, reserve potential, pipeline access, drilling costs, oil and gas prices, and environmental concerns. When evaluating these criteria, certain aspects of the Paradox Formation play may meet the exploration guidelines of major oil companies while other aspects meet the development guidelines of small, independent companies. Prospective drilling targets in the Paradox Formation play are delineated using high-quality two-dimensional (2-D) and three-dimensional (3-D) seismic data, 2-D and 3-D forward modeling/visualization tools, well control, dipmeter information, facies mapping, and detailed analyses of the diagenetic history.

The three main producing zones of the Paradox Formation are informally named the Cane Creek shale, Desert Creek zone, and Ismay zone (figure 7). Fractured shale beds in the Cane Creek shale are oil productive in the Paradox Basin fold and fault belt. The Ismay mainly produces oil from fields along a trend that crosses the southern Blanding sub-basin. The Desert Creek produces oil in fields along a trend that crosses the central Blanding sub-basin and Aneth platform. 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.

The Paradox Formation oil play area includes nearly the entire Paradox Basin (figure 5); the formation produces only gas in the southeastern part of the basin in Colorado. The Paradox Formation Play is divided into four subplays (figure 8): (1) fractured shale (described by Chidsey and others, 2004 - DOE/FC26-02NT15133-8), (2) Blanding sub-basin Desert Creek zone, (3) Blanding sub-basin Ismay zone, and (4) Aneth platform Desert Creek zone.

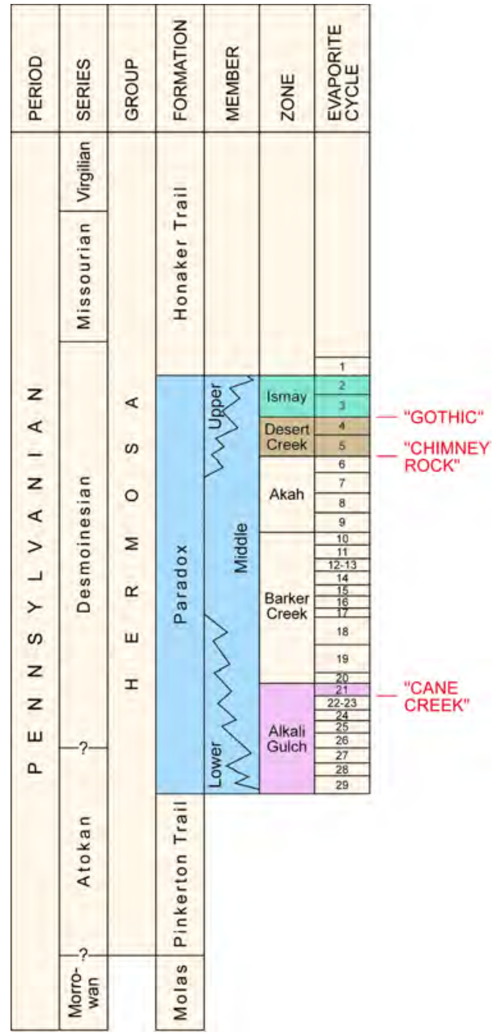


Figure 7. Pennsylvanian stratigraphic chart for the Paradox Basin; informal zones with significant production are highlighted.

Depositional Environments

In Pennsylvanian time, the Paradox Basin was rapidly subsiding along its northeast margin, but with a shallow-water carbonate shelf on the south and southwest margins of the basin that locally contained algal-mound buildups. These carbonate buildups, and the material shed from their flanks, formed petroleum traps where reservoir-quality porosity and permeability have developed.

During the Pennsylvanian, the Paradox Basin was in subtropical, dry climatic conditions along the trade-wind belt, 10° to 20° north of the paleo-equator. Prevailing winds were from present-day north (Peterson and Hite, 1969; Heckel, 1977; Parrish, 1982). Open-

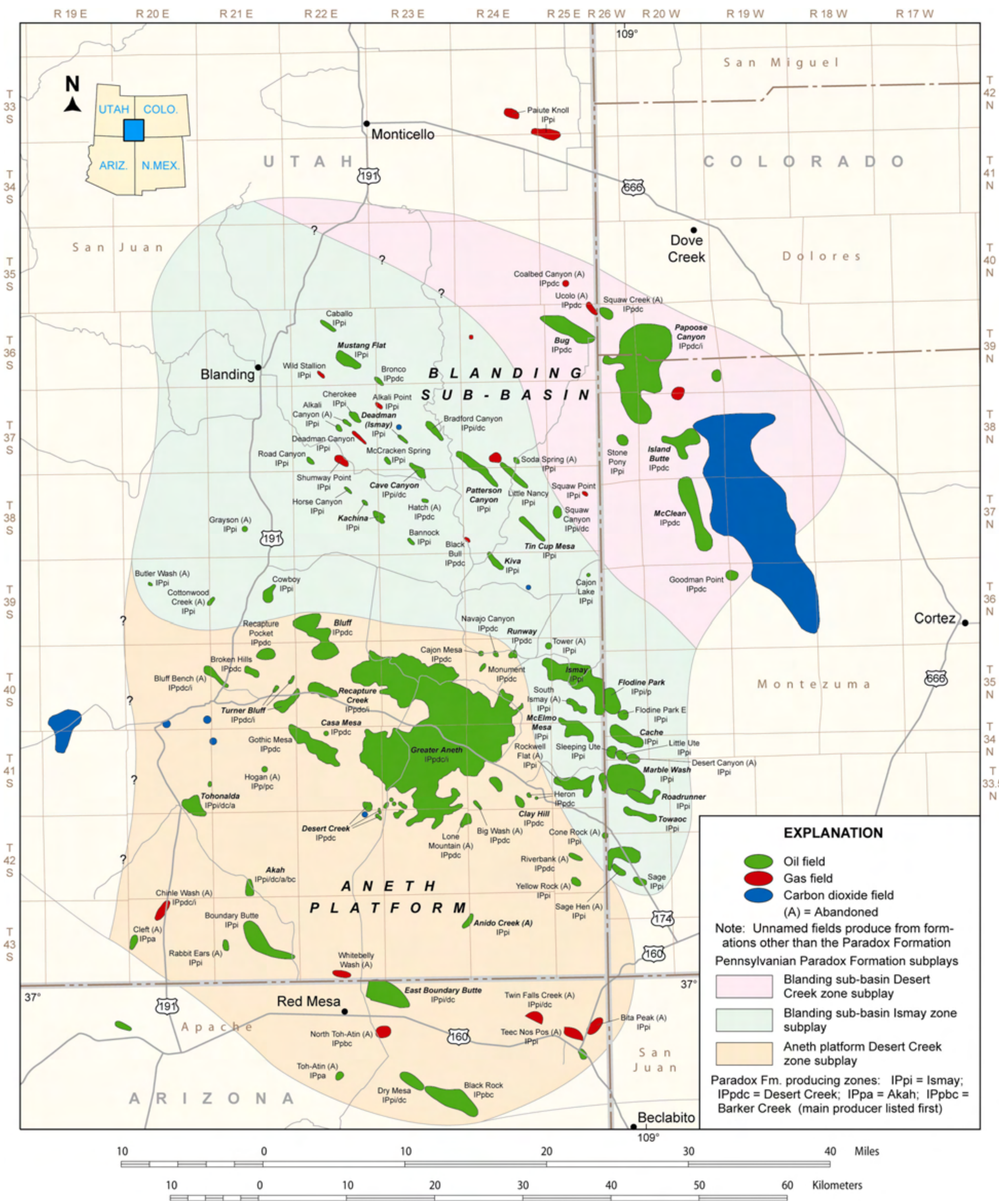


Figure 8. Location of the Paradox Formation Blanding sub-basin Desert Creek zone, Blanding sub-basin Ismay zone, and Aneth platform Desert Creek zone subplays, southeastern Utah, southwestern Colorado, and northeastern Arizona. Fields in italics have produced over 500,000 BO as of January 1, 2006. Modified from Chidsey and others (2004); Wray and others (2002).

marine waters flowed across the shallow cratonic shelf into the basin during transgressive periods. There are four postulated normal marine access ways into the Paradox Basin. The Cabezon accessway, which was located to the southeast, is generally accepted as the most likely normal marine-water conduit to maintain circulation on the shallow shelf (Fetzner, 1960; Ohlen and McIntyre, 1965; Hite, 1970). Periodic decreased circulation in the basin resulted in deposition of thick salts (halite with occasionally thinner beds of potash and magnesium salts) and anhydrite. The deeper interior of the basin to the north and northeast is composed almost entirely of salt deposits and is referred to as the evaporite salt basin (figure 9).

Cyclicity in Paradox Basin deposition was primarily controlled by glacio-eustatic fluctuations. The shape of the sea-level curve reflects rapid marine transgressions (rapid melting of ice caps) and slow, interrupted regression (slow ice cap buildup) (Imbrie and Imbrie, 1980; Denton and Hughes, 1983; Heckel, 1986). Irregular patterns within the transgressive-regressive cycles are thought to be a response to interference of orbital parameters (Imbrie and Imbrie, 1980). These cycles were also influenced by (1) regional tectonic activity and basin subsidence (Baars, 1966; Baars and Stevenson, 1982), (2) proximity to basin margin and evaporites (Hite, 1960; Hite and Buckner, 1981), (3) climatic variation and episodic blockage of

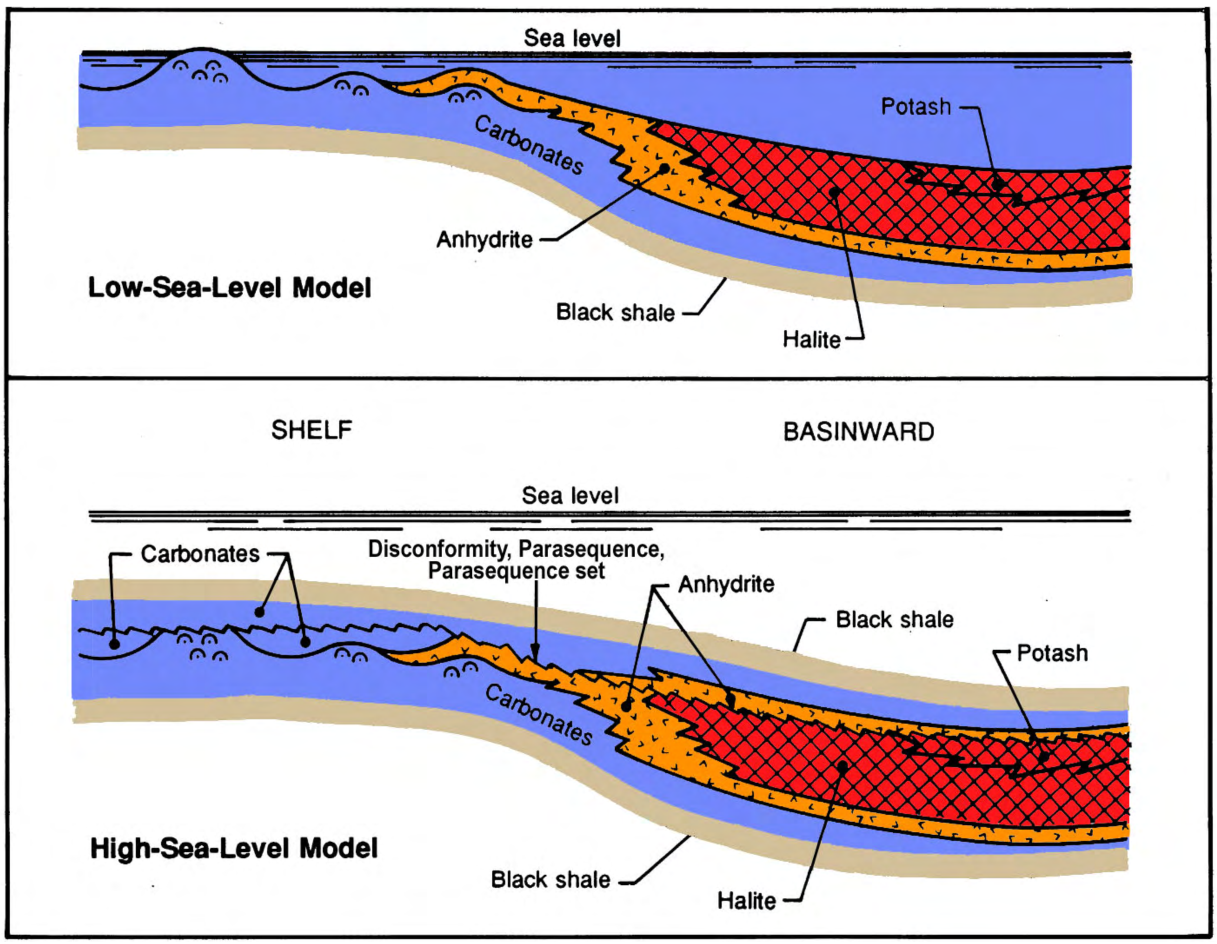


Figure 9. Diagram of the depositional sequence during Paradox time and the relationships of various basin and shelf facies. Wavy line represents disconformity, parasequence, or parasequence set. Symbol in the shelf carbonate represents algal-mound development. Modified from Hite and Cater (1972).

open marine-water conduits, and (4) fluctuations in water depth and water energy (Peterson and Ohlen, 1963; Peterson, 1966; Hite and Buckner, 1981; Heckel, 1983).

<u>Blanding sub-basin Ismay and Desert Creek zones subplays:</u> Ismay and Desert Creek zone depositional environments that trend across the Blanding sub-basin are shown schematically on figure 10. 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 rarely, open-marine, bryozoan mounds (figure 10A). The Desert Creek zone is dominantly dolomite, comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts (figure 10B).

The controls on the development of each depositional environment were water depth, salinity, prevailing wave energy, and paleostructural position. In the Ismay zone, the following

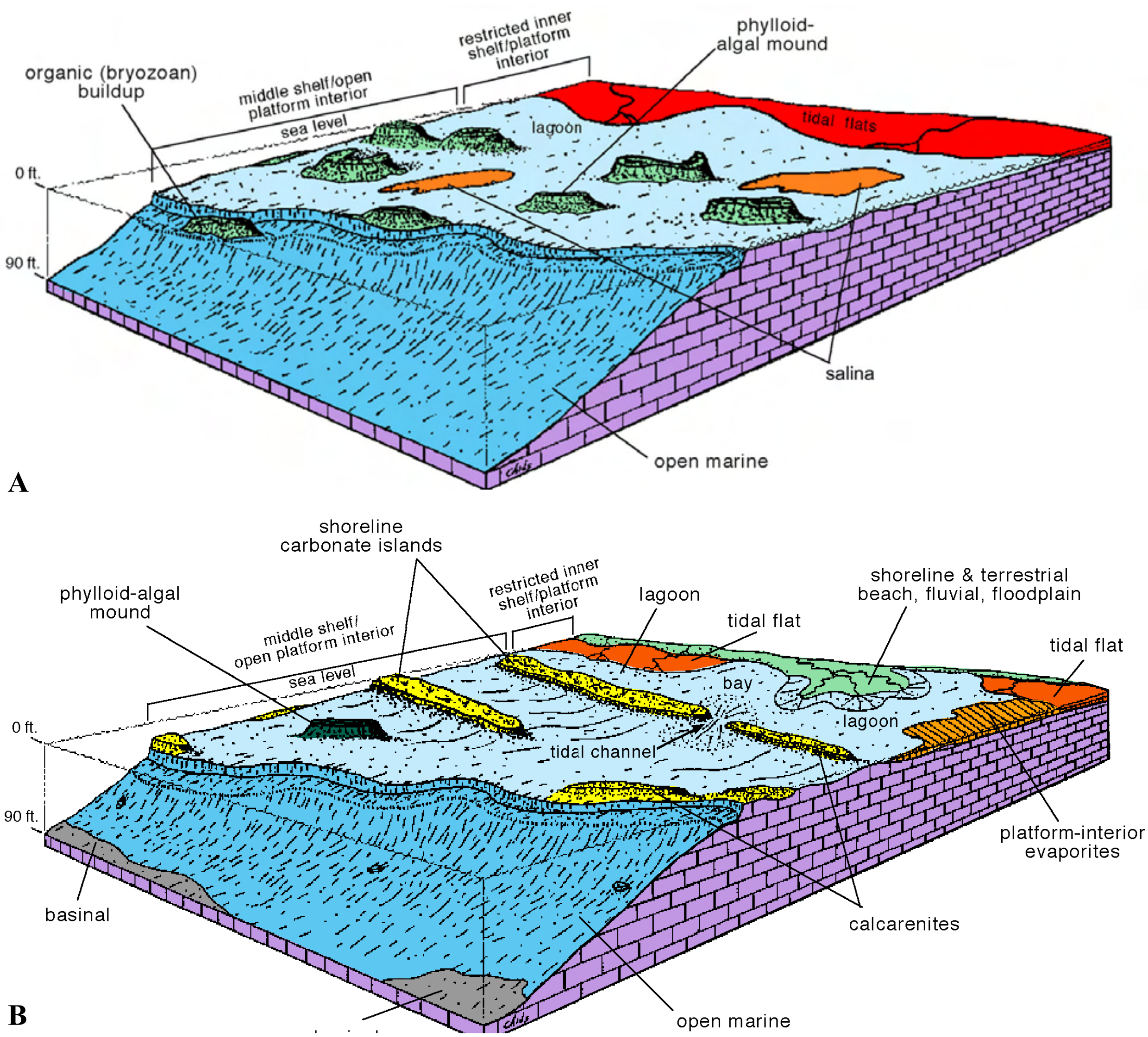


Figure 10. Block diagrams displaying major depositional environments, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

depositional environments are recognized: open-marine shelf, organic (carbonate) buildups and calcarenites at the platform edge; middle shelf or open platform interior; and restricted inner shelf or platform interior. In the Desert Creek zone, the following depositional environments are recognized: basinal, calcarenites (carbonate islands) at the platform edge; middle shelf or open platform interior; restricted inner shelf or platform interior; platform interior salinas (evaporites); and shoreline and terrestrial.

The basinal environment represents deep water (90 to 120 feet [30-40 m]) and euxinic conditions. Deposition included (1) black to dark gray, non-calcareous, non-fossiliferous mud and silty mud, (2) spiculitic lime mud, (3) pelagic lime mud with microfossils and occasional thin-shelled bivalves such as *Halobia*, and (4) thick, deep-water siliciclastic sands. The open-marine deposition was below wave base under normal-marine salinities and low-energy conditions. Deposition consisted of argillaceous and limey mud containing crinoids, brachiopods, and byrozoans.

The middle shelf or open platform interior represents a well-circulated, low- to moderate-energy, normal salinity, shallow-water (between 0 and 90 feet [0-30 m]) environment. Lithofacies from this environment form the dominant producing reservoirs in the Ismay and Desert Creek zones that trend across the Blanding sub-basin. Benthic forams, bivalve molluscs, and codiacean green algae (*Ivanovia* and *Kansasphyllum*) are common. Bryozoan mounds developed in the relatively quiet, deeper water of the middle shelf. Echinoderms are rare and open-marine cephalopods are generally absent. The principal buildup process, phylloid-algal growth, occurred during sea-level highstands. Paleotopography from Mississippian-aged normal faulting (reactivation of Precambrian faults) produced the best marine conditions for initial algal growth.

Calcarenites are recognized in both zones and represent moderate- to high-energy, regularly agitated, marine environments where shoals and/or islands developed. Sediment deposition and modification probably occurred from 5 feet (1.5 m) above sea level to 45 feet (14 m) below sea level. These platform-edge deposits include (1) oolitic and coated grain sands, (2) crinoid, foram, algal, and fusilinid sands, (3) small, benthic foram and hard peloid sands representing stabilized peloid grain flats, and (4) shoreline carbonate islands of shell hash.

The restricted inner shelf or platform interior represents shallow water (0 to 45 feet [0-14 m]), and generally low-energy and poor circulation conditions. Fauna are limited mainly to stromatolitic algae, gastropods, certain benthic forams, and ostracods. Deposits included (1) bioclastic lagoonal to bay lime mud, (2) tidal-flat muds often with early dolomite, and (3) shoreline carbonate islands with birdseye fenestrae, stromatolites, cryptoalgal laminations, and dolomitic crusts. Platform-interior evaporites, usually anhydrite, were deposited in salinity-restricted areas.

Shoreline and terrestrial siliciclastic deposits represent beach, fluvial, and flood-plain environments. These siliciclastic deposits include argillaceous to dolomitic silt with rip-up clasts, scour surfaces, or mudcracks.

Within these depositional environments, several major Ismay and Desert Creek lithofacies are recognized and mapped across the Blanding sub-basin (figures 11 through 13). Mapping of these lithofacies delineates prospective reservoir trends containing porous and productive buildups. Ismay lithofacies include open marine, middle shelf, inner shelf/tidal flat, bryozoan mounds, phylloid-algal mounds, quartz sand dunes, and anhydritic salinas. Desert Creek lithofacies include open marine, middle shelf, proto-mounds/collapse breccia, and phylloid-algal mounds.

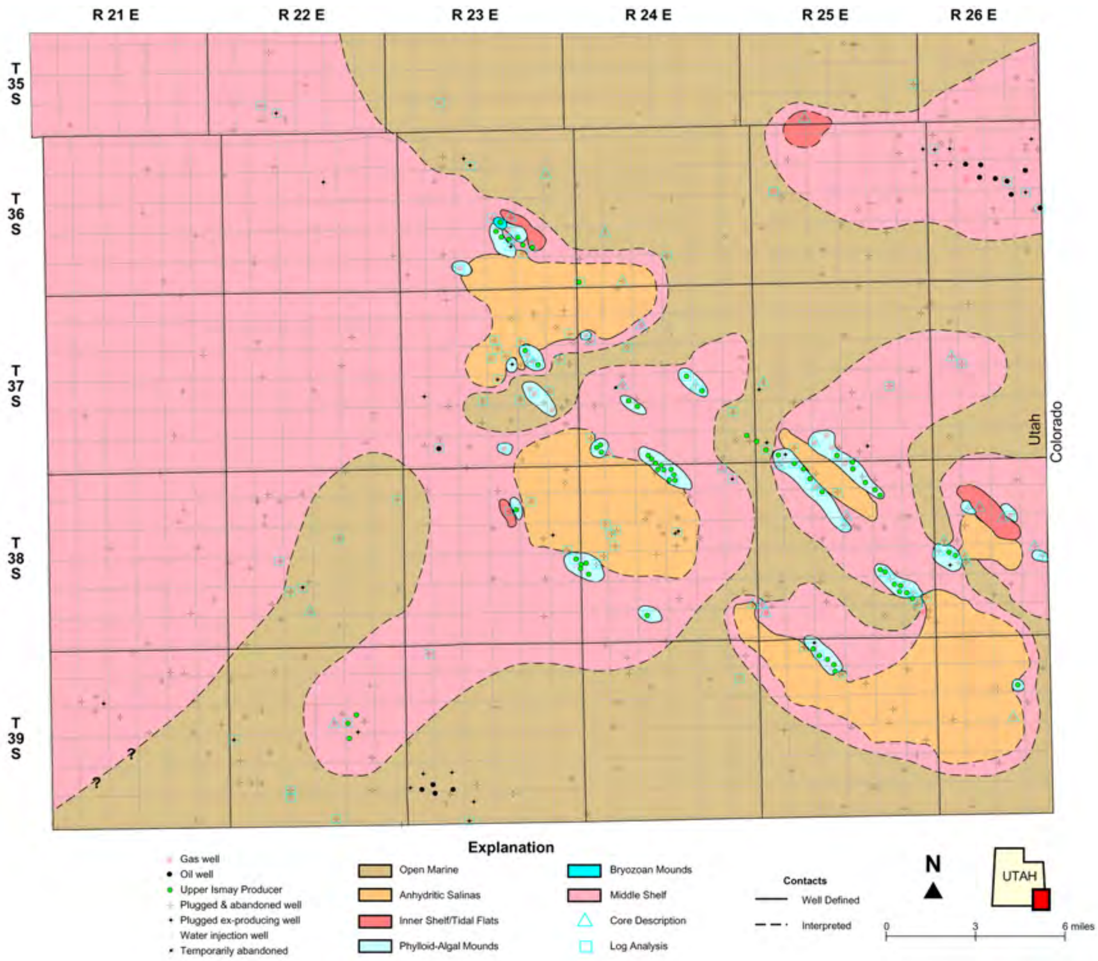


Figure 11. Regional lithofacies map of the upper part of the upper Ismay zone, Paradox Formation, in the Blanding sub-basin, Utah.

Open-marine lithofacies dominate the lower Desert Creek zone in the Blanding sub-basin where there is very little hydrocarbon potential (figure 13). However, this lithofacies developed in different areas for both the upper part (northeastern and southern regions [figure 11]) and lower part (western to north-central regions [figure 12]) of the upper Ismay zone. Middle-shelf lithofacies cover extensive areas of the upper Ismay zone and surround important intra-shelf basins described later. Bryozoan mounds, quartz sand dunes, proto-mounds and some phylloid-algal mounds, and inner shelf/tidal flats developed on the low-energy carbonates of the middle-shelf environment (figures 11 through 13).

Inner shelf/tidal flat lithofacies represent relatively small areas in geographical extent, especially in the upper part of the upper Ismay zone. However, recognizing this facies is important because inner shelf/tidal flats often form the substrate for phylloid-algal mound development. Proto-mounds/collapse breccia lithofacies are found in the Desert Creek zone and represent the initial stage of a mound buildup or one that never fully developed. They contain dolomitized and brecciated algal plates, marine cements, and internal sediments suggesting subareal exposure. Proto-mounds/collapse breccia lithofacies are usually near phylloid-algal mound lithofacies, but generally lack any significant porosity. They may appear as promising buildups on seismic, but in actuality have little potential other than as guides to

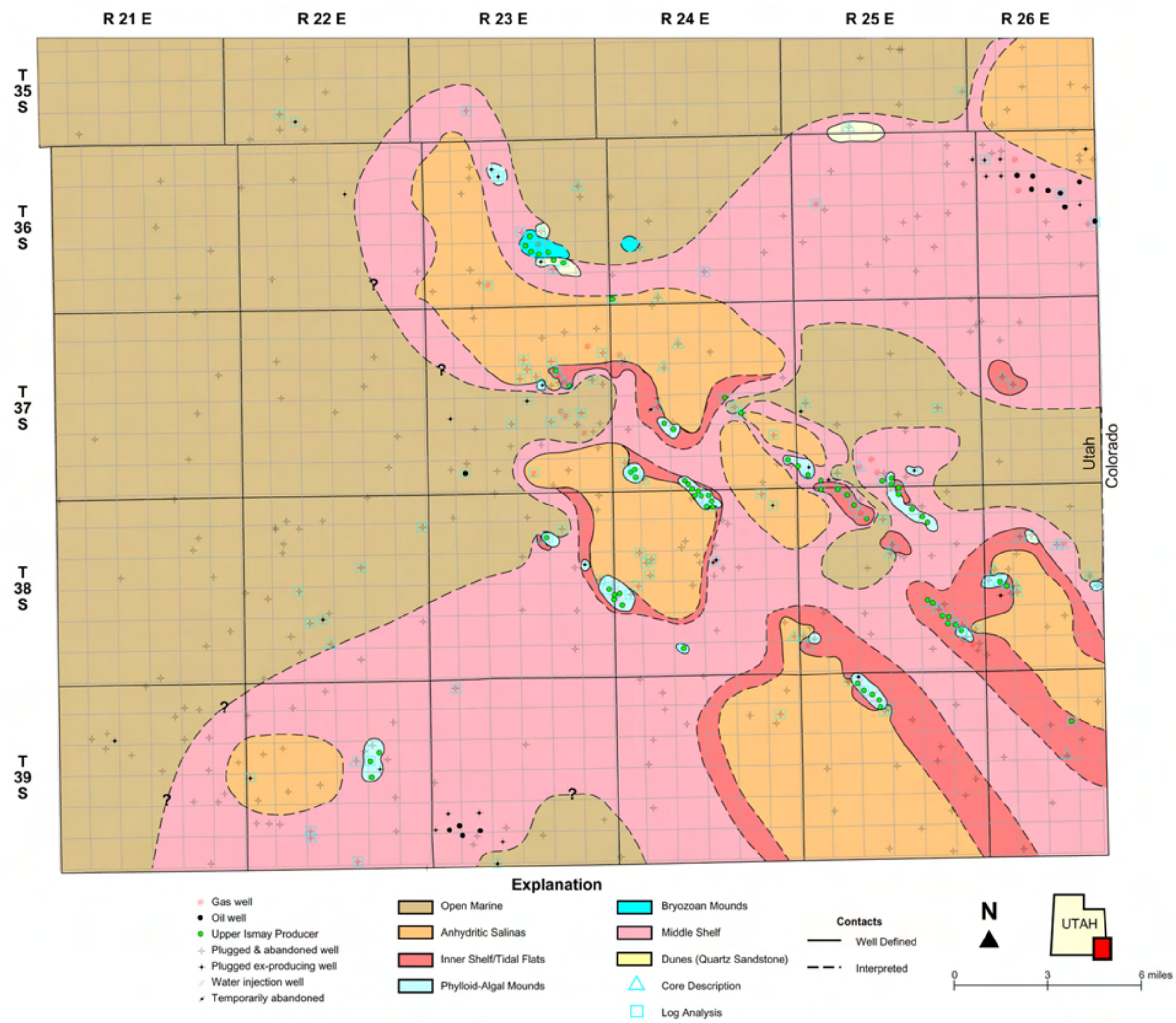


Figure 12. Regional lithofacies map of the lower part of the upper Ismay zone, Paradox Formation, in the Blanding sub-basin, Utah.

nearby fully developed mounds (figure 13). In the upper Ismay zone, most phylloid-algal mounds developed adjacent to widespread intra-shelf (anhydrite-filled) basins (figures 11 and 12). Porous Desert Creek mound lithofacies, such as the reservoir for Bug field, appear to be linear shorelines (carbonate islands) that developed on the middle shelf (figure 13). Regional lithofacies mapping clearly defines anhydrite-filled, intra-shelf basins. Inner shelf/tidal flat and associated productive, phylloid-algal lithofacies trends of the Ismay are present around the anhydritic salinas of intra-shelf basins (figures 11 and 12).

<u>Aneth platform Desert Creek zone subplay:</u> Three generalized, regional depositional environments (lithofacies) are identified in the Aneth platform Desert Creek zone subplay (figures 14 and 15): (1) open-marine, (2) shallow-shelf/shelf-margin, and (3) intra-shelf, salinity-restricted (Chidsey and others, 1996c). The open-marine lithofacies includes open-marine buildups (typically crinoid-rich mounds), open-marine crinoidal- and brachiopod-

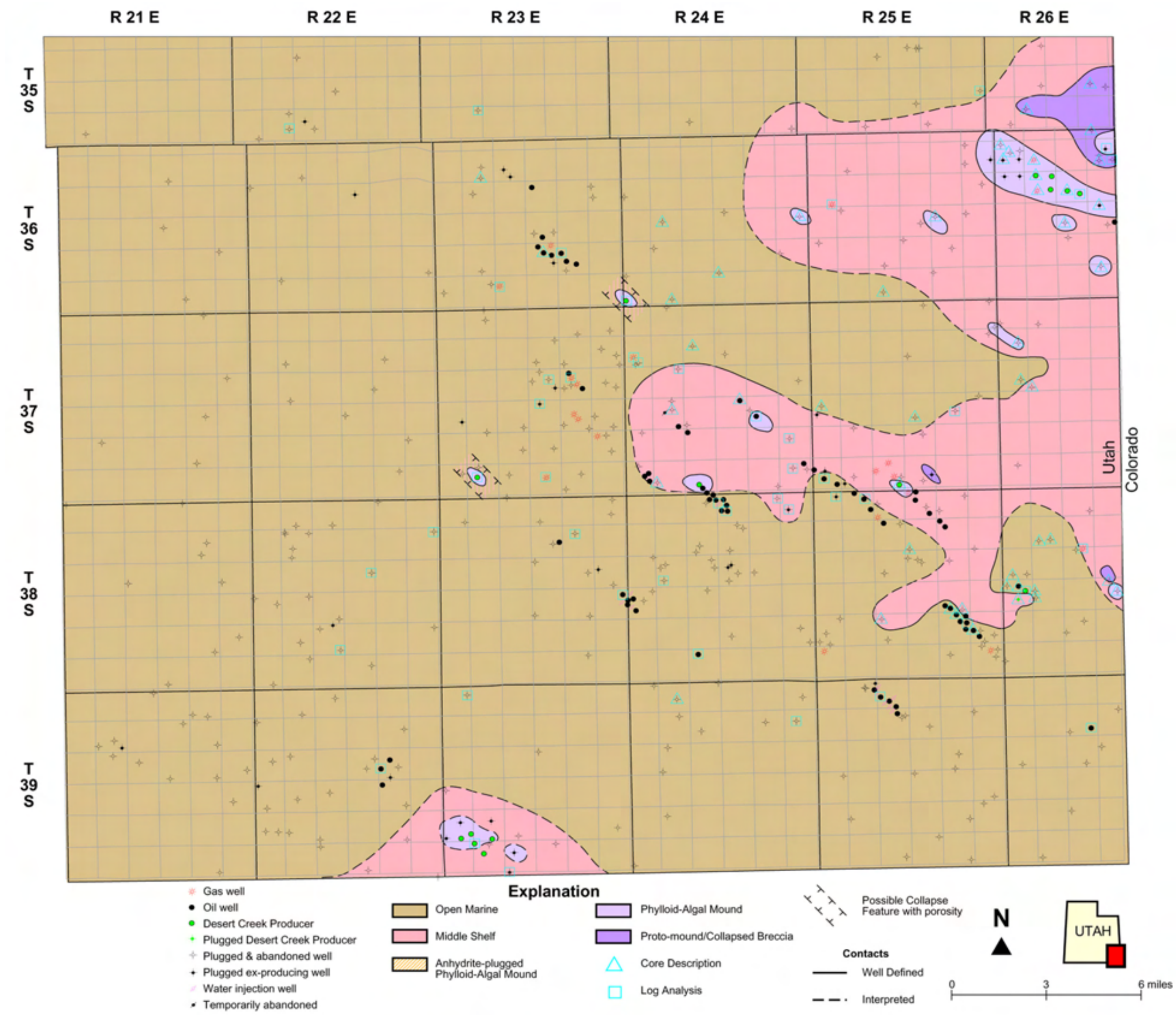


Figure 13. Regional lithofacies map of the lower Desert Creek zone, Paradox Formation, in the Blanding sub-basin, Utah.

bearing carbonate muds, euxinic black shales, wall complexes, and detrital fans. Sediments in the open-marine environment were deposited at water depths between 45 and 120 feet (14-37 m). This depositional environment is the most extensive and surrounds the shallow-shelf and shelf-margin depositional environment.

The shallow-shelf/shelf-margin depositional environment includes shallow-shelf buildups (phylloid algal, coralline algal, bryozoan, and marine-cemented buildups [mounds]), calcarenites (beach, dune, and stabilized grain flats, and oolite banks), and platform-interior carbonate muds and sands. Sediments were deposited at water depths between 0 and 40 feet (0-12 m). Karst characteristics are occasionally present over mounds. Tubular tempestites (burrows filled with coarse sand as a result of storm pumping) are found in some carbonate muds and sands. Most oil fields in the Aneth platform Desert Creek zone subplay are located within lithofacies representing this depositional environment, including the giant Greater Aneth field (figures 14 and 15).

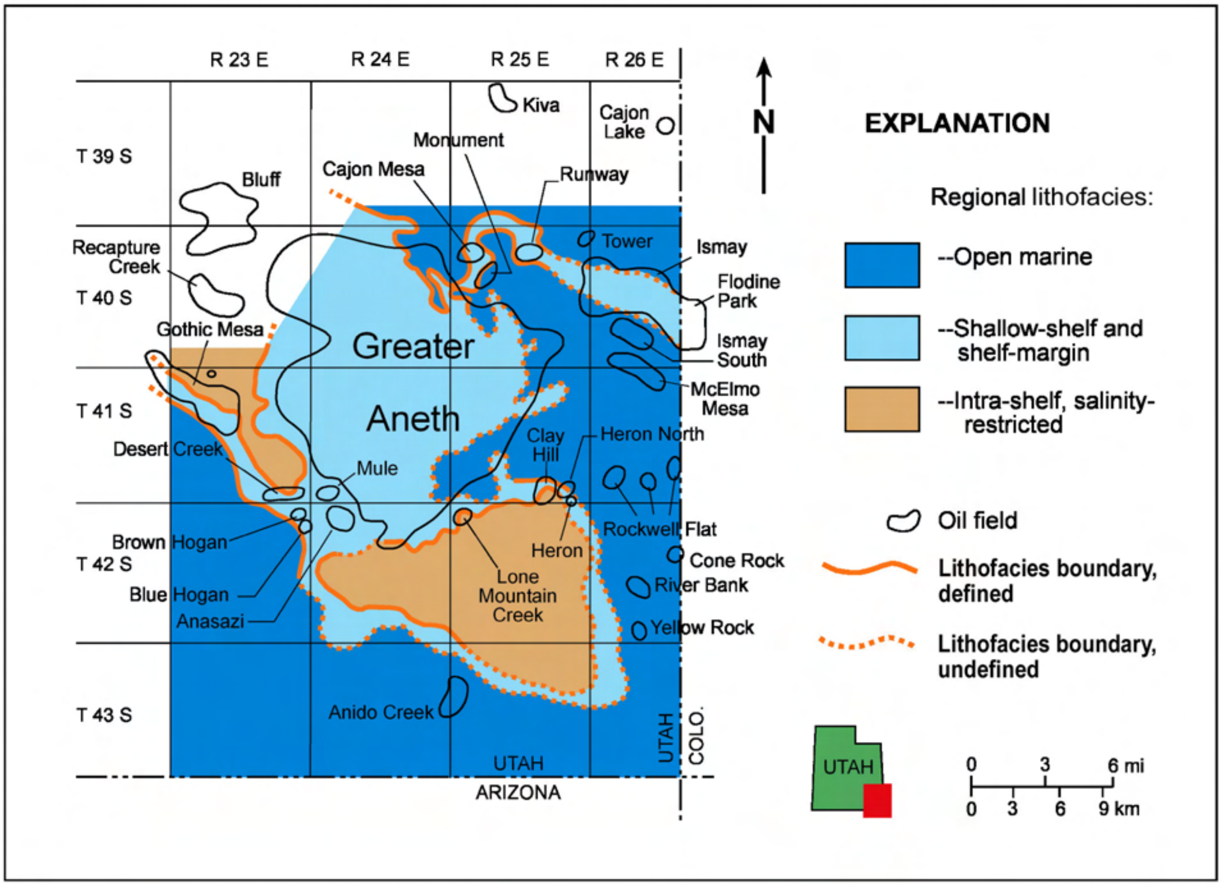


Figure 14. Map of major depositional environments/lithofacies for the Aneth platform Desert Creek zone subplay. After Chidsey and others (1996c).

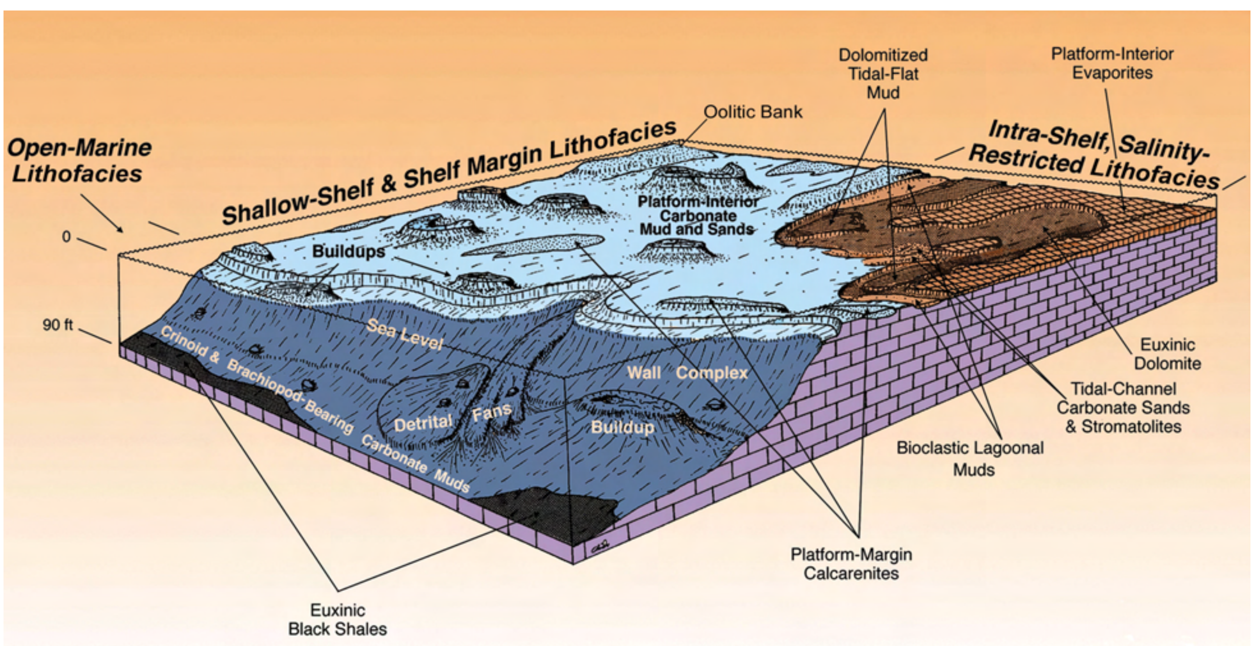


Figure 15. Block diagram displaying depositional environments within the Aneth platform Desert Creek zone subplay. After Chidsey and others (1996c).

The intra-shelf, salinity-restricted depositional environment represents small sub-basins within the shallow-shelf and shelf-margin depositional environment. The water had slightly elevated salinity compared to the other depositional environment. This depositional environment includes platform-interior evaporites, dolomitized tidal-flat muds, bioclastic lagoonal muds, tidal-channel carbonate sands and stromatolites, and euxinic dolomites. Sediments were deposited at water depths between 20 and 45 feet (6-14 m). Euxinic dolomites often display karst characteristics. Two intra-shelf sub-basins have been identified in the southeastern part of the Paradox Basin in Utah; each is separated from the open-marine by a fringe of the shallow-shelf/shelf-margin (figure 14).

Within these depositional environments, three local Desert Creek lithofacies are common: platform-interior carbonate sands and muds, platform-margin calcarenites, and carbonate buildups (figure 15) (Chidsey and others, 1996c). The platform-interior carbonate mud and sand lithofacies are widespread across the shallow shelf. This lithofacies represents a low- to moderate-energy environment. Mud and sand were deposited in subtidal (burrowed), inter-buildup, and stabilized grain-flat (pellet shoals) settings intermixed with tubular and bedded tempestites. Water depths ranged from 5 feet to 45 feet (1.5-14 m). The platform-margin calcarenite lithofacies are located along the margins of the larger shallow shelf or the rims of phylloid-algal buildup complexes. This lithofacies represents a high-energy environment where shoals and/or islands developed as a result of regularly agitated, shallow-marine processes on the shelf. Characteristic features of this lithofacies include medium-scale cross-bedding and bar-type, carbonate, sand-body morphologies. Water level ranged sea level to 20 feet (6 m). Stabilized calcarenites occasionally developed subaerial features (up to 5 feet [1.5 m] above sea level) such as beach rock, hard grounds, and soil zones.

Productive carbonate buildups are located in the shallow-shelf/shelf-margin areas. These buildups can be divided into three lithofacies types: (1) phylloid algal, (2) coralline algal, and (3) bryozoan (Eby and others, 1993; Chidsey and others, 1996c). The controls on the development of each buildup type were water depth, prevailing wave energy, and paleostructural position. The phylloid-algal buildup, the dominant producing reservoir lithofacies, represents a moderate-energy environment with well-circulated water. Water depths ranged from 1 to 40 feet (0.3-12 m). Mapping of seismic anomalies and reservoir thicknesses indicates that carbonate phylloid-algal buildups, or mounds, were doughnut or horseshoe shaped, or a composite of the two shapes (figures 16 and 17). Many of the phylloid-algal buildups were large enough to enclose interior lagoons. The Desert Creek at Greater Aneth field was deposited as a horseshoe-shaped buildup of numerous coalescing mounds capped by banks of oolitic sands, similar to the present-day Bahamas open-marine, carbonate-shelf system. Coralline-algal buildup lithofacies are located along the shallow-shelf margins facing open-marine waters or within the intra-shelf, salinity-restricted lithofacies belt (where they are non-productive). On the shallow shelf, this lithofacies represents a low- to high-energy environment with well-circulated water. Water depths ranged from 25 to 45 feet (8-14 m). These buildups are a component of the wall complex (figure 15) in association with early marine cementation and are stacked vertically. They may surround other types of buildup complexes. Bryozoan buildup lithofacies are located on the deeper flanks of phylloid-algal buildup complexes (figure 18A). This lithofacies represents a low-energy environment with well-circulated water. Water depths ranged from 25 to 45 feet (8-14 m). These lithofacies are prevalent on the shallow shelf where winds from the east, and paleotopography from Mississippian-aged normal faulting, produced better marine conditions for bryozoan colony development.

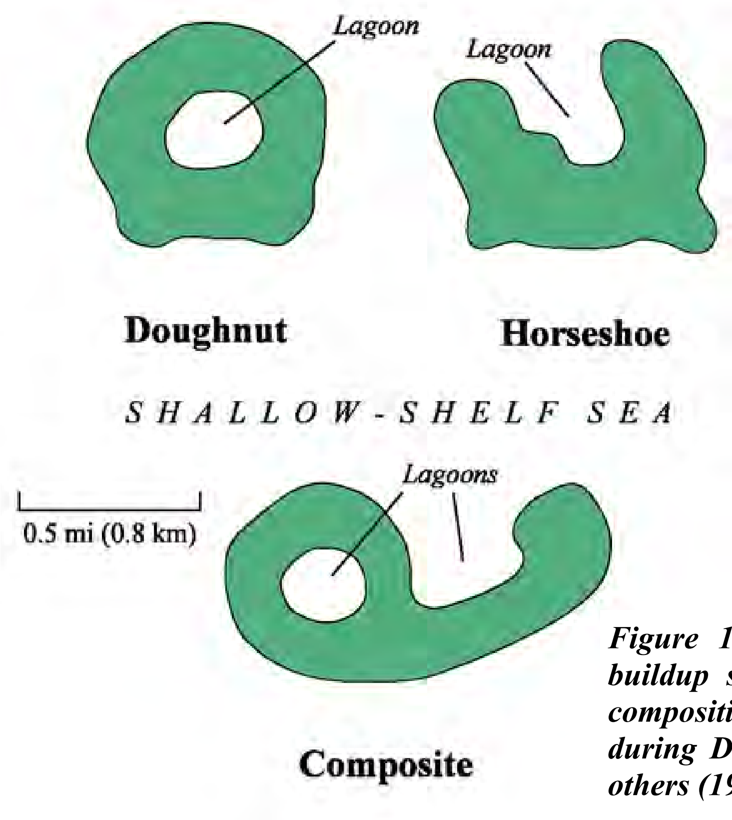


Figure 16. ***Map view of typical carbonate buildup shapes (most often phylloid algal in composition) on the shallow carbonate shelf during Desert Creek time. After Chidsey and others (1996c).***

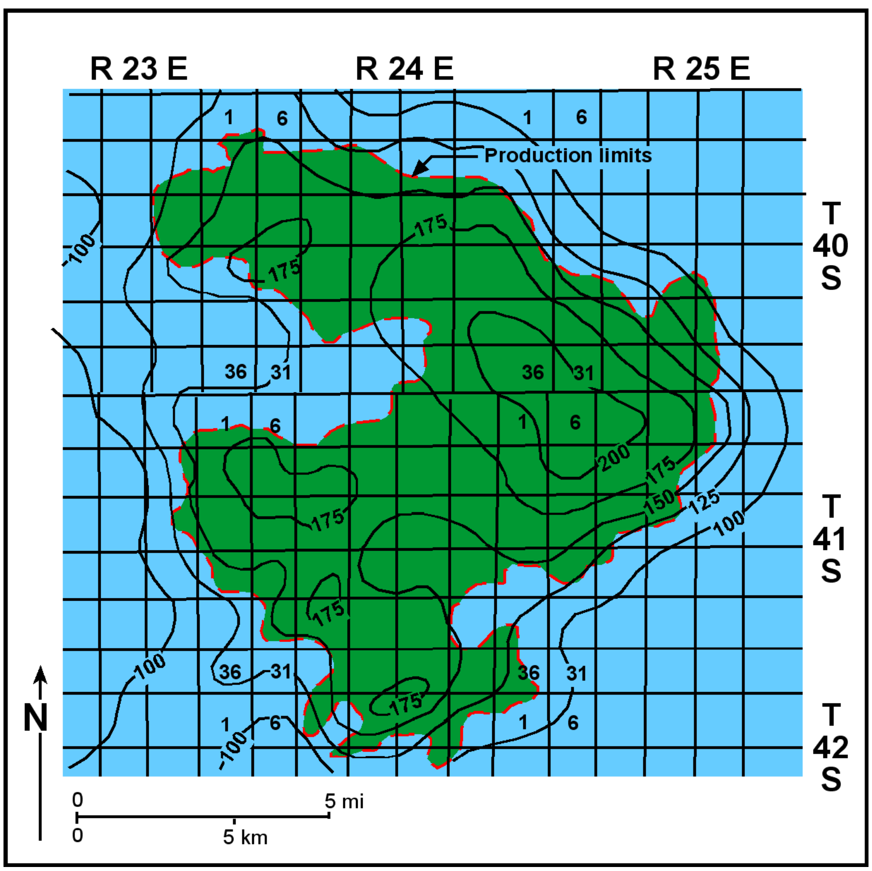


Figure 17. ***Generalized thickness map of the Desert Creek zone, Greater Aneth field, San Juan County, Utah; contour interval = 25 feet. Modified from Peterson and Ohlen (1963).***

The principal buildup process for phylloid-algal growth occurred during sea-level highstands (figure 18A) (Chidsey and others, 1996c). Phylloid-algal mounds generally developed on the platform-interior carbonate muds and sands. The mound substrate of platform-interior carbonates is referred to as the platform interval. Calcified phylloid-algal plates sheltered abundant primary "vugs," with mounds of phylloid algae building upward within the available accommodation space. As mounds grew, detrital skeletal material was shed and deposited as dipping beds along the exterior flanks and within interior lagoons. The floors of the interior lagoons consisted of muddy, marine limestone with fossils. Early marine cementation commonly occurred along mound walls facing open-marine environments. Bryozoan-dominated buildups developed in deeper water along the flanks of the phylloid-algal mounds. Coralline-algal buildups developed in association with marine-cemented walls and detrital-fan complexes.

During sea-level lowstands, these buildups experienced considerable porosity modification (figure 18B). Leached cavities, vugs, and seepage-reflux dolomites developed in the mound core and flank sediments. Evaporitic dolomites and anhydrite filled the interior lagoons. Islands consisting of high-depositional-energy calcarenites and low-depositional-energy stromatolites, as well as troughs representing tidal channels, formed on the tops of buildups during times of subaerial exposure (figures 18B and 18C). These portions of the buildups are referred to as supra-mound intervals.

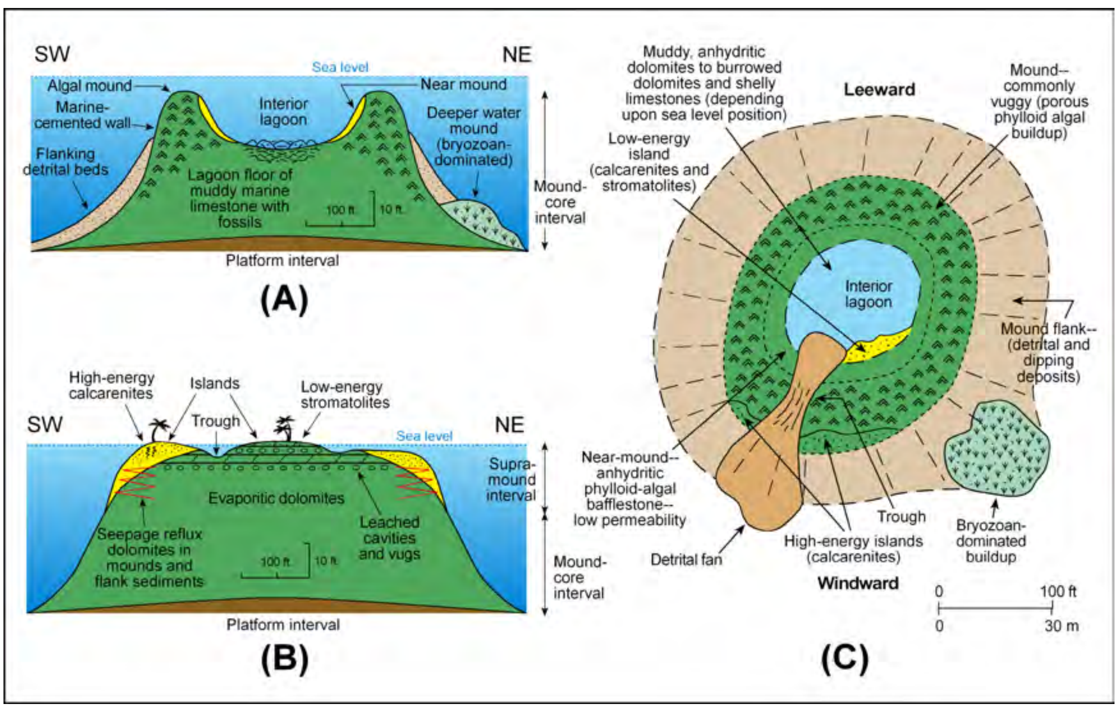


Figure 18. Detailed environmental setting of Desert Creek algal buildup features surrounding the Greater Aneth field. (A) Cross section during sea-level highstands when the mound was actively growing. (B) Cross section during sea-level lowstands when the mound experienced porosity modification, erosion of the mound margins, evaporite dolomites filled in the lagoon, and troughs (tidal channels) and islands developed on the top. (C) Map view of idealized algal buildup. After Chidsey and others (1996c).

Stratigraphy and Thickness

The Paradox Formation is part of the Pennsylvanian Hermosa Group (Baker and others, 1933) (figure 7). The 500- to 5000-foot-thick (150-1500 m) Paradox is overlain by the Honaker Trail Formation and underlain by the Pinkerton Trail Formation (Wengerd and Matheny, 1958; Hintze, 1993). The Paradox is divided into (1) a lower member consisting of interbedded black shale, siltstone, dolomite, and anhydrite, (2) a middle (saline) member consisting of thick halite beds interbedded with dolomite, dolomitic siltstone and shale, and anhydrite, and (3) an upper member of interbedded dolomite, dolomitic shale, and anhydrite.

Hite (1960) divided the middle (saline) member of the Paradox Formation in the evaporite basin into a maximum of 29 salt cycles that onlap onto the basin shelf to the west and southwest. Each cycle consists of a clastic interval/salt couplet. The clastic intervals are typically interbedded dolomite, dolomitic siltstone, organic-rich shale, and anhydrite. The clastic intervals typically range in thickness from 10 to 200 feet (3-60 m) and are generally overlain by 200 to 400 feet (60-120 m) of halite. In the interior of the basin, a typical cycle consists of a black shale facies overlain almost entirely by salt, whereas on the shelf, a cycle consists of a black shale facies overlain primarily by carbonates. The regionally extensive black shale facies allows correlation of salt cycles in the interior of the basin with carbonate cycles on the shelf.

Hite and Cater (1972) and Reid and Berghorn (1981) divided the Paradox Formation into informal zones, in ascending order: Alkali Gulch, Barker Creek, Akah, Desert Creek, and Ismay (figure 7). This usage is currently the most common in the literature, as well as in completion and production reports.

In the Blanding sub-basin, the Desert Creek and Ismay zones are relatively easy to correlate because they are bounded by shale or other units that have distinctive geophysical log responses (figures 19 and 20). The Desert Creek zone is typically dolomite, while the Ismay is mainly limestone with some dolomite units. Thickness of the Desert Creek zone averages 85 feet (24 m). It is overlain by the Gothic shale and underlain by the Chimney Rock shale, both informal units of the Paradox Formation (figure 19). The average depth to the Desert Creek in Blanding sub-basin fields is 5920 feet (1800 m). Thickness of the Ismay zone averages 230 feet (70 m). It is overlain by the Honaker Trail Formation and underlain by the Gothic shale (figure 20). The Ismay zone is subdivided into an upper interval and a lower interval separated by a 30- to 45-foot-thick (10-15 m) unit informally called the Hovenweap shale (figure 20). The average depth to the Ismay in Blanding sub-basin fields is 5630 feet (1880 m).

On the Aneth platform, the Desert Creek and Ismay zones are predominately limestone, with local dolomitic units, and are the major producers in the area; the Akah and Barker Creek zones are minor producers in comparison. Like in the Blanding sub-basin, the Desert Creek is again overlain by the Gothic shale and underlain by the Chimney Rock shale. The geophysical log response has variations that correspond to changes in lithofacies (figure 21). As a result, the Desert Creek is often subdivided into informally named intervals in the larger fields. Thickness of the Desert Creek zone averages 140 feet (45 m). The average depth to the Desert Creek in Aneth platform fields is 5530 feet (1840 m). The Ismay zone is again overlain by the Honaker Trail Formation and underlain by the Gothic shale. The geophysical log response also has variations that correspond to changes in lithofacies; however, the Hovenweap shale is not well developed (figure 22). Thickness of the Ismay zone averages 160 feet (50 m). The average depth to the Ismay in Aneth platform fields is 5320 feet (1770 m).

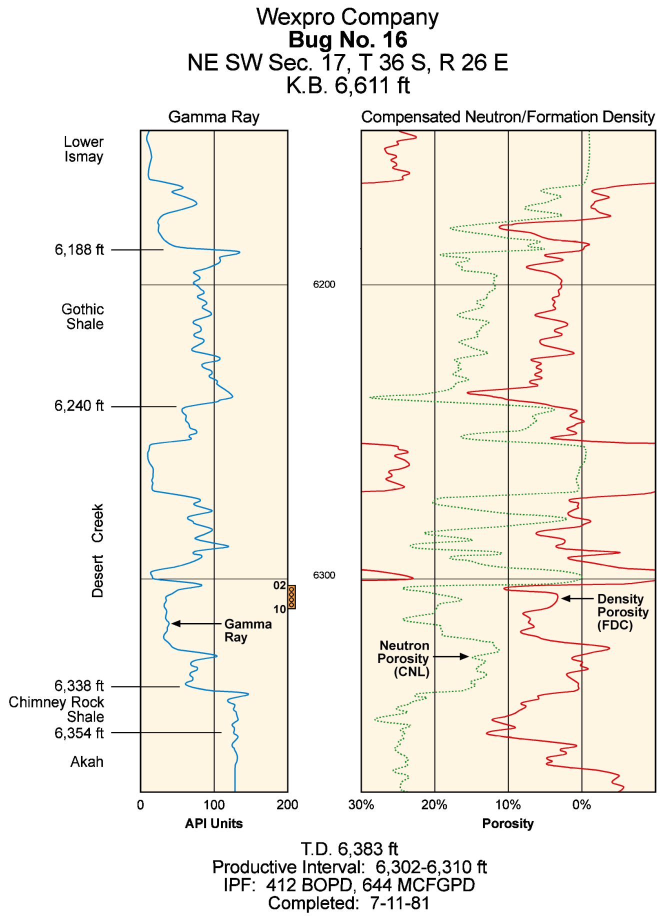


***Figure 19.** Typical gamma ray-compensated neutron/formation density log for the Desert Creek zone in the Blanding sub-basin, from the Bug No. 16 well (section 17, T. 36 S., R. 26 E., Salt Lake Base Line and Meridian [SLBL&M]), Bug field, San Juan County, Utah. Producing (perforated) interval between depths of 6302 and 6310 feet. See figure 8 for location of Bug field.*

Lithology

__**Blanding sub-basin Ismay and Desert Creek zones subplays:**__ Open-marine lithofacies are found in both the Ismay and Desert Creek zones of the Blanding sub-basin (figures 11 through 13, and 23). Rock representing this lithofacies consists of lime mudstone containing well-preserved rugose corals, crinoids, brachiopods, bryozoans, articulated thin-shelled bivalves, and benthic forams indicative of normal-marine salinities and low-energy conditions. Rock units of this lithofacies have very little effective porosity and permeability, and act as barriers and baffles to fluid flow.

Middle-shelf lithofacies are also found in both the Ismay and Desert Creek zones (figure 24). The most common depositional fabrics of this lithofacies are bioturbated lime to dolomitic mudstone with ubiquitous sub-horizontal feeding burrows, and fossiliferous peloidal wackstone. There are few megafossils and little visible matrix porosity. However, there is some fusulinid-rich lime wackestone to packstone also present in very tight, biogenically graded limestone.

Inner shelf/tidal flat lithofacies are found in the Ismay zone as dolomitized packstone and grainstone (figure 25). Clotted, lumpy, and poorly laminated microbial structures resembling small thrombolites and intraclasts are common. Megafossils and visible porosity are very rare in the inner shelf/tidal flat setting. Non-skeletal grainstone (calcarenite) composed of ooids, coated grains, and "hard peloids" occurs as high-energy deposits in some inner shelf/ tidal flat settings. Remnants of interparticle and moldic pores may be present in this lithofacies.

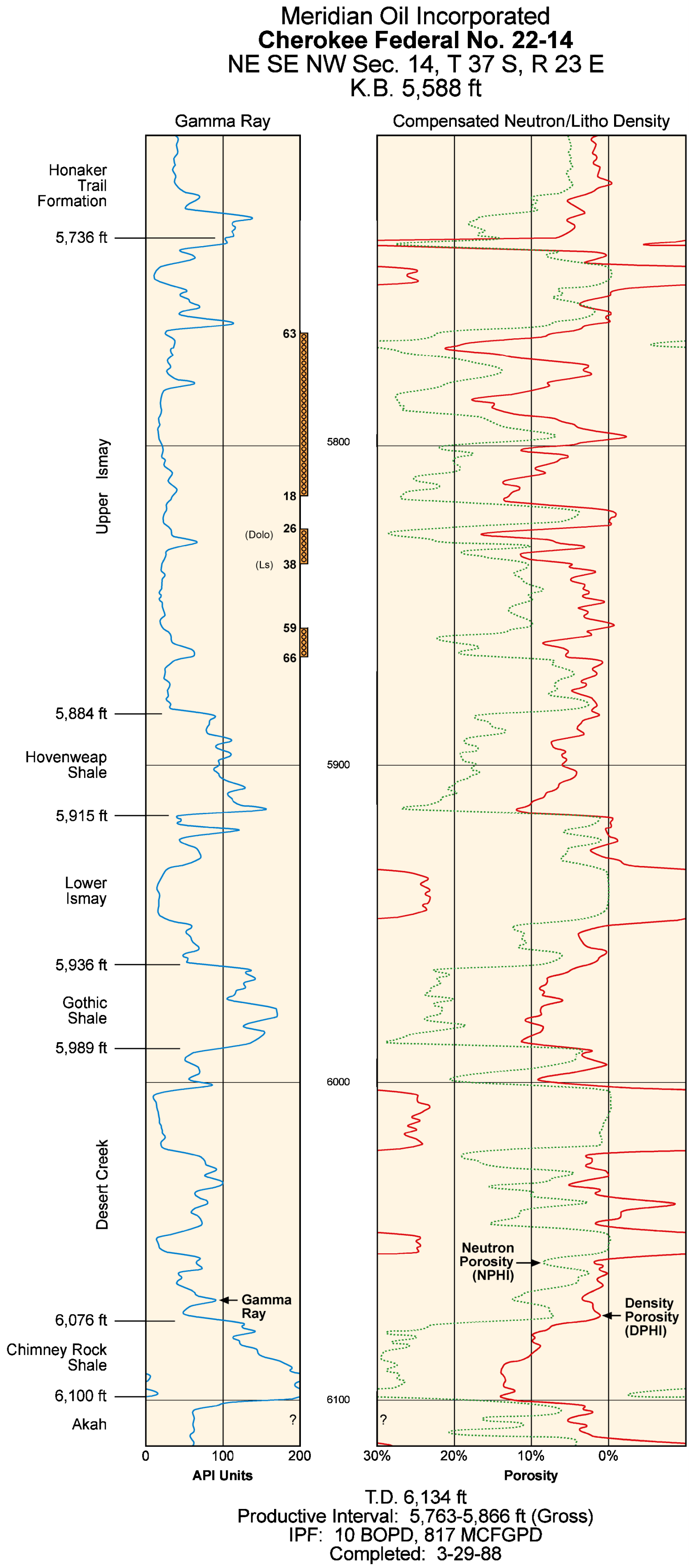


***Figure 20.** Typical gamma ray-compensated neutron/litho density log for the Ismay zone in the Blanding sub-basin, from the Cherokee Federal No. 22-14 well (section 14, T. 37 S., R. 23 E., SLBL&M), Cherokee field, San Juan County, Utah. Producing (perforated) interval between depths of 5763 and 5866 feet. See figure 8 for location of Cherokee field.*

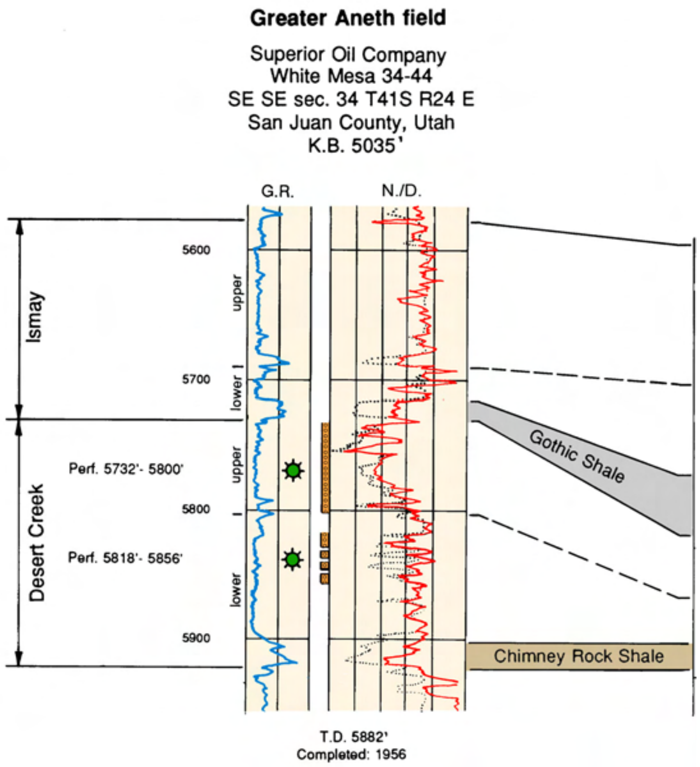


Figure 21. Typical gamma ray-compensated neutron/density log for the Desert Creek zone in the Aneth platform, from the White Mesa No. 33-44 well (section 34, T. 41 S., R. 24 E., SLBL&M), Greater Aneth field, San Juan County, Utah. Producing (perforated) interval between depths of 5732 and 5856 feet. See figure 8 for location of Greater Aneth field.

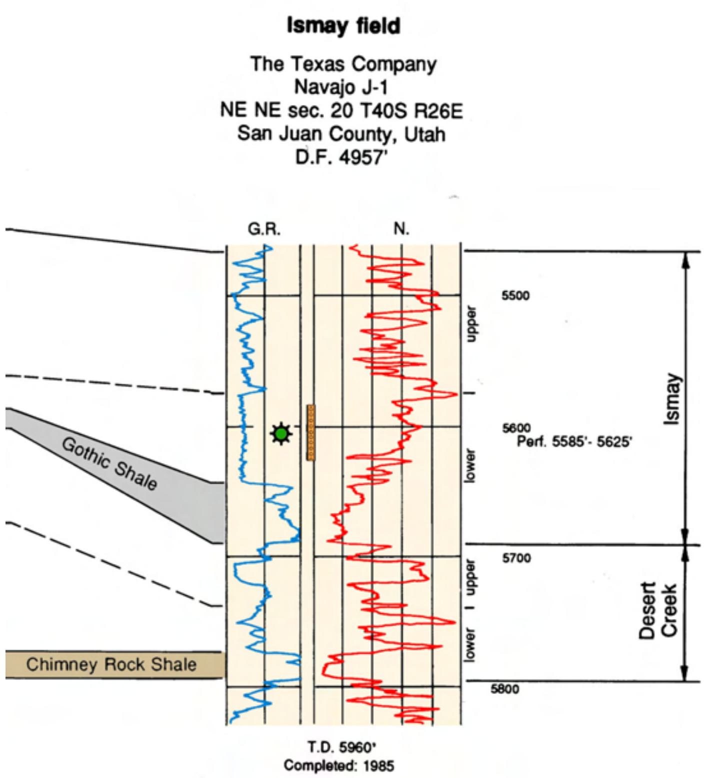


Figure 22. Typical gamma ray-compensated neutron log for the Ismay zone in the Aneth platform, from the Navajo No. J-1 well, Ismay field (section 20, T. 40 S., R. 26 E., SLBL&M), San Juan County, Utah. Producing (perforated) interval between depths of 5585 and 5625 feet. See figure 8 for location of Ismay field.

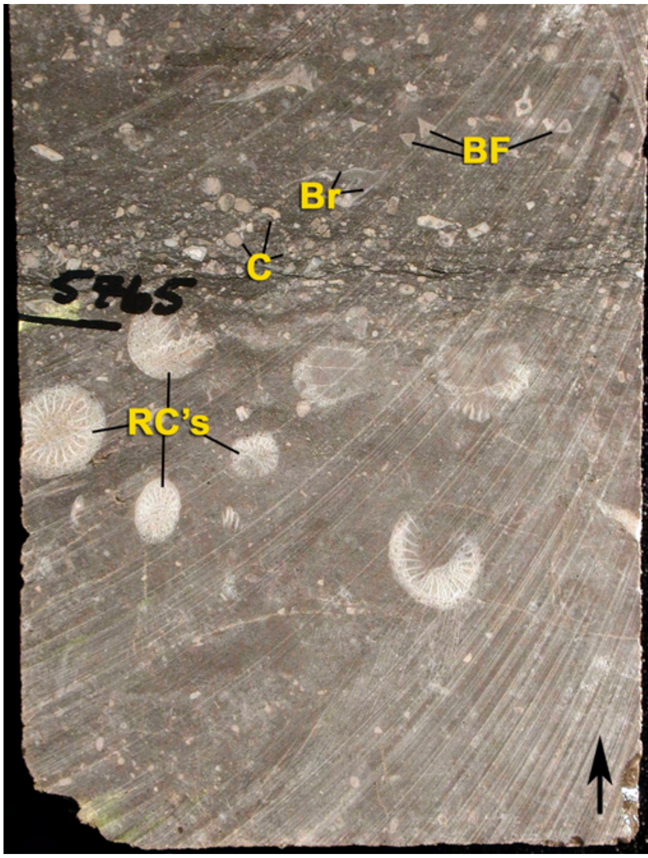


Figure 23. Typical Ismay-zone open-marine lithofacies showing well-preserved rugose corals (RC), crinoids (C), brachiopods (Br), and benthic forams (BF); No. 1-28 Cuthair wildcat well (section 28, T. 38 S., R. 22 E., SLBL&M), San Juan County, Utah, slabbed core from 5765 feet.

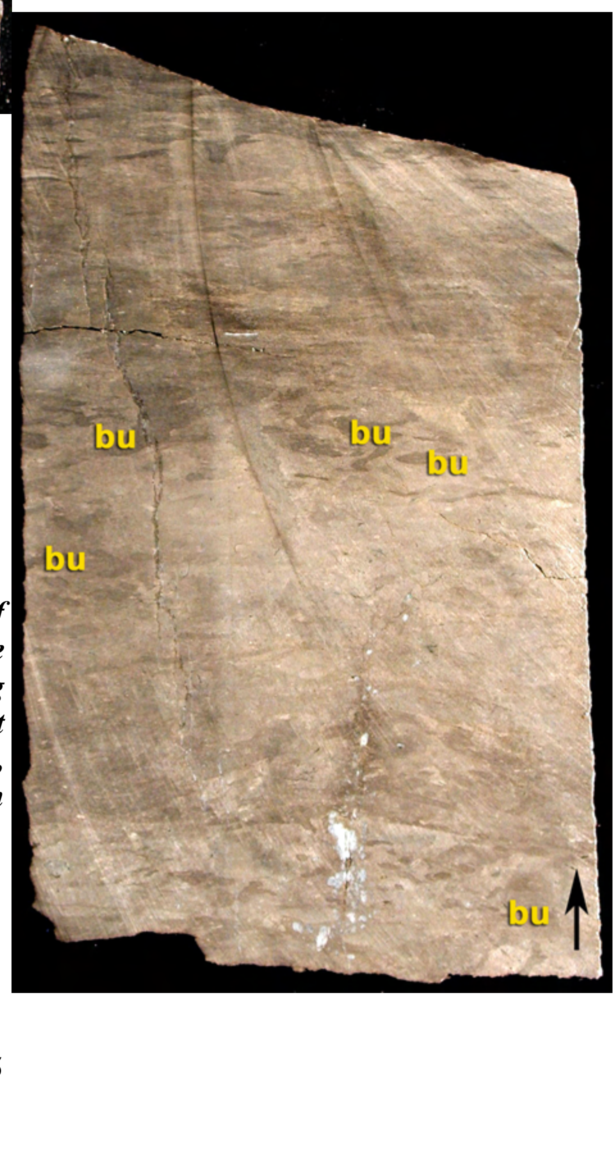


Figure 24. Typical Ismay-zone middle-shelf lithofacies showing bioturbated lime mudstone containing compacted sub-horizontal feeding burrows (bu); Tank Canyon No. 1-9 wildcat well (section 9, T. 37 S., R. 24 E., SLBL&M), San Juan County, Utah, slabbed core from 5412.5 feet.

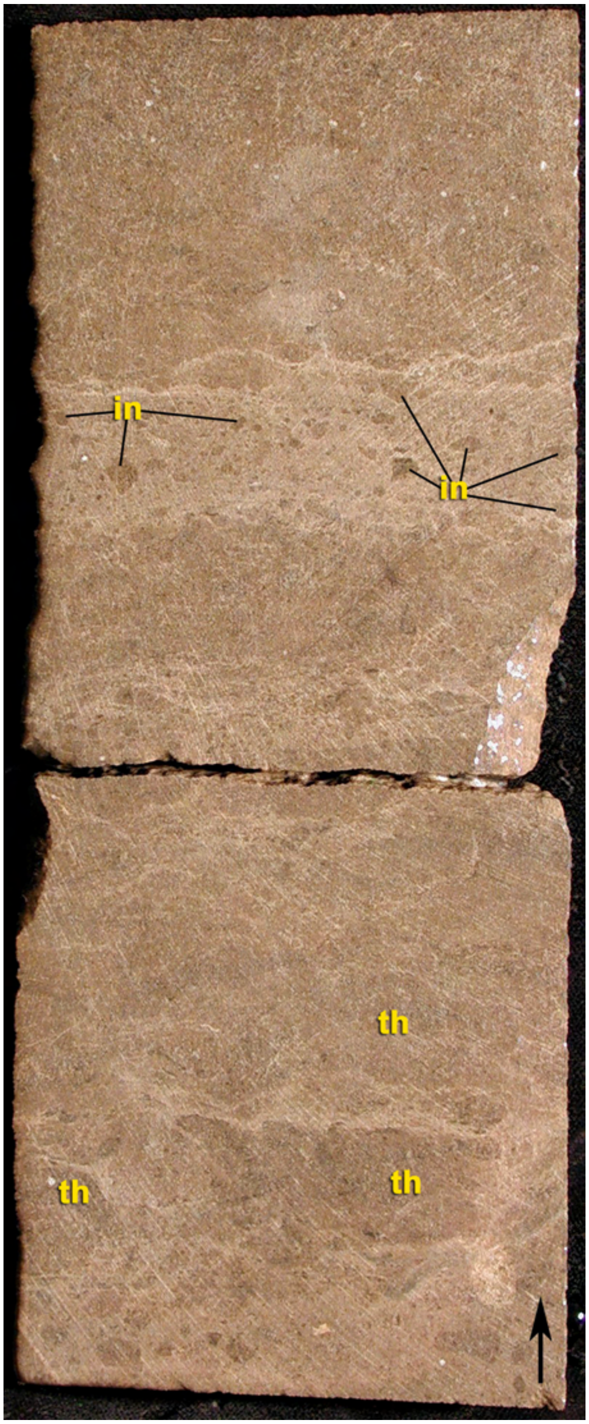


Figure 25. Typical Ismay-zone inner shelf/ tidal flat lithofacies showing dolomitized lumpy microbial structures resembling small thrombolites (th) and intraclasts (in) composed of desiccated and redeposited thrombolitic fragments; Tin Cup Mesa No. 2-23 well (section 23, T. 38 S., R. 25 E., SLBL&M), Tin Cup Mesa field, San Juan County, Utah, slabbed core from 5460.5 feet.

Bryozoan mound lithofacies are found in the Ismay zone as mesh-like networks of tubular and sheet-type (fenestrate) bryozoans (figure 26). These bryozoans provide the binding agent for lime mud-rich mounds. Crinoids and other open-marine fossils are common. Large, tubular bryozoans and marine cement are also common in areas of high-energy, and possibly shallow, water. Porosity is mostly confined to preserved intraparticle spaces.

Phylloid-algal mound lithofacies are found in both the Ismay and Desert Creek zones (figures 11 through 13, and 27). Very large phylloid-algal plates of *Ivanovia* (the dominant genus in the Ismay zone) and skeletal grains create bafflestone or bindstone fabrics. In mound interiors, algal plates are commonly found in near-growth positions surrounded by lime mud (figure 27A). On the high-energy margins of algal mounds, algal plates and skeletal grains serve as substrates for substantial amounts of botryoids and other early-marine cements, and internal sediments (figure 27B). Desert Creek mounds are dolomitized, contain plates of the *Kansasphyllum* (figure 27C), and show evidence of subaerial exposure (breccia or beach rock). Pore types include primary shelter pores preserved between phylloid-algal plates and secondary moldic pores.

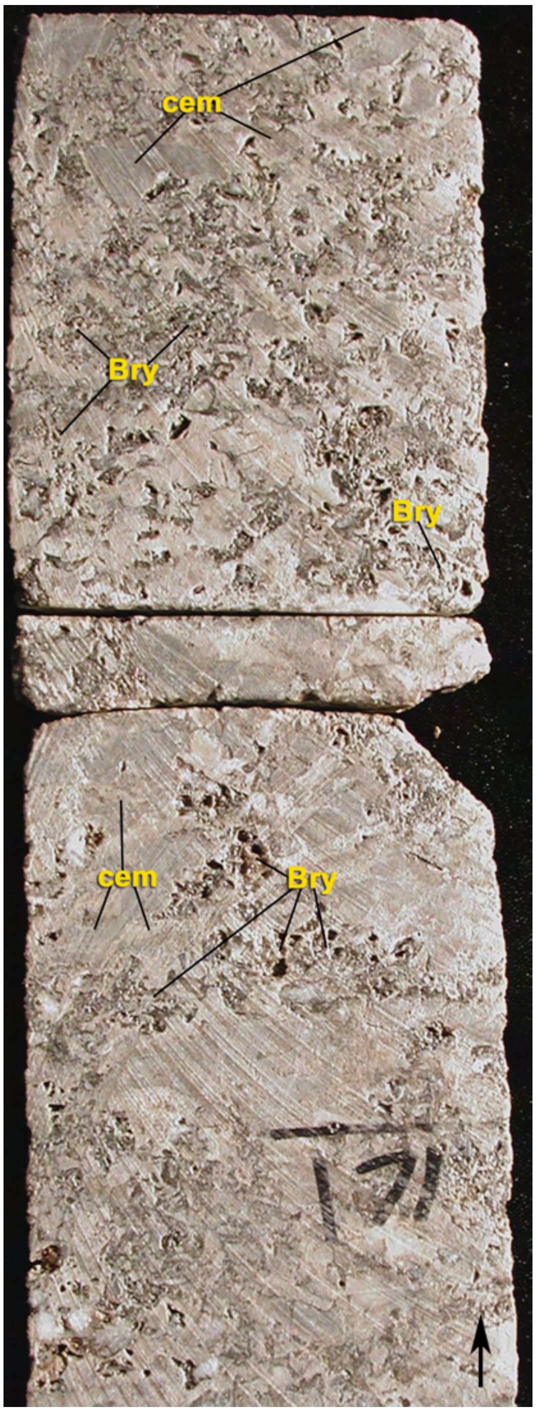
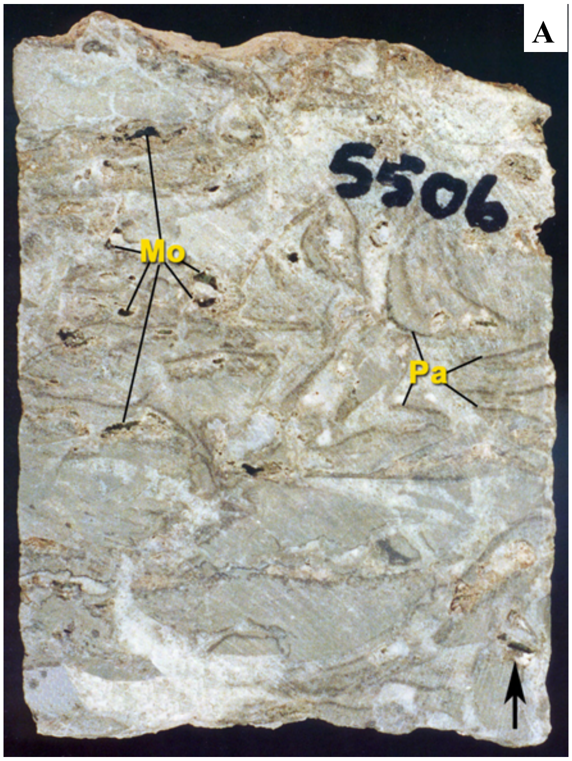


Figure 26. Typical Ismay-zone bryozoan-mound lithofacies showing large tubular bryozoans (Bry) and "lumps" of marine cement (cem). Scattered phylloid-algal plates are also present. This mound fabric is typical of higher energy, and possibly shallower water than the mud-dominated fabrics. Mustang No. 3 well (section 26, T. 36 S., R. 25 E., SLBL&M), Mustang Flat field, San Juan County, Utah, slabbed core from 6171 feet.



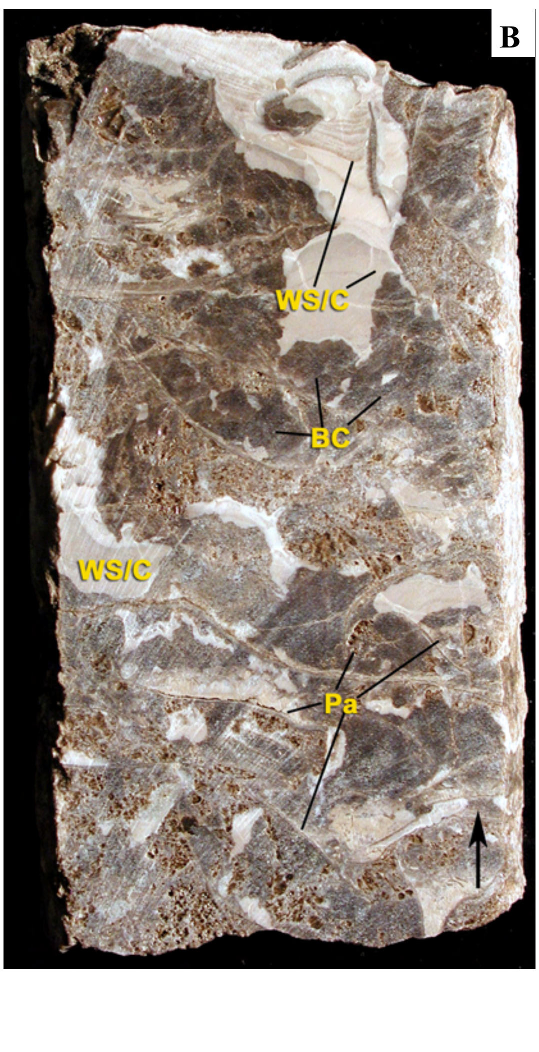


***Figure 27.** Typical Ismay and Desert Creek phylloid-algal mound facies. (A) Ismay bafflestone fabric showing large phylloid-algal plates (Pa) in near-growth positions surrounded by light gray lime muds; note the scattered moldic pores (Mo) that appear black here. Tin Cup Mesa No. 3-26 well (section 26, T. 38 S., R. 25 E., SLBL&M), Tin Cup Mesa field, San Juan County, Utah, slabbed core from 5506 feet. (B) Ismay bindstone (cementstone) showing very large phylloid-algal plates (Pa), loose skeletal grains, and black marine botryoids (BC) as well as light brown, banded, internal sediments and marine cements (WS/C); note the patches of preserved porosity within coarse skeletal sediments between algal plates. Bonito No. 41-6-85 wildcat well (section 6, T. 38 S., R. 25 E., SLBL&M), San Juan County, Utah, slabbed core from 5590.5 feet. (C) Desert Creek mound composed of dolomitized algal plates of the genus Kansasphyllum (arrows); May Bug No. 2 well (section 7, T. 36 S., R. 26 E., SLBL&M), Bug field, San Juan County, Utah, slabbed core from 6310 feet.*

Anhydrite salina lithofacies are found within locally thick accumulations in upper Ismay (upper and lower parts) intra-shelf basins (figures 11 and 12). Anhydrite growth forms include nodular-mosaic ("chicken-wire"), palmate, and banded anhydrite (figure 28). Large palmate crystals probably grew in a gypsum aggregate indicative of subaqueous deposition. Detrital and chemical evaporites (anhydrite) filled in the relief around palmate structures. Thin, banded couplets of pure anhydrite and dolomitic anhydrite are products of very regular chemical changes in the evaporite intra-shelf basins. These varve-like couplets are probably indicative of relatively "deep-water" evaporite precipitation.

Aneth platform Desert Creek zone subplay: Platform-interior carbonate mud and sand lithofacies are represented by grainstone, packstone, wackestone, and mudstone fabrics. Rocks representing this lithofacies typically contain the following diagnostic constituents: soft-pellet muds, hard peloids, grain aggregates, crinoids and associated skeletal debris, and fusulinids. The platform-interior carbonate mud and sand lithofacies can contain reservoir-quality rocks if dolomitized. However, effective porosity and permeability are highly variable.

Calcarenite lithofacies include grainstone (figures 29 and 30) and packstone fabrics. Rocks representing this facies typically contain the following diagnostic constituents: oolites, coated grains, hard peloids, bioclastic grains, shell lags, and intraclasts.

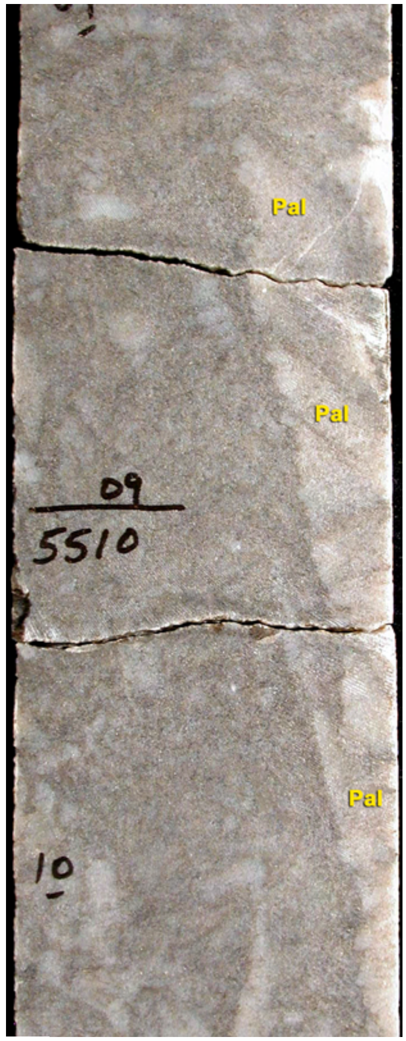
Phylloid-algal buildup lithofacies can be subdivided into shelter, mud-rich, and solution breccia lithofacies. Rocks representing shelter, phylloid-algal buildup lithofacies contain in-place phylloid-algal plates (*Ivanovia* and *Eugonophyllum*), encrusting forams (for example *Tetrataxis*), soft peloidal mud, and minor amounts of internal sediment (mud or grains deposited after storms [suspended load]). The depositional fabric is predominantly bafflestone (figure 31). These rocks have a high faunal diversity. The mud-rich, phylloid-algal buildup lithofacies are represented by bafflestone, wackestone, and mudstone fabrics. Rocks of this lithofacies contain in-place phylloid-algal plates surrounded by lime mud, fine skeletal debris, and microfossils. The solution breccia, phylloid-algal buildup lithofacies includes disturbed rudstone and floatstone with some packstone fabrics. Rocks of this lithofacies contain chaotic phylloid-algal and exotic clasts, peloids, and internal sediments (muds).

Coralline-algal buildup lithofacies consists of selectively dolomitized bindstone, boundstone, and framestone fabrics. Rocks representing this facies contain calcareous, encrusting and bulbous coralline (red) algae, variable amounts of lime mud, microfossils, and calcispheres.

Bryozoan buildup lithofacies are represented by bindstone, bafflestone, and packestone fabrics that are rarely dolomitized. Rocks of this lithofacies contain the following diagnostic constituents: bryozoan colonies (*Chaetetes*), small rugose corals, scattered small calcareous sponges and phylloid-algal plates, microfossils, and lime muds.

Greater Aneth field (figures 2 and 8), Utah's largest oil producer, was discovered in 1956 and has produced over 440 million BO (70 million m^3) (Utah Division of Oil, Gas and Mining, 2006). The primary reservoir at Greater Aneth field consists of limestone (algal boundstone/bafflestone and oolitic, peloidal, and skeltal grainstone and packstone) and finely crystalline dolomite. The Desert Creek zone in the unit is divided into two subzones: a lower interval composed predominantly of phylloid-algal buildup lithofacies, and an upper interval composed of oolitic-peloidal calcarenite lithofacies (figures 30 through 32) (Peterson and Ohlen, 1963; Babcock, 1978a, 1978b, 1978c, 1978d; Peterson, 1992; Moore and Hawks, 1993). These subzones create a west-northwest-trending reservoir buildup (figure 17).

A



B

C

Figure 28. Anhydrite growth forms typically found in anhydrite salina facies of upper Ismay intra-shelf basins. (A) Nodular-mosaic ("chicken-wire") anhydrite; Tank Canyon No. 1-9 wildcat well (section 9, T. 37 S., R. 24 E. SLBL&M), San Juan County, Utah, slabbed core from 5343 feet. (B) Large palmate crystals of anhydrite (Pal) along the right margin of this core segment probably grew in a gypsum aggregate that resembled an inverted candelabra while the remainder of the core segment consists of detrital and chemical anhydrite that filled in the relief around the palmate structure; Sioux Federal No. 30-1 wildcat well (section 30, T. 38 S., R. 25 E., SLBL&M), San Juan County, Utah, slabbed core from 5510 feet. (C) Thin (cm-scale), banded couplets of pure anhydrite (white to light gray) and dolomitic anhydrite (brown); Montezuma No. 41-17-74 wildcat well (section 17, T. 37 S., R. 24 E., SLBL&M), San Juan County, Utah, slabbed core from 5882 feet.

Figure 29. Typical Desert Creek-zone dolomitized grainstone, calcarenite lithofacies; North Heron No. 35-C well (section 35, T. 41 S., R. 25 E., SLBL&M), Heron field, San Juan County, Utah, slabbed core from 5589 feet.

Figure 30. Typical Desert Creek-zone oolitic grainstone; Aneth No. 27-D-4 well (section 27, T. 40 S., R. 24 E., SLBL&M), Greater Aneth field, San Juan County, Utah, slabbed core from 5620 feet. Note excellent moldic porosity development.

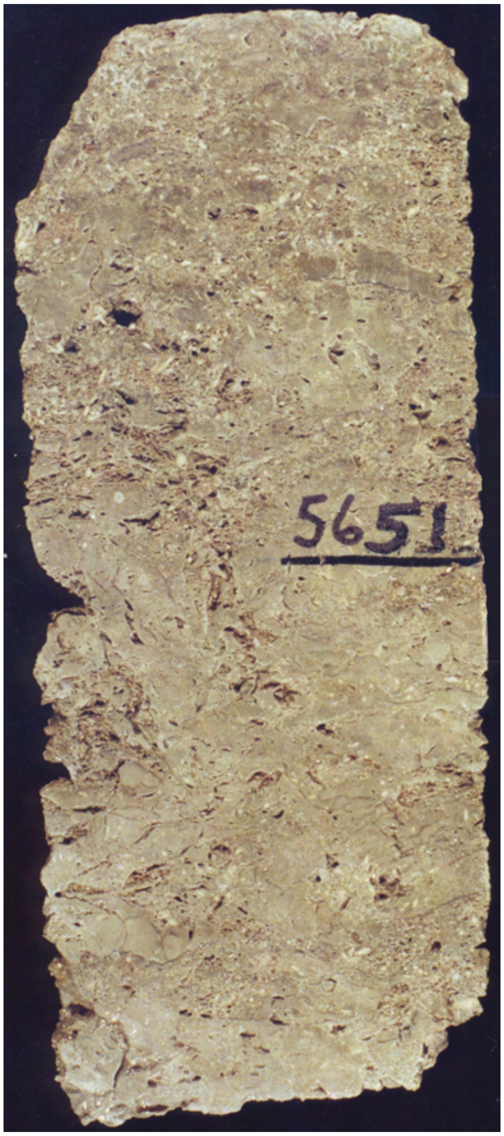


Figure 31. Typical highly productive Desert Creek-zone phylloid-algal plate bafflestone; Anasazi No. 1 well (section 5, T. 42 S., R. 24 E., SLBL&M), Greater Aneth field, San Juan County, Utah, slabbed core from 5651 feet. Note good visual shelter porosity.

Hydrocarbon Source and Seals

Hydrocarbons in Paradox Formation reservoirs were generated from source rocks within the formation itself. Organic-rich informal units, such as the Cane Creek, Chimney Rock, and Gothic shales (figure 7), are well-established source rocks (Hite and others, 1984; Nuccio and Condon, 1996). These rocks are composed of black, sapropelic shale and shaley dolomite (Morgan, 1993). The average total organic carbon (TOC) content of the black shale in Cane Creek shale is 15 percent with some samples containing up to 28 percent (Grummon, 1993). The Chimney Rock shale has from 1 to 3 percent TOC and a mean vitrinite reflectance (R_o mean) of 1.3 to 2.5 percent (Hite and others, 1984; Peterson, 1992). The Gothic shale has from 1.5 to near 4 percent TOC and an R_o mean of 0.8 to 1.2 percent (Hite and others, 1984; Peterson, 1992). Other, deeper shale facies in the Paradox Formation contain as much as 13 percent TOC (Hite and others, 1984). Peterson (1992) calculated a cumulative thickness of more than 1000 feet (330 m) of organic-rich rocks in the Paradox.

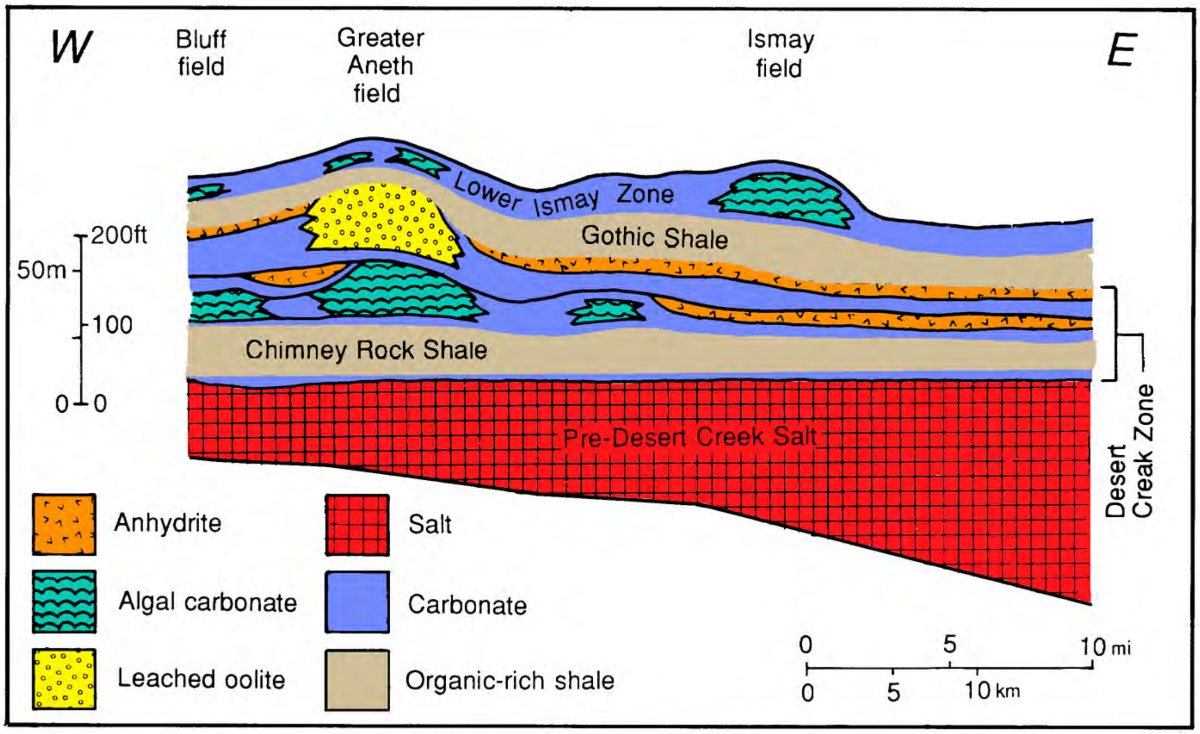


Figure 32. Diagrammatic lithofacies cross section, Greater Aneth field, southeastern Utah. Datum is base of the Desert Creek zone of the Paradox Formation. Modified from Peterson (1992).

Hydrocarbon generation occurred during maximum burial in the Late Cretaceous and early Tertiary. Hydrocarbons were then expelled and subsequently migrated, primarily along fracture and fault planes, into carrier beds, structures, or carbonate buildups (stratigraphic traps).

Vertical reservoir seals for the Paradox producing zones are shale, halite, and anhydrite within the formation; lateral seals are permeability barriers created by unfractured, off-mound (non-buildup) mudstone, wackestone, and anhydrite.

Structure and Trapping Mechanisms

Trap types in the Blanding sub-basin and Aneth platform regions include stratigraphic, stratigraphic with some structural influence, combination stratigraphic/structural, and diagenetic. Regional dip is gently to the north-northeast towards the center of the basin. Hydrocarbons are most often stratigraphically trapped in porous and permeable rocks within Ismay and Desert Creek carbonate buildups described earlier. The trap is formed as these buildups rapidly thin and grade laterally into impermeable mudstone, wackestone, and anhydrite. They are effectively sealed by impermeable platform intervals at the base and a relatively thick layer of anhydrite (20 feet [6 m]) or shale (for example, the 50-foot-thick [15 m] Gothic shale above the Desert Creek zone) at the top. The best stratigraphic traps in the region are associated with phylloid-algal buildup and associated calcarenite lithofacies. These traps are widely distributed, generally small to moderate in size, and can be readily identified on seismic records. However, Greater Aneth field is the exception in terms of size (figures 5 and 8), and is Utah's largest oil producer. Structural relief is often shown on top of structure maps for the Desert Creek zone (or the Ismay zone) at Greater Aneth (figure 33) and numerous other fields in the region. However, this relief is created by the variations between the thick mound, or carbonate buildup, and thinner off-mound lithofacies (figure 17) (Babcock, 1978a). Overlying units are generally thin and drape over the buildup; however, there is usually no surface expression of these features.

Many carbonate buildups appear to have developed on subtle anticlinal noses or structural closures (figure 34). These structures may represent paleobathymetric highs formed by pre-Pennsylvanian reactivation of basement faults, or simply longshore current-formed mudbars on the Paradox shallow-marine shelf (Babcock, 1978a). These "highs" provided the substrate for algal growth and mound buildup. An opposite view is presented by Matheny and Longman (1996). They contend that fields such as Bug (figure 35), Cutthroat, Island Butte, and Spargo (figure 8) produce from phylloid-algal buildups deposited in sea-floor lows resulting from dissolution of halite in the underlying Akah zone (figure 7). Phylloid-algal lithofacies thickness was dictated by the timing and amount of halite dissolution – the greater the halite dissolution during algal growth, the thicker the potential reservoir (Matheny and Longman, 1996).

In some instances, stratigraphic traps have been enhanced by true structural relief, fracturing, and minor normal faults. Other traps include carbonate buildups located directly on anticlines. For example, Desert Creek field (figure 8) produces from a carbonate-buildup reservoir located directly on the crest of a north-northwest to south-southeast-trending anticline with 300 feet (100 m) of four-way closure (figure 36). A 500-foot (150 m), down-to-the-east normal fault parallels the west flank of the structure. Production from other anticlinal traps on the Aneth platform is found at Tohonadla in San Juan County, Utah (Norton, 1978), and Boundary Butte East in Apache County, Arizona (Dunn, 1978) (figure 8).

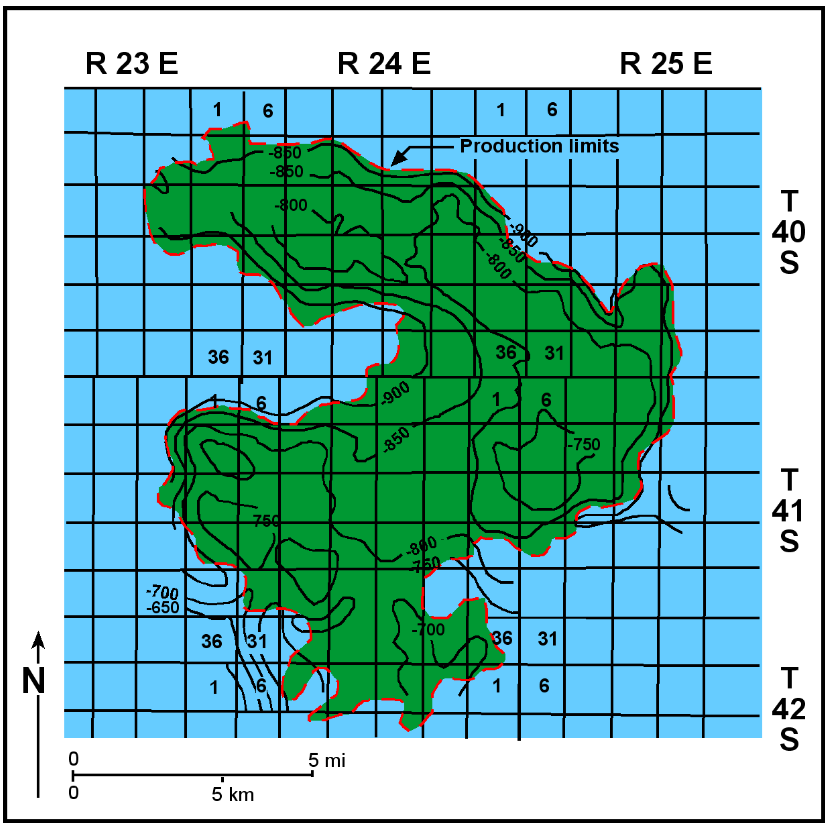


Figure 33. Structure contour map of the top of the Desert Creek zone, Greater Aneth field, San Juan County, Utah; contour interval = 50 feet. Modified from Peterson (1992).

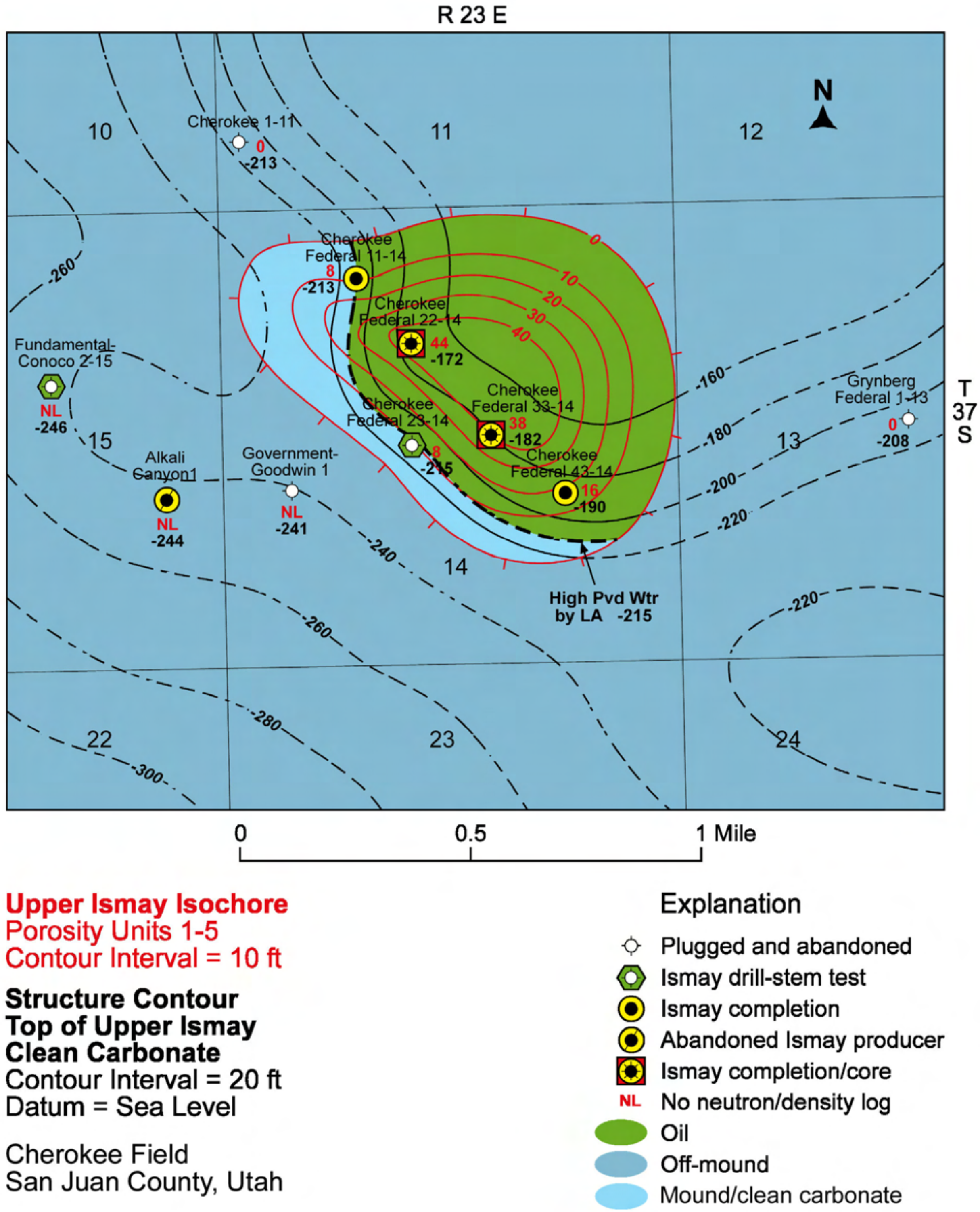


Figure 34. Map of combined top of structure and isochore of porosity, upper Ismay-zone mound, Cherokee field, San Juan County, Utah.

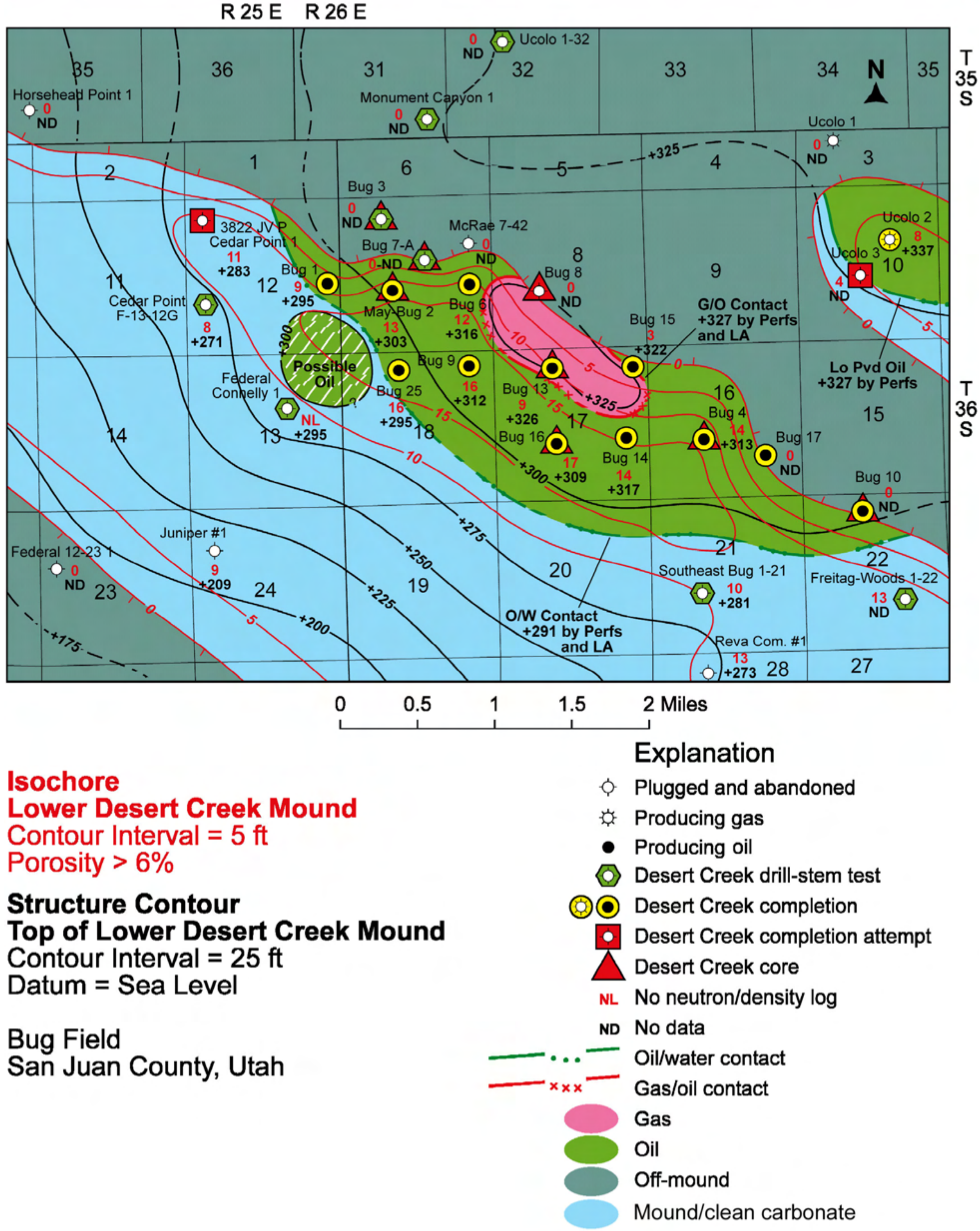


Figure 35. Map of combined top of structure and isochore of lower Desert Creek-zone mound, Bug field, San Juan County, Utah.

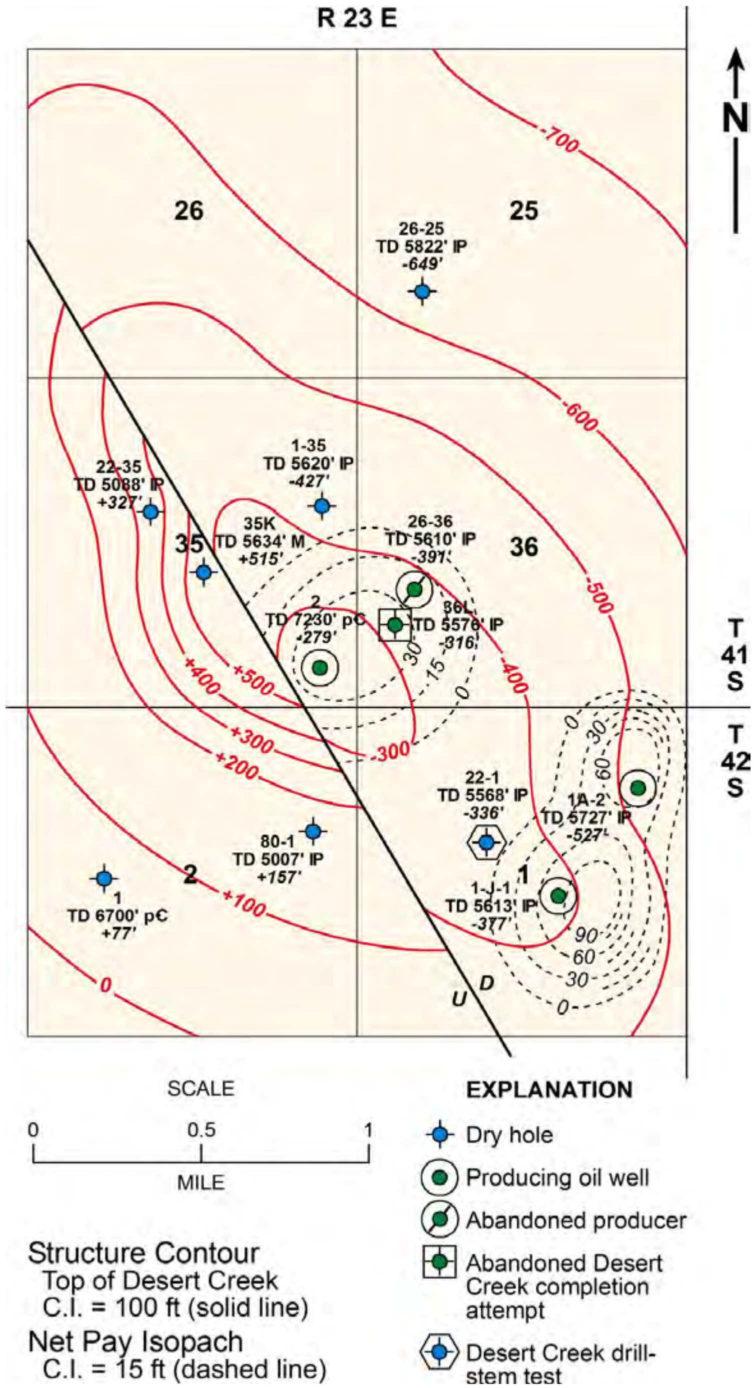


Figure 36. Map of combined top of structure and isochore of the Desert Creek-zone mound, Desert Creek field, San Juan County, Utah. Modified from Lauth (1978b).

Diagenesis is commonly a major component of trap development and reservoir heterogeneity in the carbonate buildups of Blanding sub-basin and Aneth platform fields. Dolomitzation and the creation of microporosity can yield reservoir quality in carbonate fabrics that are typically non-productive, such as wackestone and packstone (Chidsey and others, 1996; Eby and Chidsey, 2001; Chidsey, 2002; Chidsey and Eby, 2002). The reservoir at Bug field (figure 8) is an elongate, northwest-trending, dolomitized carbonate buildup in the lower Desert Creek zone. The trapping mechanism is primarily an updip porosity pinchout (figure 35).

Reservoir Properties

The Paradox Formation has heterogeneous reservoir properties because of (1) lithofacies with varying porosity and permeability, (2) carbonate buildup (mound) relief and flooding surfaces (parasequence boundaries), and (3) diagenetic effects. The extent of these factors, and how they are combined, affect the degree to which they create barriers to fluid flow. Identification and correlation of depositional lithofacies and parasequences in individual Paradox reservoirs is critical to understanding their effect on water/carbon dioxide injection programs, production rates, and paths of petroleum movement.

Porosity and permeability: Paradox porosity in carbonate reservoirs ranges from 7 to 16 percent with typical porosity averaging 11 percent. Permeability is highly variable, generally ranging from less than 1 up to 55 millidarcies (mD) with an average of 14 mD. At Greater Aneth field (figure 8), the porosity averages 10.2 percent (averaging 16.5 percent in selected intervals) and permeability ranges from less than 3 up to 30 mD, averaging 10 mD (Moore and Hawks, 1993).

Diagenesis and pore types: The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing carbonate rocks of the Desert Creek and Ismay zones can be an indicator of reservoir flow capacity, storage capacity, potential for water- and/or CO_2-flooding, and horizontal drilling. The framework grains of carbonate buildups consist predominantly of phylloid-algal plates, with lesser amounts of brachiopods, bryozoans, pelloids, oolites, ostracods, and forams. They yield primary porosity such as shelter (figure 37), interparticle (figure 38), and intraparticle (particularly in bryozoan-dominated buildups) (figure 39) pore types. Where these pore types are well developed, the reservoirs have excellent hydrocarbon storage and fluid-flow capacity, and are good candidates for CO_2 flooding.

Most shallow-shelf/shelf-margin carbonate buildups, or mounds, had relief with exposure occurring when sea level fell. This setting produced four major, generally early, diagenetic environments (figure 40): (1) fresh-water (meteoric) vadose zone (above the water table, generally at or near sea level), (2) meteoric phreatic zone (below the water table), (3) marine phreatic zone, and (4) mixing zone (Longman, 1980). The "iceberg" principle (the Ghyben-Herzberg theory) – which is that for every foot the water table rises above sea level there may be 20 feet (6 m) of fresh water below the water table, a 1:20 ratio – can generally be applied to both carbonate-mound and island buildups (Friedman and Sanders, 1978). The typical early diagenetic events occurred in the following order (figure 41): (1) early marine cementation which may include first-generation micrite and fibrous isopachous cementation, second-generation botryoidal cementation, and third-generation radiaxial cementation (note: early-marine cements are not always present), (2) post-burial, replacement, rhombic dolomite cementation due to seepage reflux, (3) vadose and meteoric phreatic diagenesis including leaching/dissolution, neomorphism, and fresh-water cementation (dogtooth, stubby, and small equant calcite), (4) mixing-zone dolomitization, (5) syntaxial cementation, (6) anhydrite cementation/replacement, and (7) minor silica replacement.

That portion of the carbonate buildup facing the open-marine environment was generally a steep-wall complex where early-marine cements (such as fibrous isopachous, botryoidal, and radiaxial cements) were deposited from invading sea water flowing through the system and filled most original pore space (figures 40, 42, and 43). Locally, cemented zones

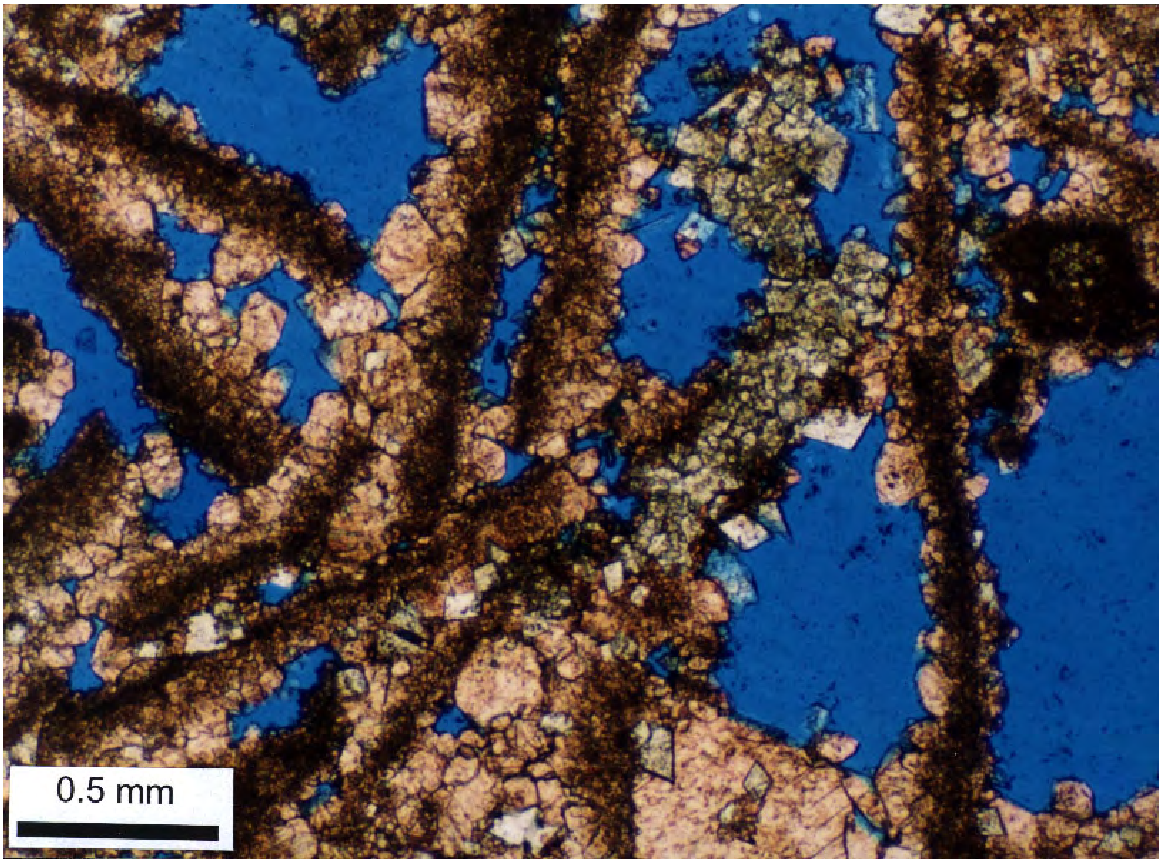


Figure 37. Typical Desert Creek-zone primary shelter and early solution porosity within a phylloid-algal bafflestone partially occluded by stubby to equant to dogtooth spar cements of probably meteoric phreatic origin; porosity = 12.5 percent, permeability 53.8 mD by core-plug analysis. These types of cements have degraded the permeability of these solution-enhanced pore systems. Runway No. 10-C-5A well (section 10, T. 40 S., R. 25 E., SLBL&M), photomicrograph (plane light) from 6127.4 feet, Runway field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

can have a major impact on reservoir flow and storage capacity. The opposite side of the mound typically bordered a hypersaline lagoon filled with dense brine that seeped into the phreatic zone (seepage reflux) to form a wedge-shaped zone of early, low-temperature dolomite – both early replacement dolomite and dolomite cement. Seepage reflux dolomization is usually complete dolomitization. Little original fabric/matrix remains. Crystals are fine to medium grained, often sucrosic; intercrystalline porosity dominates (figure 44). Seepage reflux overprints the fresh-water phreatic, marine phreatic, and mixing zones across the entire extent of the mound buildup. Thick seepage reflux dolomites are often proximal to evaporite-plugged lagoonal sediments. Locally, seepage reflux dolomitization can enhance both reservoir flow and storage capacity. Those reservoirs with excellent storage capacity may be considered candidates for CO_2 flooding projects.

The meteoric and marine phreatic zones were separated by a mixing zone (fresh and sea water), all of which changed with sea-level fluctuation. Most carbonate buildups have a mixing-zone and as well as fresh-water overprint. Some early dolomitization took place in the

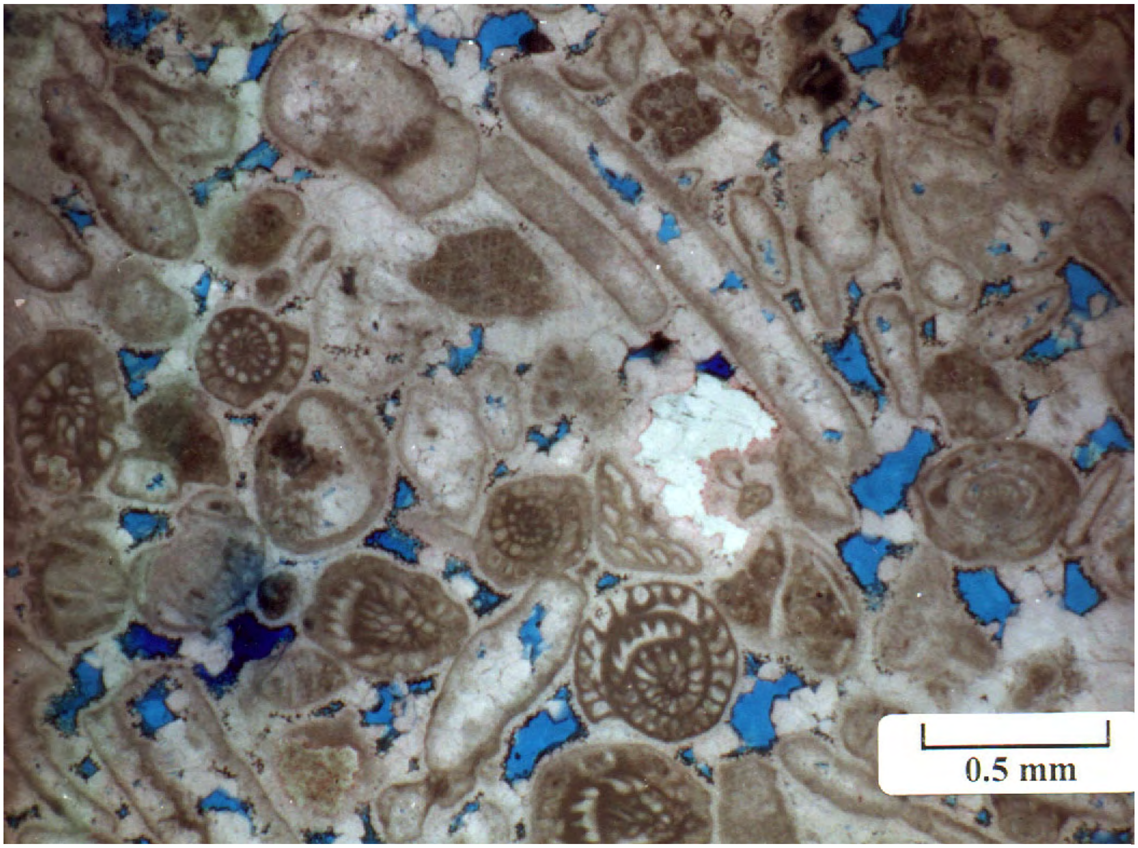


Figure 38. Typical Ismay-zone interparticle porosity developed in a high-energy calcarenite skeletal and aggregate grainstone; porosity = 4.6 percent, permeability = 0.018 mD by core-plug analysis. Among the typical grains of this facies are benthic forams (including fusulinids), phylloid-algal plates, "hard" peloids or micritized skeletal grains, and grain aggregates. The scattered pores (in blue) visible in this image are principally the remnants of primary interparticle space between the skeletal components of this grainstone. Early marine isopachous cements, followed by probable meteoric dogtooth calcite spar and minor anhydrite (in white) have occluded most of the original interparticle porosity. Little Ute No. 1 well (section 11, T. 34 S., R. 20 W.), photomicrograph (plane light with white card technique [diffused light using a piece of paper on the stage of the microscope]) from 5940.5 feet, Little Ute field, Montezuma County, Colorado. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

mixing zone (figure 45). Dissolution was the dominant porosity-enhancing process of meteoric diagenesis and creates molds, vugs, and channels (figure 46). Much of the original fabric remains or can be determined. However, some grainstone, packstone, and calcarenite have only non-connected moldic pores that result in classic "heart break" reservoirs. Early dissolution of lime muds also created microporosity. Indicative cements include stubby to equant calcite and dogtooth calcite spars that sporadically line pores (figure 37). Vadose zones generally have less cement than the fresh-water phreatic zones. The depth/thickness of the meteoric vadose and fresh-water phreatic zones is dependent on the extent and duration of subaerial exposure as well as the amount of meteoric water influx. Locally, meteoric diagenesis enhances reservoir

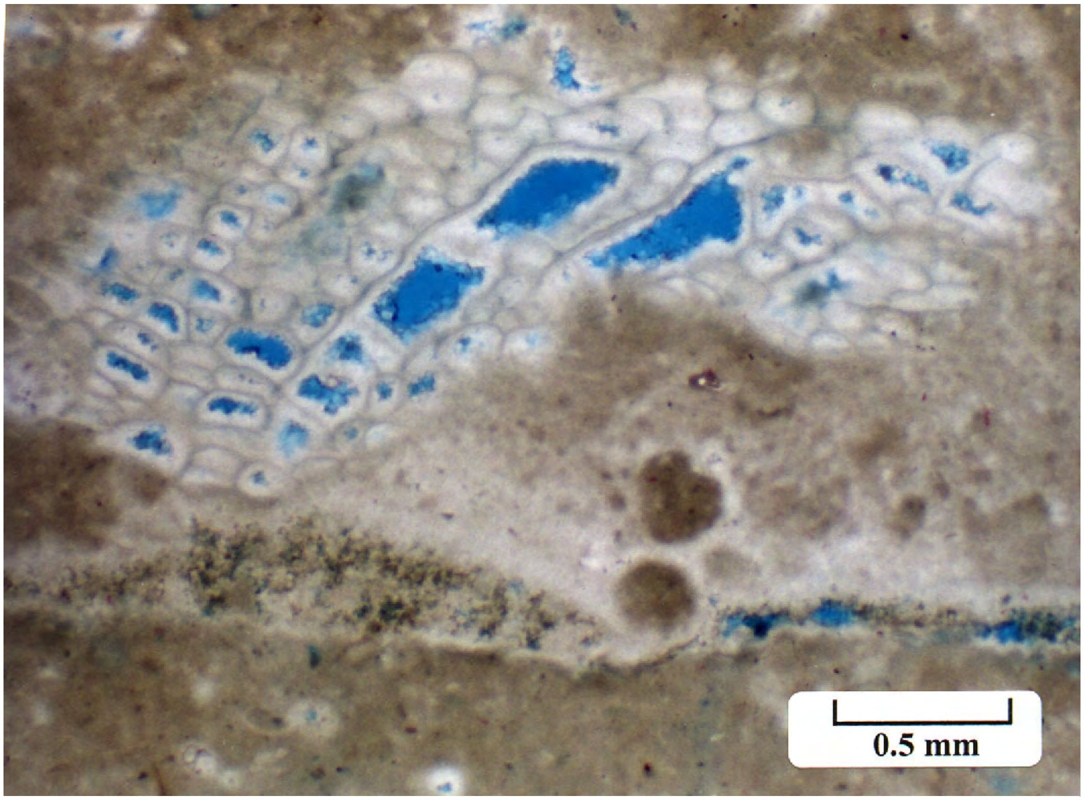


Figure 39. Ismay-zone intraparticle porosity; porosity = 9.8 percent, permeability = 12.2 mD by core-plug analysis. Open pores (in blue) are shown here within the uncemented chambers of encrusting organisms surrounded by lime muds. This sample is from within a phylloid-algal mound core. Little Ute No. 1 well (section 11, T. 34 S., R. 20 W.), photomicrograph (plane light with white card technique) from 5870.9 feet, Little Ute field, Montezuma County, Colorado. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

performance. Subaerial exposure of carbonate buildups, for example the Desert Creek zone at Bug field (figure 8), occasionally produced intense, early micro-box-work porosity. Figure 47 shows the pattern of patchy dolomite dissolution which includes a micro-box-work pattern of pores. Some of the pores in this view occur between elongate, rectilinear networks of dolomite laths. Micro-box-work porosity represents an important site for exploiting untapped hydrocarbons using horizontal drilling. Extensively leached intervals may have both excellent storage and flow capacity, and should be considered candidates for CO_2 flooding projects.

Post-burial diagenesis included additional syntaxial cementation, silicification, late coarse calcite spar formation, saddle dolomite cementation, stylolitization, additional anhydrite replacement, late dissolution (microporosity development), and bitumen plugging (figure 41). There is an observed progression from least to most important (syntaxial cementation to anhydrite replacement) which relates to increased reservoir heterogeneity in Paradox reservoirs. Some of these diagenetic products create barriers and baffles to fluid flow, such as the case where anhydrite and bitumen (or solid hydrocarbons) plug pores and pore throats. They are not observed on seismic records, are difficult to predict, and locally influence reservoir

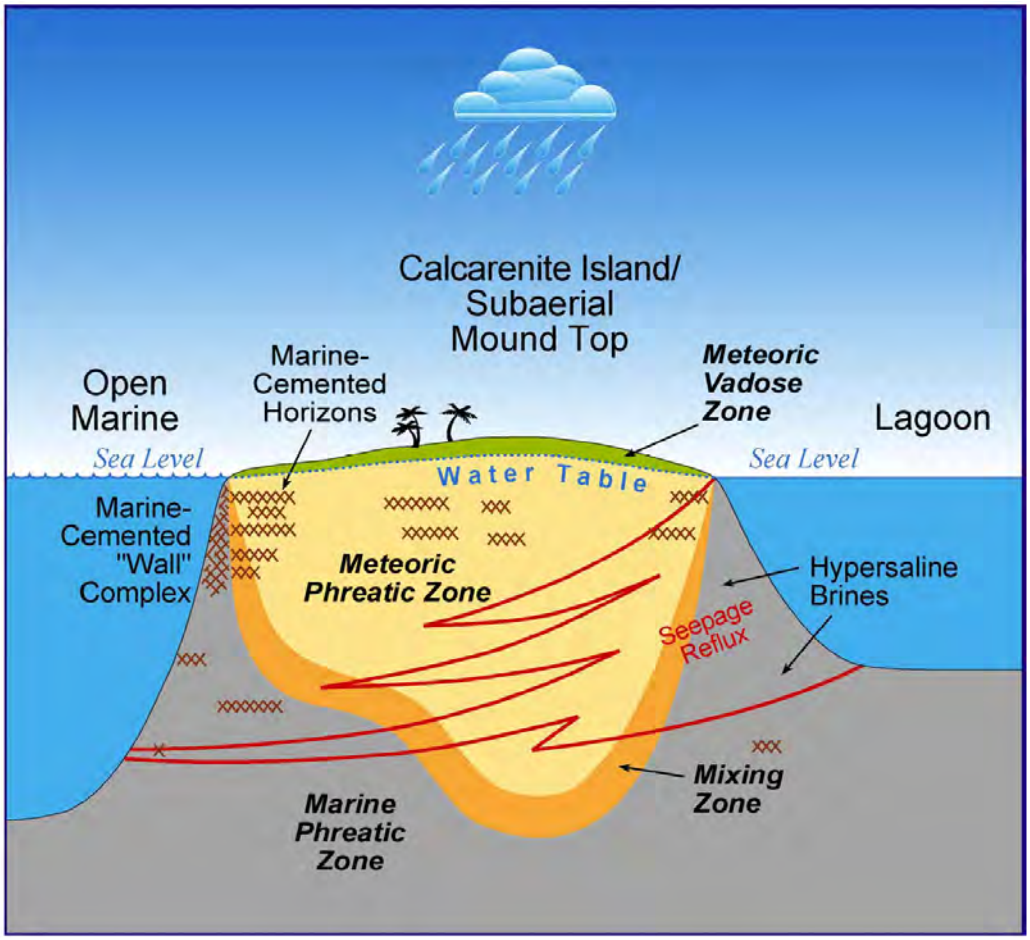


Figure 40. Model of early diagenetic environments found in the Desert Creek zone of the Paradox Formation, southern Paradox Basin (modified from Longman, 1980).

performance, storage capacity, and drainage. Some reservoirs, the Ismay zone in Cherokee field for example (figure 8), display intense microporosity (figures 48 and 49) that developed late, along solution fronts by the action of aggressive hydrothermal solutions from depth (carbon dioxide escaping from Mississippian Leadville Limestone or from deep decarboxylation of organic matter). Microporosity increases storage capacity, but limits fluid recovery. Microporosity represents an important site for untapped hydrocarbons and possible targets for horizontal drilling.

Engineering data: Paradox net-pay thickness is also variable, depending primarily on diagenesis, and ranges from 9 to 100 feet (3-30 m) averaging 35 feet (11 m). The average Paradox reservoir temperature is 126ºF (52ºC). Initial water saturations range from 25 to 50 percent (averaging 34 percent), salinities range from 80,000 to 349,000 parts per million, and resistivities (R_w) range from 0.045 to 0.07 ohm-m at 68ºF (20ºC). Initial reservoir pressures average about 2200 pounds per square inch (psi [15,000 kPa]). The reservoir drive mechanisms for Paradox reservoirs are predominantly solution gas but include gas-cap expansion, water drive, gas/pressure depletion, fluid expansion, and gravity drainage.

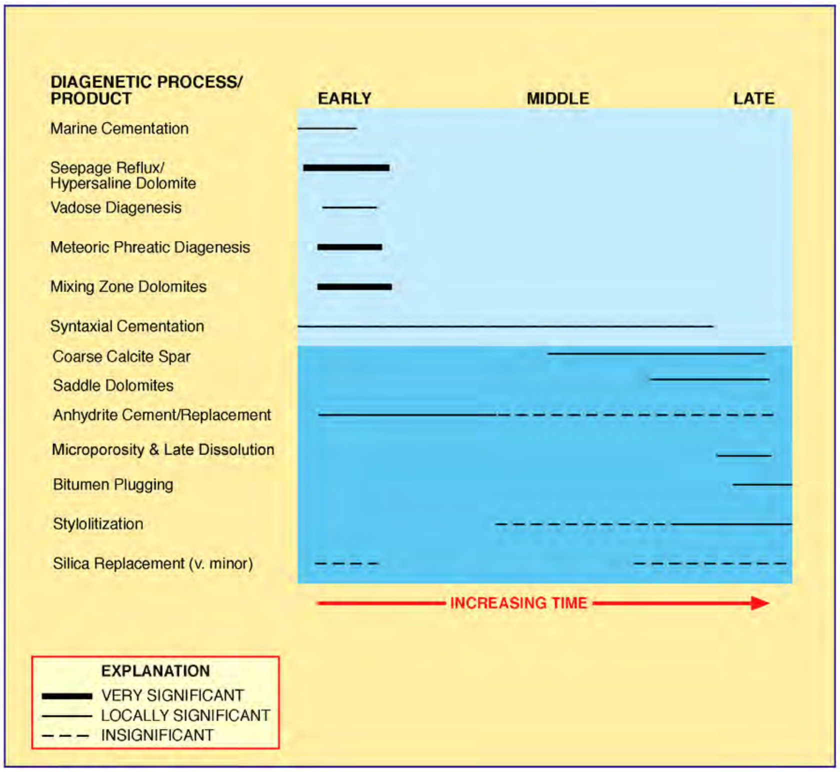


Figure 41. Typical diagenetic sequence through time based on thin section analysis, Ismay and Desert Creek zones.

Figure 42. Typical pattern of marine cementation within the well-lithified Desert Creek zone "wall" complex. Figure 3-20. Slabbed core segments from the Blue Hogan No. 1-J-1 well Blue Hogan No. 1-J-1 well (section 1, T. 42 S., R. 23 E., SLBL&M), slabbed core from 5415.5 to 5416.1 feet, Desert Creek field, San Juan County, Utah.

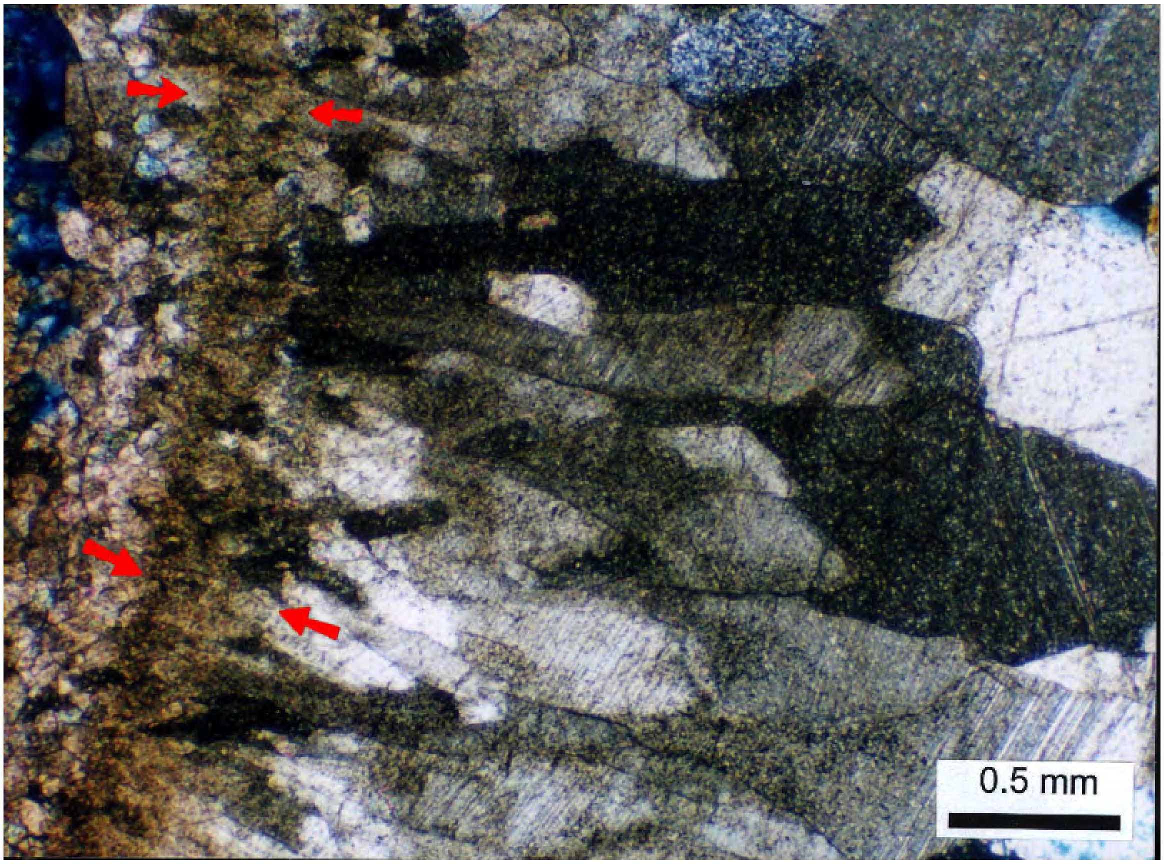


***Figure 43.** Two generations of probable early-marine cements. The earlier generation was a brown micritic to microfibrous cement (between arrows) which was followed by a bladed radiaxial generation. Filling of most original pore space was by the radiaxial cements. Blue Hogan No. 1-J-1 well (section 1, T. 42 S., R. 23 E., SLBL&M), photomicrograph (crossed nicols) from 5420.3 feet, Desert Creek field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.*

Well, production, and reservoir data for individual fields that have produced over 500,000 BO (80,000 m^3) in the Paradox Formation play are summarized in tables 1 and 2. For detailed summaries of these fields see Stowe (1972), Babcock (1978a, 1978b, 1978c, 1978d), Brown (1978, 1983), Campbell (1978), Dunn (1978), Krivanek (1978, 1981, 1993), Lauth (1978a, 1978b), Mecham (1978a, 1978b), Mickel (1978a, 1978b, 1978c), Miesner (1978), Norton (1978), Reid and Stevenson (1978), Riggs (1978), Spencer (1978), Wold (1978), Martin (1981, 1983), Lehman (1983), Ott and Roylance (1983), Scanlon and Wendling (1983), Matheny and Martin (1987), Dawson (1988), Herrod and Gardner (1988), Peterson (1992), Baars (1993), Crawley-Stewart and Riley (1993a, 1993b), Lentz (1993), Moore and Hawks (1993), Ross and Handley (1993), Steele and White (1993), Chidsey and others (1996a), Oline (1996), Scott (2003), Colorado Oil & Gas Conservation Commission (2006), and Utah Division of Oil, Gas and Mining (2006).

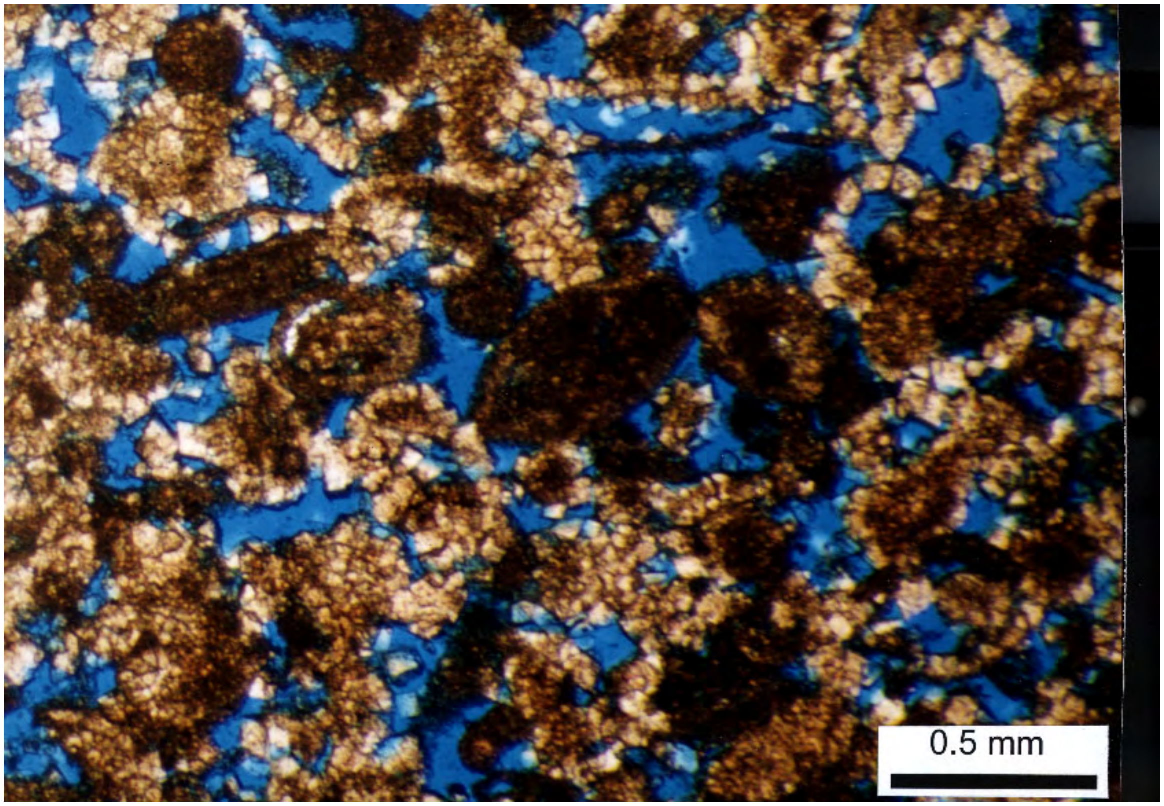


Figure 44. Typical Desert Creek-zone dolomitized, well-sorted, pelloidal/oolitic/ bioclastic grainstone; porosity = 13.4 percent, permeability = 33.9 mD by core-plug analysis. Note the very fine crystalline dolomite formed by seepage reflux processes followed by partial dissolution and other meteoric overprints. The combination of both processes has led to good storage potential and excellent flow capacity. North Heron No. 35-C well (section 35, T. 41 S., R. 25 E., SLBL&M), photomicrograph (plane light) from 5569.2 feet, Heron field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

Oil and Gas Characteristics

The produced Paradox oils are commonly sweet, paraffinic crudes. The API gravity of the oil ranges from 38º to 53º (averaging 43º); the gas-oil ratio ranges between 250 and 76,500 cubic feet/bbl. Oil colors are predominantly green, but can be dark to light green, brownish green, dark to yellowish to light reddish brown, straw yellow, or black. The viscosity of the crude oil ranges from 33 to 49 seconds at 100ºF (38ºC); in Saybolt Univeral Seconds (sus) the viscosity averages 0.46 sus at 104ºF (40ºC). The pour point of the crude oil ranges from 0 to 50ºF (0-10ºC). The average weight percent sulfur and nitrogen of produced Paradox hydrocarbon liquids are 0.07 and 0.037, respectively (Stowe, 1972).

Paradox reservoirs produce associated gas that is fairly uniform in composition, averaging 66 percent methane, 16 percent ethane, 9 percent propane, 4 percent butane, 2 percent pentane, 1 percent hexane and higher fractions, 1 percent nitrogen, and 0.2 percent carbon dioxide, and occasionally a trace of hydrogen sulfide and helium (Moore and Sigler,

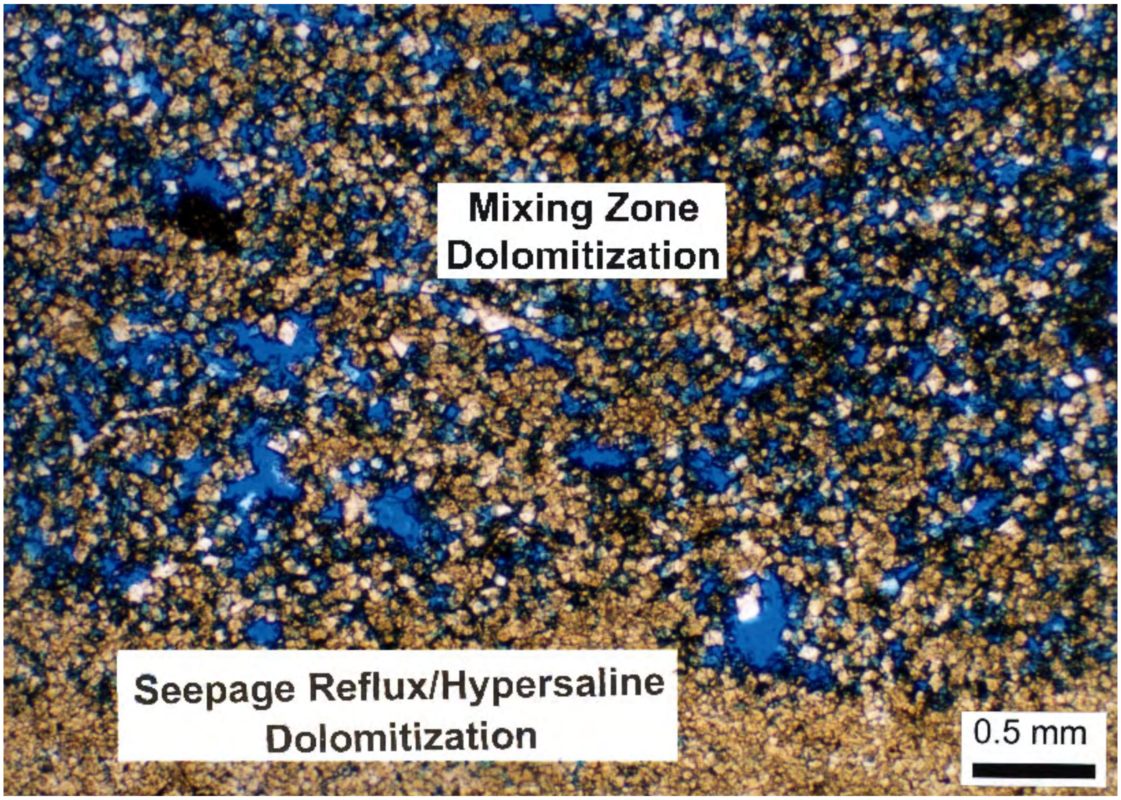


Figure 45. Desert Creek-zone dolomitized wackestone/packstone showing the contrast between probable seepage reflux/hypersaline dolomitization toward the base and more porous mixing-zone dolomitization above; porosity = 20.3 percent, permeability = 39.8 mD by core-plug analysis. Note "ghosts" of probable ostracods and crinoids. Runway No. 10-C-5A well (section 10, T. 40 S., R. 25 E., SLBL&M), photomicrograph (plane light) from 6120.2 feet, Runway field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

1987). The gas heating value averages 1400 British thermal units/cubic foot (Btu/ft^3); the specific gravity averages 0.794. One exception to the typical gas compositions in the Paradox is Akah field, San Juan County, Utah, where the reservoir contains 13 percent nitrogen and 18 percent carbon dioxide; the gas heating value is 863 Btu/ft^3 (Stowe, 1972; Moore and Sigler, 1987).

Oil and gas properties for individual fields that have produced over 500,000 BO (80,000 m^3) in the Paradox Formation play are summarized in tables 3 and 4.

Production

Nine fields in the Blanding sub-basin Desert Creek zone subplay have produced crude oil and associated gas. These fields have combined to produce nearly 16 million BO (2.5 million m^3) and 67 BCFG (1.9 BCMG) from the Desert Creek zone (Scott, 2003; Colorado Oil & Gas Conservation Commission, 2006; Utah Division of Oil, Gas and Mining, 2006). There are currently about 50 active Desert Creek producers in these fields. Five fields have produced over 500,000 BO (80,000 m^3) (figure 8 and table 1).

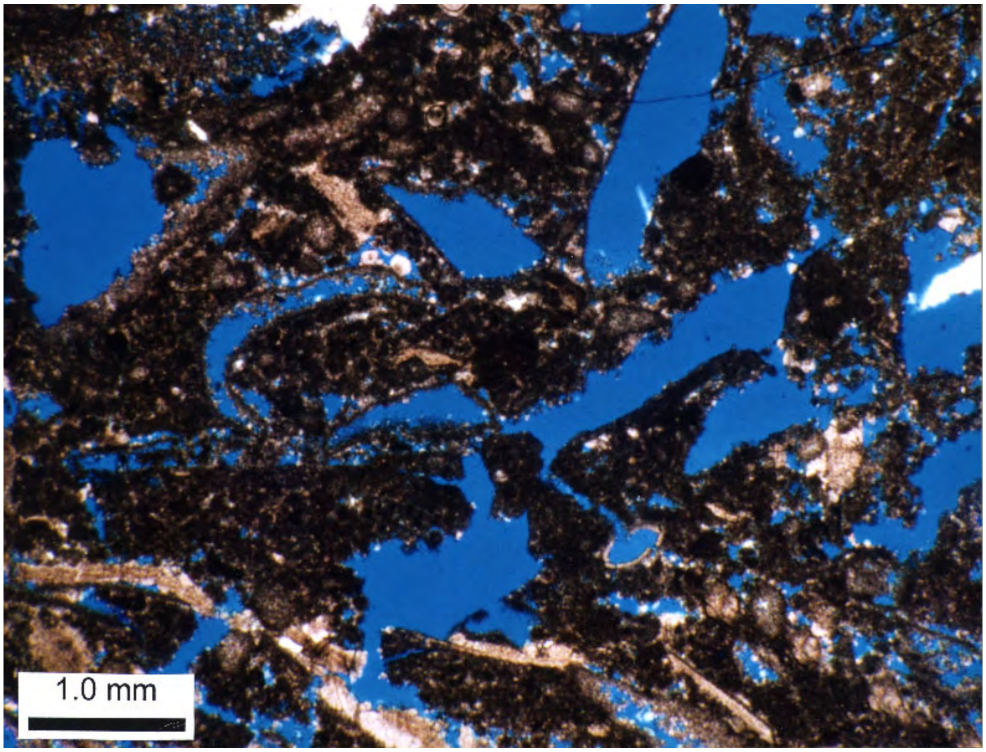


Figure 46. Desert Creek-zone grainstone/packstone showing interconnected solution-channel and moldic porosity with very little visible meteoric cements; porosity = 13.2 percent, permeablility = 20.4 mD by core-plug analysis. Mule No. 31-M well (section 31, T. 41 S., R. 24 E., SLBL&M), photomicrograph (plane light) from 5729.8 feet, Greater Aneth field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

Forty-five fields in the Blanding sub-basin Ismay zone subplay have produced crude oil and associated gas. These fields have combined to produce over 40 million BO (6.4 million m^3) and 105 BCFG (3.0 BCMG) from the Ismay zone (Scott, 2003; Colorado Oil & Gas Conservation Commission, 2006; Utah Division of Oil, Gas and Mining, 2006). There are currently about 130 active Ismay producers in these fields. A few scattered fields produce or are now abandoned in the Desert Creek zone. Fourteen fields have produced over 500,000 BO (80,000 m^3) from the Ismay zone (figure 8 and table 1).

Twenty-two fields – three in Arizona and the rest in Utah (figure 8) – in the Aneth platform Desert Creek zone subplay have produced crude oil and associated gas. These fields have combined to produce nearly 454 million BO (72 million m^3) and 416 BCFG (11.8 BCMG) (including cycled gas) from the Desert Creek zone; of this total over 440 million BO (70 million m^3) and 385 BCFG (10.9 BCMG) have been produced from Greater Aneth field (Utah Division of Oil, Gas and Mining, 2006). There are currently about 510 active Desert Creek producers in these fields; over 460 wells are in Greater Aneth field. Ten fields have produced over 500,000 BO (80,000 m^3) (figure 8 and table 1). There are several fields on the Aneth platform that have also produced from the Ismay zone, from commingled Ismay and Desert Creek zones, or the Akah and Barker Creek zones (several Arizona fields). However, most of these fields are abandoned: Anido Creek, Cleft, Rabbit Ears, Toh-Atin, Twin Falls, and Bita Creek fields, for example (figure 8).

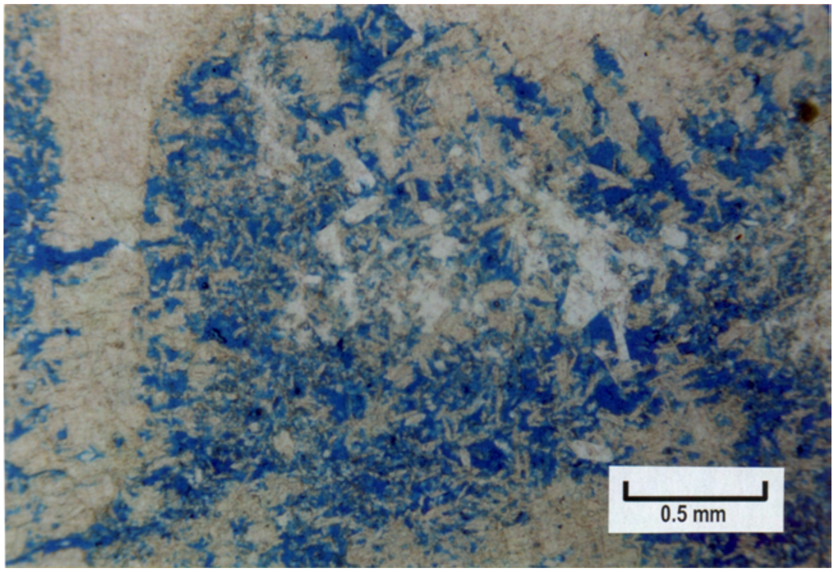


Figure 47. Desert Creek-zone dolomitized, phylloid-algal bafflestone showing a pattern of patchy dolomite dissolution which includes a "micro-box-work" pattern of pores (in blue); porosity = 10.5 percent, permeability = 7.5 mD by core-plug analysis. Bug No. 10 well (section 22, T. 36 S., R. 26 E., SLBL&M), photomicrograph (plane light with white card technique) from 6327.5 feet, Bug field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

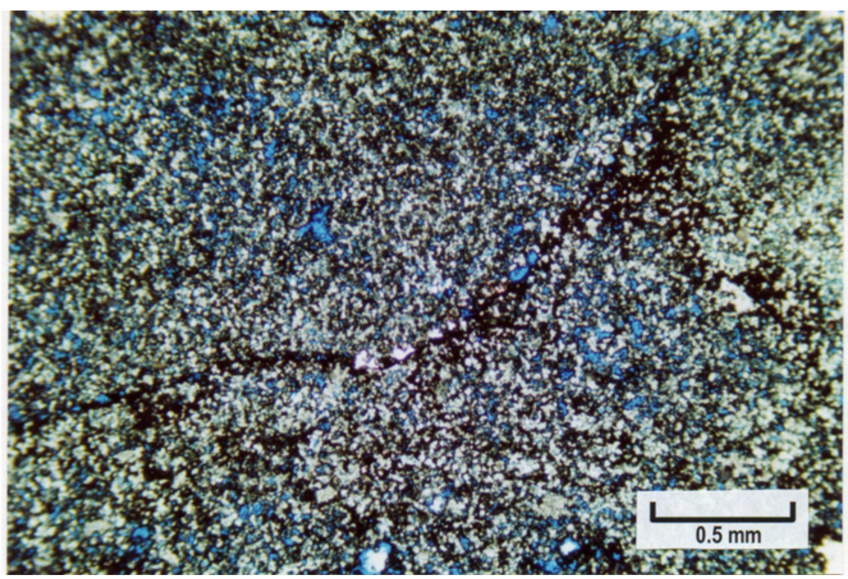


Figure 48. Ismay-zone peloidal packstone/grainstone dominated by microporosity and bitumen plugging; porosity = 22.9 percent, permeability = 215 mD. Cherokee No. 22-14 well (section 14, T. 37 S., R. 23 E., SLBL&M), photomicrograph (plane light) from 5768.7 feet, Cherokee field, San Juan County, Utah. Photomicrograph by David E. Eby, Eby Petrography & Consulting, Inc.

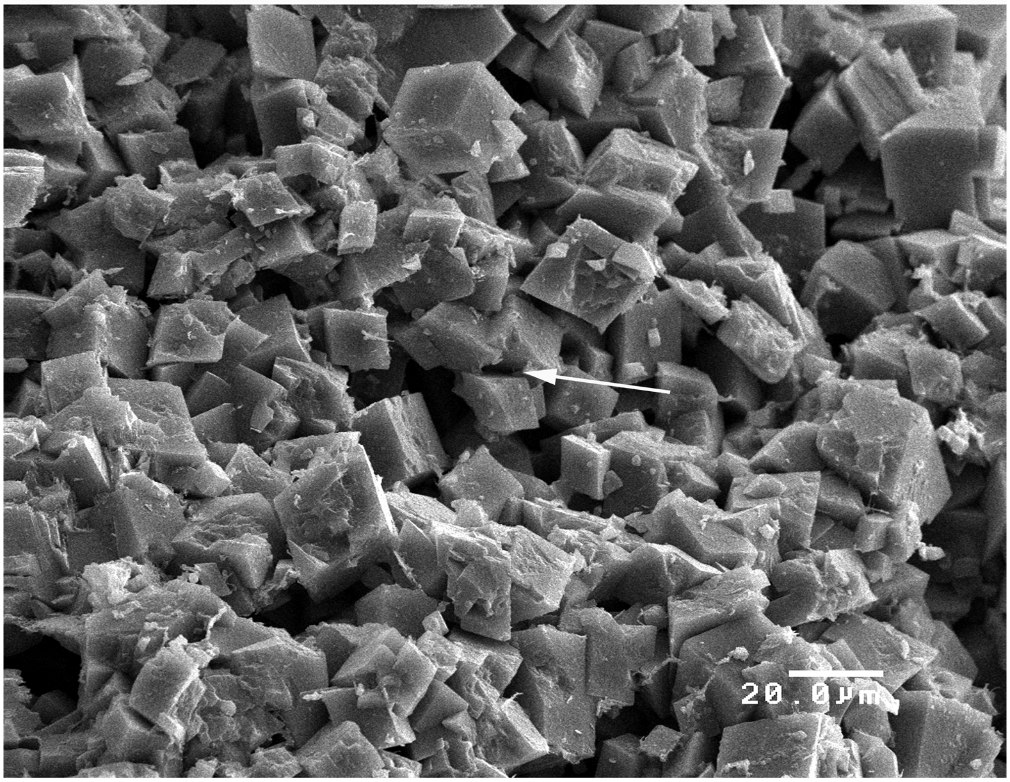


Figure 49. Ismay-zone packstone/grainstone displaying well-developed dolomite rhombs exhibiting abundant intercrystalline microporosity (arrow); porosity = 23.6 percent; permeability = 103 mD by core-plug analysis. Cherokee No. 33-14 well (section 14, T. 37 S., R. 23 E., SLBL&M), scanning electron microscope photomicrograph (scale represents 20 microns [0.02 mm]) of a core plug from 5781.2 feet, Cherokee field, San Juan County, Utah. Photomicrograph by Louis H. Taylor, Standard Geological Services, Inc.

In 2005, the monthly production from the Paradox Formation averaged 353,000 BO (56,000 m^3) and 0.5 BCFG (0.01 BCMG) (Colorado Oil & Gas Conservation Commission, 2006; Utah Division of Oil, Gas and Mining, 2006; Steve Rauzi, Arizona Geological Survey, written communication, 2006). Production peaks in the Paradox play have been strongly influenced by production at Greater Aneth field: in the late 1950s and early 1960s as the field was being developed, the onset of water and carbon dioxide floods in 1962 and 1985, respectively, and an extensive horizontal drilling program in the 1990s. Production also increased from a number of significant discoveries during the 1980s in the Blanding sub-basin Desert Creek and Ismay zones subplays (table 1). Production received boosts again in the 1990s with horizontal drilling in the Cane Creek shale and a series of discoveries in satellite mounds around Greater Aneth field. Production in the Paradox Formation play has declined since 2000 due to maturing fields where no new enhanced oil recovery programs have been initiated. There have also been no significant discoveries since the early 1990s due to limited exploratory drilling.

Table 2. Reservoir data for fields in the Blanding sub-basin Desert Creek-zone, Blanding sub-basin Ismay-zone, and Aneth platform Desert Creek-zone subplays, Pennsylvanian Paradox Formation play.

State	County	Field	Zone	Pay (feet)	Porosity (%)	Perm. (mD)	Temp. (°F)	Initial Reservoir Pressure (psi)	Water Saturation	Resistivity of Formation Water	Salinity	Drive
Blanding Sub-Basin Desert Creek Zone Subplay												
Colorado	Montezuma	Island Butte [1]	Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	McClean [1, 2, 3]	Desert Creek	30	14	250	130	3595	69	0.045@68°F	348,534	solution gas/water drive
Colorado	Dolores/Montezuma	Papoose Canyon [1, 4]	Desert Creek	9	12.2	4.4	NA	3416	53	NA	NA	gas cap expansion
Utah	San Juan	Bug [5, 6, 7]	Desert Creek	15	11	27.5	170	3550	32	0.03@BHT	331,831	gas cap expansion/solution gas/limited water drive
Blanding Sub-Basin Ismay Zone Subplay												
Colorado	Montezuma	Cache [1, 8]	Ismay	57	10.4	12.3	NA	2170	35	0.11@68°F	62,700	solution gas/part water drive
Colorado	Montezuma	Flodine Park [1, 9]	Ismay	41	11	13	NA	2212	41	NA	NA	solution gas
Colorado	Montezuma	Marble Wash [1, 10]	Ismay	15	10	2	NA	2250	NA	0.051@68°F	234,685	solution gas
Colorado	Montezuma	Roadrunner [1]	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	Towaoc [1, 11]	Ismay	16	10	25	NA	2290	44	NA	NA	solution gas/water drive
Utah	San Juan	Cave Canyon [12]	Ismay	75	14	55	132	2121	11	0.02@BHT	NA	fluid expansion/solution gas
Utah	San Juan	Deadman-Ismay [13]	Ismay	62	13	0.9	132	2441	18-46	0.047@68°F	NA	gas expansion/depletion
Utah	San Juan	Ismay [14, 15]	Ismay	24	11.2	16.5	131	2205	41	NA	NA	solution gas
Utah	San Juan	Kachina [16]	Ismay	100	13	8	132	2108	23	NA	NA	solution gas
Utah	San Juan	Kiva [17]	Ismay	38	16	21.9	135	1862	24	NA	NA	solution gas
Utah	San Juan	McElmo Mesa [18]	Ismay	29	9	NA	119	2176	37	NA	NA	water drive
Utah	San Juan	Mustang Flat [19]	Ismay	30	9	4	126	2642	34	NA	NA	gas expansion/water drive
Utah	San Juan	Patterson Canyon [20, 21]	Ismay	17	13	10	128	2572	41	0.054@68°F	222,554	solution gas/water drive
Utah	San Juan	Tin Cup Mesa [22, 23, 24]	Ismay	50	14.3	8.3	121	2080	31	0.065@77°F	256,894	solution gas
Aneth Platform Desert Creek Zone Subplay												
Arizona	Apache	Boundary Butte East [25]	Ismay-Desert Creek-Akah	20	8	2.3	NA	1550	20	NA	62,000	gas expansion/solution gas
Utah	San Juan	Akah [26]	Ismay-Desert Creek-Akah	NA	NA	NA	112	1875	NA	NA	NA	water drive/gas expansion
Utah	San Juan	Anido Creek [27]	Ismay-Desert Creek	19	8	24	105	1974	28	NA	80,000-100,000	solution gas/fluid expansion
Utah	San Juan	Bluff [28, 29]	Desert Creek	33	7.5	0.3	140	1800	NA	NA	NA	solution gas
Utah	San Juan	Clay Hill [30]	Desert Creek	40	14	30	115	2000	25	0.03@130°F	191,000	solution gas
Utah	San Juan	Desert Creek [31]	Desert Creek	26	13	5	126	2005	28	NA	NA	solution gas/fluid expansion
Utah	San Juan	Gothic Mesa [32]	Desert Creek	10	8.8	1.6	124	2150	45	NA	NA	pressure depletion
Utah	San Juan	Greater Aneth [33, 34, 35]	Desert Creek	50	12	20	125	2170	24	NA	150,000	solution gas/fluid expansion
Utah	San Juan	Recapture Creek [36]	Ismay-Desert Creek	19	10.9	1.6	130	2175	23	NA	160,000	solution gas/weak water drive
Utah	San Juan	Runway [37]	Desert Creek	50	11.9	17.3	126	2162	10-63	0.07@67°F	199,709	gas expansion
Utah	San Juan	Tohonadla [38]	Ismay-Desert Creek-Akah	25	6.5	12.5	126	1895	24	NA	82,000	solution gas
Utah	San Juan	Turner Bluff [39, 40]	Desert Creek	15	9	2	124	1637	28	0.07@68°F	120,000	solution gas

NA = not available

[1]Scott (2003), [2]Matheny and Martin (1987), [3]Mickel (1978a), [4]Miesner (1978), [5]Martin (1983), [6]Oline (1996), [7]Krivanek (1981), [8]Wold (1978), [9]Mecham (1978a), [10]Brown (1978), [11]Spencer (1978), [12]Lentz (1993), [13]Ross and Handley (1993), [14]Mecham (1978b), [15]Dawson (1988), [16]Crawley-Stewart and Riley (1993a), [17]Crawley-Stewart and Riley (1993b), [18]Mickel (1978b), [19]Brown (1983), [20]Martin (1981) [21]Krivanek (1978), [22]Ott and Roylance (1983), [23]Herrod and Gardner (1988), [24]Steele and White (1993), [25]Dunn (1978), [26]Riggs (1978), [27]Lauth (1978a), [28]Campbell (1978), [29]Baars (1993), [30]Lehman (1983), [31]Lauth (1978b), [32]Reid and Stevenson (1978), [33]Babcock (1978a, 1978b, 1978c, 1978d), [34]Peterson (1992), [35]Moore and Hawks (1993), [36]Scanlon and Wendling (1983), [37]Chidsey and others (1996a), [38]Norton (1978), [39]Mickel (1978c), [40]Krivanek (1993).

Table 3. Oil properties for fields in the Blanding sub-basin Desert Creek-zone, Blanding sub-basin Ismay-zone, and Aneth platform Desert Creek-zone subplays, Pennsylvanian Paradox Formation play.

State	County	Field	Zone	Gas/Oil Ratio	Oil Characteristics					
					API Gravity	Color	Viscosity	Pour Point (°F)	Sulfur (%)	Nitrogen (%)
Blanding Sub-Basin Desert Creek Zone Subplay										
Colorado	Montezuma	Island Butte	Desert Creek	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	McClean [1, 2]	Desert Creek	2200	46°	light reddish brown	NA	0.09	NA	NA
Colorado	Dolores/Montezuma	Papoose Canyon [3]	Desert Creek	NA	50°	light green/straw yellow	NA	NA	NA	NA
Utah	San Juan	Bug [4, 5]	Desert Creek	1900	47°	light reddish brown	NA	0	NA	NA
Blanding Sub-Basin Ismay Zone Subplay										
Colorado	Montezuma	Cache [6]	Ismay	918	45°	NA	0.35 sus	NA	NA	NA
Colorado	Montezuma	Flodine Park [7]	Ismay	NA	45°	green	NA	NA	NA	NA
Colorado	Montezuma	Marble Wash [8]	Ismay	2200	42°	NA	NA	NA	NA	NA
Colorado	Montezuma	Roadrunner	Ismay	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	Towaoc [9]	Ismay	754	42°	NA	NA	NA	NA	NA
Utah	San Juan	Cave Canyon [10]	Ismay	529	44°	black	NA	NA	0	NA
Utah	San Juan	Deadman-Ismay [11]	Ismay	5556	40-47°	NA	NA	5-10	NA	NA
Utah	San Juan	Ismay [12, 13]	Ismay	NA	46°	brownish green	33 sec@100°F	10	0.05	0.02
Utah	San Juan	Kachina [14]	Ismay	745	39°	NA	0.443 sus	55	NA	NA
Utah	San Juan	Kiva [15]	Ismay	645	41°	NA	0.64 sus	35	NA	NA
Utah	San Juan	McElmo Mesa	Ismay	NA	NA	NA	NA	NA	NA	NA
Utah	San Juan	Mustang Flat [16]	Ismay	76,508	53°	NA	NA	NA	NA	NA
Utah	San Juan	Patterson Canyon [17]	Ismay	NA	42°	yellow brown	NA	>0	NA	NA
Utah	San Juan	Tin Cup Mesa [18]	Ismay	1390	44°	yellow brown	NA	15	NA	NA
Aneth Platform Desert Creek Zone Subplay										
Arizona	Apache	Boundary Butte East [19]	Ismay-Desert Creek-Akah	NA	41°	NA	NA	NA	NA	NA
Utah	San Juan	Akah [20]	Ismay	NA	39°	dark green	NA	25	0.2	0.06
Utah	San Juan	Anido Creek [21]	Ismay-Desert Creek	NA	43°	green	NA	NA	NA	NA
Utah	San Juan	Bluff [12, 22, 23]	Desert Creek	NA	41.4°	green	38 sec@100°F	25	0.05	0.019
Utah	San Juan	Clay Hill [24]	Desert Creek	NA	41°	NA	NA	NA	NA	NA
Utah	San Juan	Desert Creek [12, 25]	Desert Creek	NA	39°	green	40 sec @100°F	50	0.11	0.04
Utah	San Juan	Gothic Mesa [12, 26]	Desert Creek	NA	42°	green	37 sec@100°F	25	0.05	0.03
Utah	San Juan	Greater Aneth [12, 27]	Desert Creek	665	38-42°	green	0.53 sus	10	0.07	0.04
Utah	San Juan	Recapture Creek [12, 28]	Ismay-Desert Creek	NA	40°	green	35 sec@100°F	20	0.1	0.03
Utah	San Juan	Runway [29]	Desert Creek	967	40.5°	dark green	0.314 sus	NA	0	NA
Utah	San Juan	Tohonadla [12, 30]	Ismay	NA	38°	brownish green	40 sec@100°F	20	0.09	0.07
Utah	San Juan	Turner Bluff [31]	Desert Creek	259	43°	dark brown	NA	NA	0.1	NA

NA = not available, sus = Saybolt Univeral Seconds, sec = seconds

[1]Matheny and Martin (1987), [2]Mickel (1978a), [3]Miesner (1978), [4]Martin (1983), [5]Oline (1996), [6]Wold (1978), [7]Mecham (1978a), [8]Brown (1978), [9]Spencer (1978), [10]Lentz (1993), [11]Ross and Handley (1993), [12]Stowe (1972), [13]Mecham (1978b), [14]Crawley-Stewart and Riley (1993a), [15]Crawley-Stewart and Riley (1993b), [16]Brown (1983), [17]Krivanek (1978), [18]Steele and White (1993), [19]Dunn (1978), [20]Riggs (1978), [21]Lauth (1978a), [22]Campbell (1978), [23]Baars (1993), [24]Lehman (1983), [25]Lauth (1978b), [26]Reid and Stevenson (1978), [27]Moore and Hawks (1993), [28]Scanlon and Wendling (1983), [29]Chidsey and others (1996a), [30]Norton (1978), [31]Krivanek (1993).

Table 4. Gas properties for fields in the Blanding sub-basin Desert Creek-zone, Blanding sub-basin Ismay-zone, and Aneth platform Desert Creek-zone subplays, Pennsylvanian Paradox Formation play.

State	County	Field	Zone	Gas Characteristics											
				Methane (%)	Ethane (%)	Propane (%)	Butane (%)	Pentaine (%)	Hexane + (%)	Nitrogen (%)	CO2 (%)	Helium (%)	Hydrogen Sulfide (%)	BTU	Specific Gravity
Blanding Sub-Basin Desert Creek Zone Subplay															
Colorado	Montezuma	Island Butte	Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	McClean [1, 2, 3]	Desert Creek	78	14	5	2	0.5	0.4	0.5	0.05	0.01	0	1254	0.715
Colorado	Dolores/Montezuma	Papoose Canyon [4]	Desert Creek	63	18	10	5	2	0.5	2	0.3	0.1	0	1475	0.870
Utah	San Juan	Bug [5, 6]	Desert Creek	78	13	5	2	0.5	0.3	0.63	0.08	0	0	1232	0.717
Blanding Sub-Basin Ismay Zone Subplay															
Colorado	Montezuma	Cache [7]	Ismay	66	16	9	3	NA	1	NA	0.6	NA	NA	1436	0.851
Colorado	Montezuma	Flodine Park [4]	Ismay	75	13	6	3	1	0.2	2	0.5	0.1	0	1247	0.763
Colorado	Montezuma	Marble Wash	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	Roadrunner	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Colorado	Montezuma	Towaoc [8]	Ismay	56	18	13	7	3	0.5	2	0.1	.02	0	1607	NA
Utah	San Juan	Cave Canyon	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Utah	San Juan	Deadman-Ismay [9]	Ismay	74	15	7	2	0	0	1.3	0.05	0	0	1294	NA
Utah	San Juan	Ismay	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Utah	San Juan	Kachina [10]	Ismay	65	17	10	NA	NA	NA	NA	NA	NA	Tr	1464	0.909
Utah	San Juan	Kiva [11]	Ismay	65	15	10	NA	NA	NA	NA	NA	NA	Tr	1515	0.9
Utah	San Juan	McElmo Mesa [12]	Ismay	61	19	11	5	2	1	1.8	0.1	Tr	0	NA	NA
Utah	San Juan	Mustang Flat	Ismay	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.6
Utah	San Juan	Patterson Canyon [13]	Ismay	57	22	12	5	2	2	0.2	0.2	NA	NA	1568	0.937
Utah	San Juan	Tin Cup Mes [14]	Ismay	69	15	9	3	1	0.5	1	0.4	NA	NA	1400	0.68
Aneth Platform Desert Creek Zone Subplay															
Arizona	Apache	Boundary Butte East [15]	Ismay-Desert Creek-Akah	70	4	2	0.8	0.3	0.2	8.2	13.8	1.0	0.1	871	0.778
Utah	San Juan	Akah [16]	Ismay-Desert Creek-Akah	57	6	NA	NA	NA	NA	13	18	NA	NA	863	NA
Utah	San Juan	Anido Creek	Ismay-Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Utah	San Juan	Bluff [4]	Desert Creek	75	14	5	2	1	0.5	2	0.4	Tr	0	1640	0.954
Utah	San Juan	Clay Hill [17]	Desert Creek	54	23	13	6	2	2	1	0.3	0	Tr	1636	0.970
Utah	San Juan	Desert Creek [4]	Desert Creek	65	18	9	4	2	0.6	3	0.1	Tr	0	1412	0.836
Utah	San Juan	Gothic Mesa	Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1150	NA
Utah	San Juan	Greater Aneth [4, 18, 19]	Desert Creek	62	18	11	5.5	2.5	<1	0	0.1	0	0	1450	NA
Utah	San Juan	Recapture Creek [19, 20]	Ismay-Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1425	0.834
Utah	San Juan	Runway [21]	Desert Creek	72	15	7	3	1	0.6	1.1	0.6	0	0	1366	0.779
Utah	San Juan	Tohonadla [4]	Ismay-Desert Creek-Akah	60	22	9	4	1	0.3	3	0.2	0.1	0	1449	0.861
Utah	San Juan	Turner Bluff	Desert Creek	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA = not available

[1]Scott (2003), [2]Matheny and Martin (1987), [3]Mickel (1978a), [4]Moore and Sigler (1987), [5]Martin (1983), [6]Oline (1996), [7]Wold (1978), [8]Spencer (1978), [9]Ross and Handley (1993), [10]Crawley-Stewart and Riley (1993a), [11]Crawley-Stewart and Riley (1993b), [12]Mickel (1978b), [13]Krivanek (1978), [14]Steele and White (1993), [15]Dunn (1978), [16]Riggs (1978), [17]Lehman (1983), [18]Moore and Hawks (1993), [19]Stowe (1972), [20]Scanlon and Wendling (1983), [21]Chidsey and others (1996a).

Exploration Potential and Trends

Blanding Sub-Basin Ismay and Desert Creek Zones Subplays

Mapping the upper Ismay-zone lithofacies as two intervals (upper and lower parts) delineates very prospective reservoir trends that contain porous, productive carbonate buildups (figures 11 and 12). The mapped lithofacies trends clearly define anhydrite-filled, intra-shelf basins. Lithofacies and reservoir controls imposed by the anhydritic, intra-shelf basins should be considered when selecting the optimal location and orientation of any horizontal drilling for undrained reserves, as well as identifying new exploration trends. Projections of the inner shelf/tidal flat and mound trends around the intra-shelf basins identify potential exploration targets, which could be developed using horizontal drilling techniques (figures 50 and 51). Drilling horizontally from known phylloid-algal reservoirs along the inner shelf/tidal flat trend could encounter previously undrilled porous buildups. Intra-shelf basins are not present in the lower Desert Creek zone of the Blanding sub-basin (figure 13). However, drilling horizontally from productive mound lithofacies along linear shoreline trends could also encounter previously undrilled porous Desert Creek intervals and buildups.

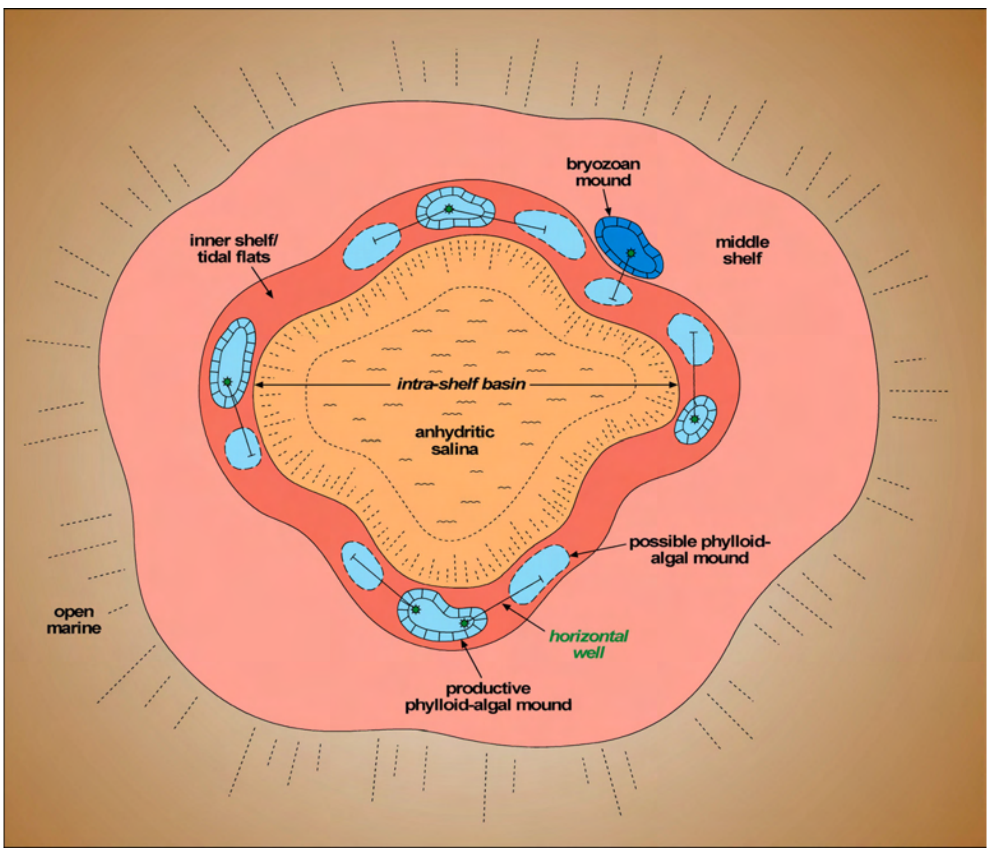


Figure 50. Map view of an ideal upper Ismay intra-shelf basin surrounded by a ring of inner shelf/tidal flat sediments (shown in red) which encase phylloid-algal mound clusters (in light blue). The central portion of the intra-shelf basin is the location of thick anhydrite (in orange) accumulation. Outboard from the inner shelf/tidal flat and mound fairway are low-energy middle-shelf and open-marine carbonates.

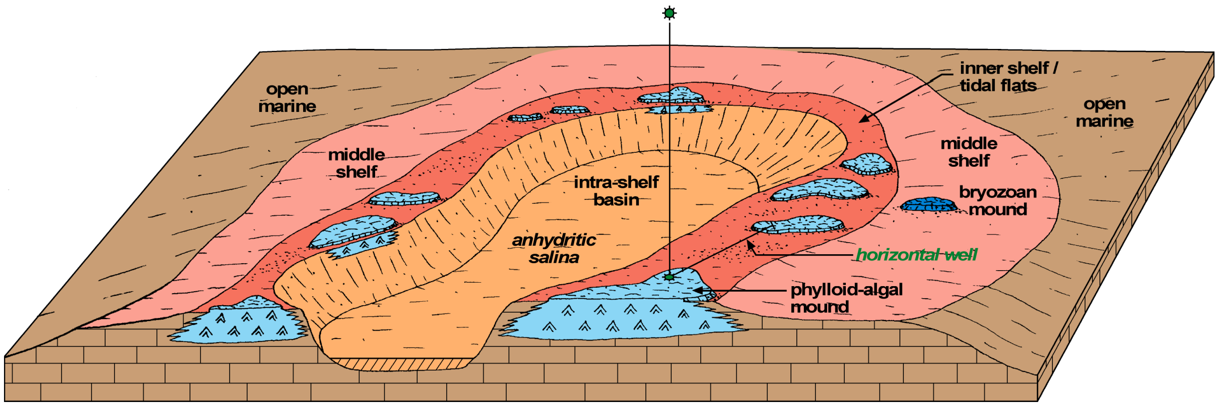


Figure 51. Cut-away block diagram showing the possible spatial relationships of upper Ismay facies types controlled by an intra-shelf basin. Phylloid-algal mounds (in light blue) are the principal reservoir within a curvilinear band that rims the intra-shelf basin. A hypothetical vertical well into a known mound reservoir is used as a kick-off location for horizontal drilling into previously undrained mounds.

Aneth Platform Desert Creek Zone Subplay

The shallow-shelf/shelf-margin depositional environment includes shallow-shelf carbonate buildups, platform-margin calcarenites, and platform-interior carbonate muds and sands (described earlier). Pervasive marine cement may be indicative of "wall" complexes suggesting potential nearby carbonate buildups, particularly phylloid-algal mounds (figure 40). Carbonate buildups, tidal-channel carbonate sands, and other features often appear promising on seismic records. However, if these carbonate buildups are located within the open-marine and intra-shelf, salinity-restricted depositional environments/lithofacies (figures 14 and 52), the reservoir quality is typically poor. Porosity and permeability development, if present, is limited or plugged with anhydrite in these respective depositional environments.

Platform-margin calcarenites are located along the margins of the larger shallow shelf or the rims of phylloid-algal buildup complexes. Mapping indicates a relatively untested lithofacies belt of shallow-shelf, calcarenite carbonate deposits (figure 52). This narrow, but long, belt of calcarenites is between the open-marine and margins of intra-shelf, salinity-restricted depositional environments. Calcarenite buildups represent high-energy environments where shoals and/or islands developed. However, algal meadows, phylloid-algal buildups, and stromatolite mats were also present in this lithofacies belt (figure 53) (Chidsey and Eby, 1997).

Heron field (figures 14 and 52) is an excellent example of the type of traps which potentially lie within the 20-mile-long (32 km) lithofacies belt described above. The trap for the field is a lenticular, northwest- to southeast-trending linear mound/beach complex, 0.8 miles (1.3 km) long and 0.5 miles (0.8 km) wide (Chidsey and others, 1996b). The reservoir consists of five units: (1) a basal, dolomitized, phylloid-algal (bafflestone) buildup, (2) an anhydrite-plugged, phylloid-algal (bafflestone) limestone buildup, (3) a fusilinid-bearing, lime-wackestone interval, (4) a dolomitized packstone interval with anhydrite nodules, and (5) a porous (15 percent), sucrosic, dolomitized grainstone and packstone interval. This last unit is the main reservoir, and consists of alternating 2- to 4-foot-thick (0.6-1.2 m) packages of uniform beach calcarenite and poorly sorted foreshore and storm-lag rudstone or breccia deposits.

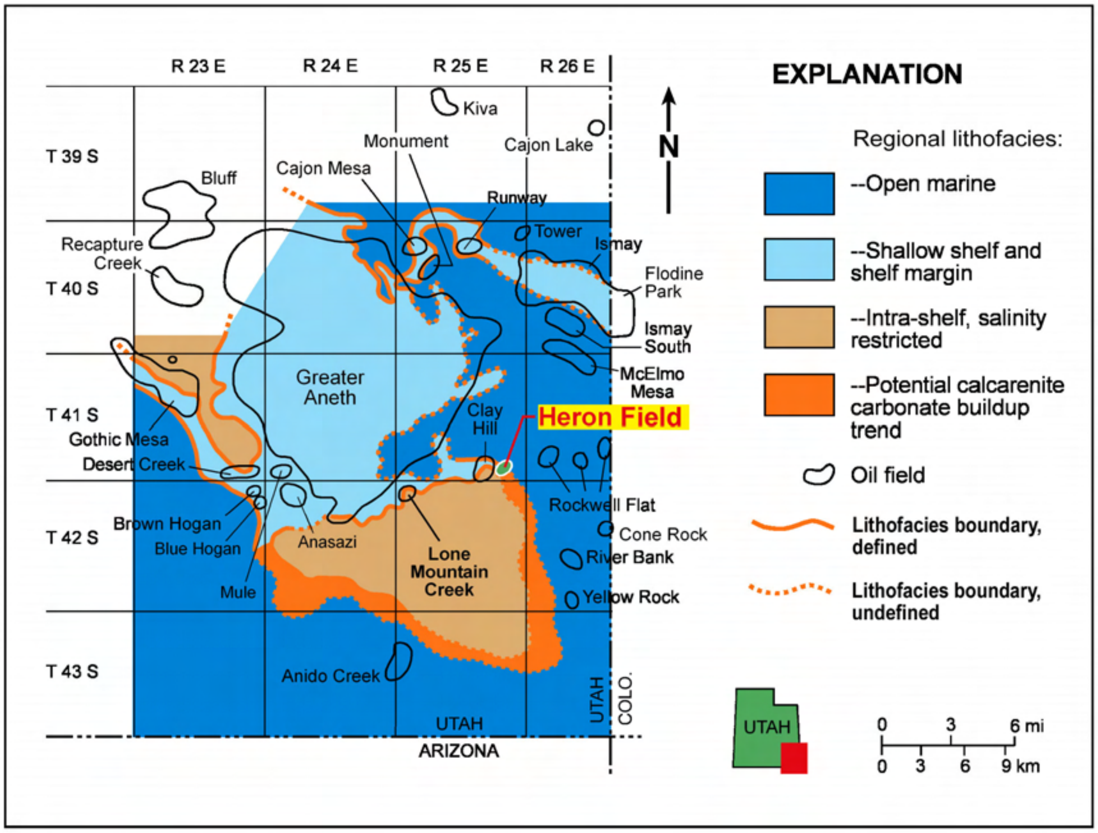


Figure 52. Potential calcarenite buildup trend (orange) within the regional lithofacies belts of the Desert Creek zone, southeastern Utah. Heron field (highlighted) is an excellent example of a lenticular, mound/beach complex hydrocarbon trap in this trend.

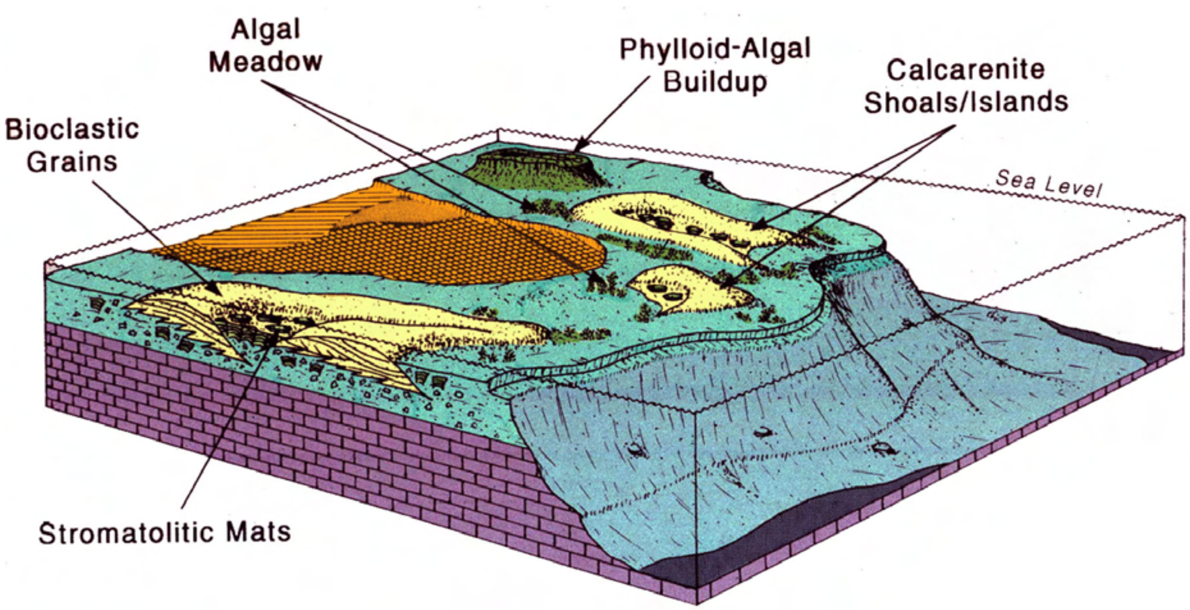


Figure 53. Depositional environments of the calcarenite lithofacies along the narrow shelf margin between the open-marine and intra-shelf, salinity-restricted lithofacies belts.

Platform-margin calcarenite traps have both negative and positive characteristics for hydrocarbon production. Negative characteristics include (1) small reservoir size and storage capacity, (2) poor definition on seismic records, (3) limited distribution, (4) common bitumen plugging, and (5) rapid production declines. Positive characteristics include (1) excellent overall reservoir properties, (2) a common association with phylloid-algal buildups, (3) good potential for water/CO_2 floods, and (4) an extensive untested trend (Chidsey and Eby, 1997).

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for this project under the U. S. Department of Energy (DOE) Preferred Upstream Management Program (PUMPII). All play maps, reports, databases, and other deliverables produced for the PUMPII project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. 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*.

The technology-transfer plan included the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. 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 field operators from the oil-producing provinces of Utah that also extend into Wyoming or Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management and Bureau of Indian Affairs). The members of the Technical Advisory and Stake Holders Boards receive all quarterly technical reports and copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data, especially data pertaining to best practices. During the quarter, project team members joined Utah Stake Holders Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah, on March 28, 2006. Project activities, results, and recommendations were presented at this meeting.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides 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 Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Utah Geology/Oil, Coal, and Energy*, which describes the UGS/DOE cooperative studies (PUMPII, Paradox Basin [two projects], Ferron Sandstone, Bluebell field, Green River Formation), 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 PUMPII project page, http://geology.utah.gov/emp/pump/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) quarterly technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities:

> "The Jurassic Navajo Sandstone Central Utah Thrust Belt Exploration Play" by Thomas C. Chidsey, Jr., Cedar City, Utah, February 6, 2006, to the Iron County (Utah) Comprehensive Land Use Planning Project Working Committee, Iron County Commissioners, and general public.

> "The Jurassic Navajo Sandstone Central Utah Thrust Belt Exploration Play, Millard County, Utah" by Thomas C. Chidsey, Jr., Delta, Utah, February 23, 2006, to the Great Basin Historical Society and general public.

The petroleum geology of the central Utah thrust belt play, the recent oil discovery of Covenant field, play potential, land-use issues, and the economic impact on the counties were part of these presentations.

Project Publications

Chidsey, T.C., Jr., and Morgan, C.D., 2006, Major oil plays in Utah and vicinity – quarterly technical progress report for the period October 1 to December 31, 2005: U.S. Department of Energy, DOE/FC26-02NT15133-14, 57 p.

Utah Geological Survey, 2006, Utah! 100 years of exploration… and still the place to find oil and gas: Utah Geological Survey Public information Series 71, 20 p.

CONCLUSIONS AND RECOMMENDATIONS

1. A combination of depositional and structural events created the right conditions for oil generation and trapping in the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado, Wyoming, and Arizona. Oil plays are specific geographic areas having petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors.

2. The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with small portions in northeastern Arizona and the northwestern corner of New Mexico. The most prolific oil and gas play in the Paradox Basin is the Pennsylvanian Paradox Formation play. The Paradox Formation has produced over 500 million bbls

(80 million m^3) of sweet, paraffinic oil and 650 BCFG (18 billion m^3) from more than 70 fields. The main producing zones are referred to as the Desert Creek and Ismay. The Paradox Formation oil play area includes nearly the entire Paradox Basin. The Paradox Formation Play is divided into four subplays: (1) fractured shale, (2) Blanding sub-basin Desert Creek zone, (3) Blanding sub-basin Ismay zone, and (4) Aneth platform Desert Creek zone.

3. In Pennsylvanian time, the Paradox Basin was rapidly subsiding in a subtropical arid environment with a shallow-water carbonate shelf on the south and southwest margins of the basin that locally contained carbonate buildups. In the Blanding sub-basin, Ismay-zone reservoirs are dominantly limestones composed of small, phylloid-algal buildups; locally variable, inner-shelf, skeletal calcarenites; and rarely, open-marine, bryozoan mounds. Desert Creek-zone reservoirs are dominantly dolomite comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts. On the Aneth platform, Desert Creek reservoirs include shallow-shelf buildups (phylloid-algal, coralline-algal, and bryozoan buildups [mounds]), calcarenites (beach, dune, and oolite banks). Here, the Desert Creek and Ismay zones are predominately limestone, with local dolomitic units.

4. Phylloid-algal mound lithofacies in both the Ismay and Desert Creek zones contain large phylloid-algal plates of *Ivanovia*, *Kansasphyllum*, or *Eugonophyllum* and skeletal grains create bafflestone or bindstone fabrics. Bryozoan buildup lithofacies are represented by bindstone, bafflestone, and packestone fabrics that are rarely dolomitized. Calcarenite lithofacies include grainstone and packstone fabrics containing oolites, coated grains, hard peloids, bioclastic grains, shell lags, and intraclasts.

5. Hydrocarbons in Paradox Formation reservoirs were generated from source rocks within the formation itself during maximum burial in the Late Cretaceous and early Tertiary. Organic-rich units, informally named the Cane Creek, Chimney Rock, and Gothic shales, are composed of black, sapropelic shale and shaley dolomite. Vertical reservoir seals for the Paradox producing zones are shale, halite, and anhydrite within the formation; lateral seals are permeability barriers created by unfractured, off-mound (non-buildup) mudstone, wackestone, and anhydrite.

6. Trap types in the Blanding sub-basin and Aneth platform regions include stratigraphic, stratigraphic with some structural influence, combination stratigraphic/structural, and diagenetic. Many carbonate buildups appear to have developed on subtle anticlinal noses or structural closures.

7. The Paradox Formation has heterogeneous reservoir properties because of depositional lithofacies with varying porosity and permeability, carbonate buildup (mound) relief and flooding surfaces (parasequence boundaries), and diagenetic effects. The extent of these factors, and how they are combined, affect the degree to which they create barriers to fluid flow. Identification and correlation of depositional lithofacies and parasequences in individual Paradox reservoirs is critical to understanding their effect on water/carbon dioxide injection programs, production rates, and paths of petroleum movement. The

typical early diagenetic events occurred in the following order: (1) early marine cementation, (2) post-burial, replacement, rhombic dolomite cementation due to seepage reflux, (3) vadose and meteoric phreatic diagenesis including leaching/dissolution, neomorphism, and fresh-water cementation, (4) mixing zone dolomitization, (5) syntaxial cementation, and (6) anhydrite cementation/replacement. Post-burial diagenesis included additional syntaxial cementation, silicification, late coarse calcite spar formation, saddle dolomite cementation, stylolitization, additional anhydrite replacement, late dissolution (microporosity development), and bitumen plugging.

8. Mapping the Ismay-zone lithofacies delineates very prospective reservoir trends that contain productive carbonate buildups around anhydrite-filled intra-shelf basins. Lithofacies and reservoir controls imposed by the anhydritic intra-shelf basins should be considered when selecting the optimal location and orientation of any horizontal drilling for undrained reserves. Projections of the inner shelf/tidal flat and mound trends around the intra-shelf basins identify potential exploration targets. Pervasive marine cement may be indicative of "wall" complexes of shallow-shelf carbonate buildups suggesting potential nearby carbonate buildups, particularly phylloid-algal mounds. Platform-margin calcarenites in the Desert Creek zone are located along the margins of the larger shallow shelf or the rims of phylloid-algal buildup complexes. Mapping indicates a relatively untested lithofacies belt of calcarenite carbonate deposits south and southeast of Greater Aneth field.

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