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

(Contract No. DE-2600BC15128)

DELIVERABLE 1.1.3
REGIONAL PARADOX FORMATION FACIES MAPS, BLANDING SUB-BASIN, SAN JUAN COUNTY, UTAH

Submitted by

Utah Geological Survey
Salt Lake City, Utah 84114
December 2003

UTAH GEOLOGICAL SURVEY

Contracting Officer's Representative

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DISCLAIMER

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INTRODUCTION

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

An extensive and successful horizontal drilling program has been conducted in the giant Greater Aneth field (figure 1). However, to date, only two horizontal wells have been drilled in small Ismay and Desert Creek fields. The results from these wells were disappointing due to poor understanding of the carbonate facies and diagenetic fabrics that create reservoir heterogeneity. These small fields, and similar fields in the basin, are at high risk of premature abandonment. At least 200 million barrels (31.8 million m^3) of oil will be left behind in these small fields because current development practices leave compartments of the heterogeneous reservoirs undrained. Through proper geological evaluation of the reservoirs, production may be increased by 20 to 50 percent through the drilling of low-cost single or multilateral horizontal legs from existing vertical development wells. In addition, horizontal drilling from existing wells minimizes surface disturbances and costs for field development, particularly in the environmentally sensitive areas of southeastern Utah and southwestern Colorado.

GEOLOGIC SETTING

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with a small portion in northeastern Arizona and the northwestern most corner of New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast trending evaporitic basin that predominately developed during the Pennsylvanian (Desmoinesian), about 330 to 310 million years ago (Ma). During the Pennsylvanian, a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The Uncompahgre Highlands (uplift) is bounded along the southwestern flank by a large basement-involved, high-angle reverse fault identified from geophysical seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest — the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and then continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993). The Paradox Basin is surrounded by other uplifts and basins that formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1).

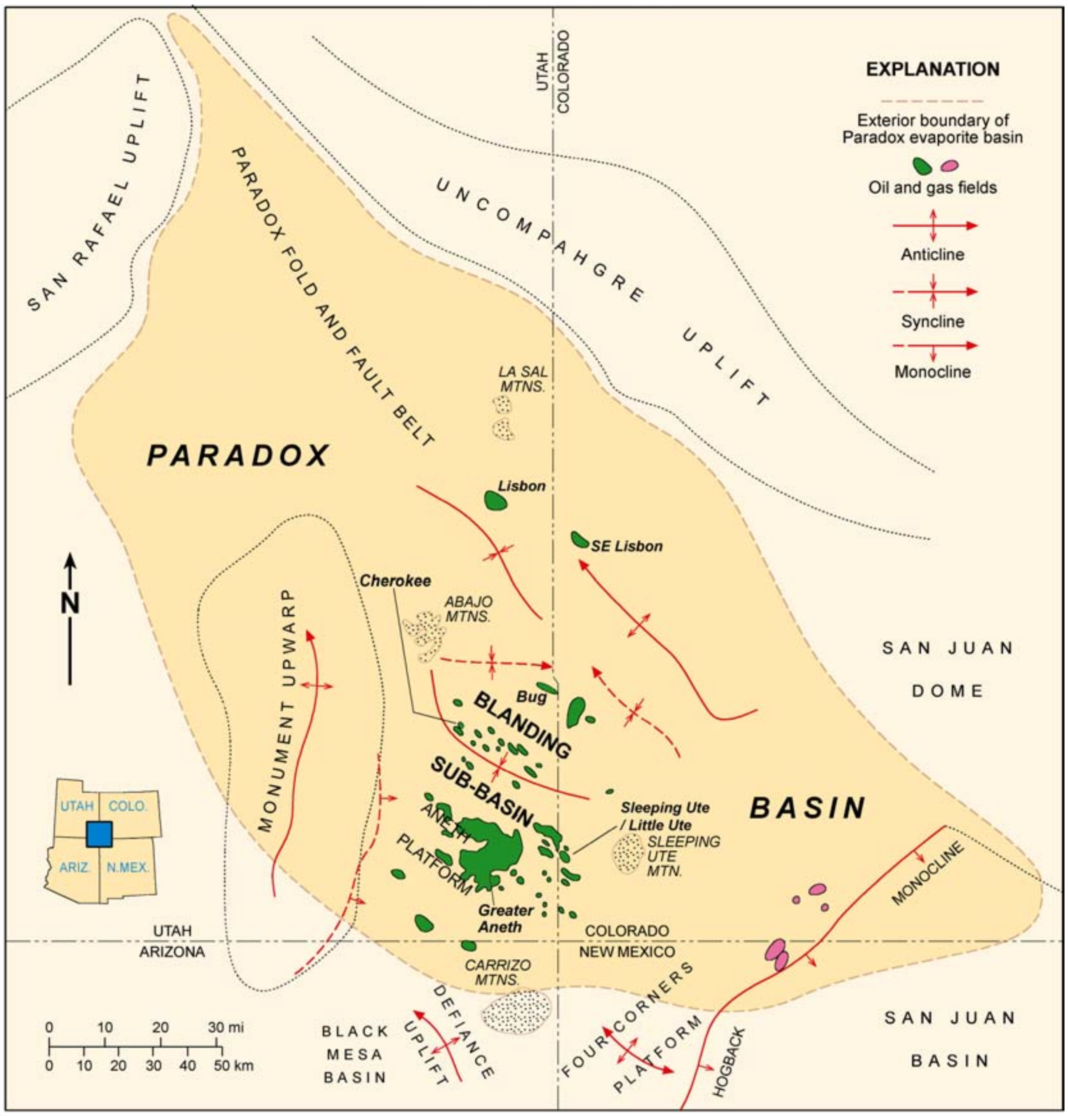


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

The Paradox Basin can generally be divided into 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 1). The relatively undeformed Blanding sub-basin and Aneth platform developed on a subtropical shallow-marine shelf and shelf-margin that locally contained algal-mound and other carbonate facies buildups. The codiacean green algae *Ivanovia* was the dominant genus in the algal buildups of the Paradox Formation. Hydrocarbons are stratigraphically trapped in porous and permeable units within carbonate buildups. These units are effectively sealed by impermeable marine mud and/or anhydrite at the base, flank, and top of the buildup. The source of the oil is several black, organic-rich shales within the Paradox Formation (Hite and others, 1984; Nuccio and Condon, 1996).

The two main producing zones of the Paradox Formation in the Blanding sub-basin are informally named the Ismay and the Desert Creek (figure 2). Reservoirs within the Utah portion of the upper Ismay zone of the Paradox Formation are dominantly limestones composed of small, phylloid-algal buildups; locally variable, inner-shelf, skeletal calcarenites; and rare, open-marine, bryozoan mounds (figure 3A). The Ismay produces oil from fields in the southern Blanding sub-basin (figure 4). The Desert Creek zone is dominantly dolomite comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts (figure 3B). The Desert Creek produces oil in fields in the central Blanding sub-basin (figure 4). Both the Ismay and Desert Creek buildups generally trend northwest-southeast. Various facies changes and extensive diagenesis have created complex reservoir heterogeneity within these two diverse zones.

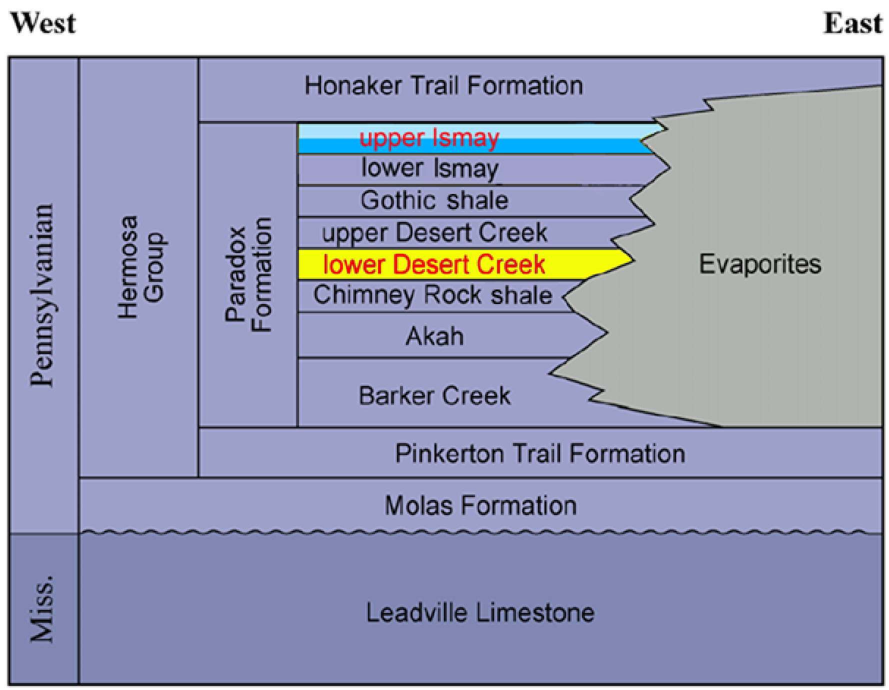


Figure 2. Pennsylvanian stratigraphy of the southern Paradox Basin including informal zones of the Paradox Formation; the upper Ismay and lower Desert Creek zones productive in case-study fields are highlighted. For this study the upper Ismay zone has been further divided into two units – the "upper part" and the "lower part."

REGIONAL FACIES TRENDS IN THE UPPER ISMAY AND LOWER DESERT CREEK ZONES OF THE BLANDING SUB-BASIN OF THE PARADOX BASIN, UTAH

Regional subsurface mapping of depositional facies for the two productive intervals of the upper Ismay and lower Desert Creek zones shows considerable spatial heterogeneity of the reservoir and non-reservoir rock types. In the Ismay, the location and shape of several anhydrite-rich, intra-shelf basins play major roles in the deposition and orientation of productive phylloid-algal buildups, as well as the shoreline facies that wrap around these evaporite basins. Facies distal from the anhydrite-filled basins generally contain less favorable reservoir rocks, whereas most phylloid-algal buildups and porous inner-shelf facies are very close to the intra-shelf basins. The two mapped, upper Ismay zone intervals show considerable differences in the distribution of these anhydrite basins and their surrounding facies. The Desert Creek zone in the Blanding sub-basin contains several of the same facies as the Ismay zone, the most notable exception being the intra-shelf evaporite basins which are discussed later.

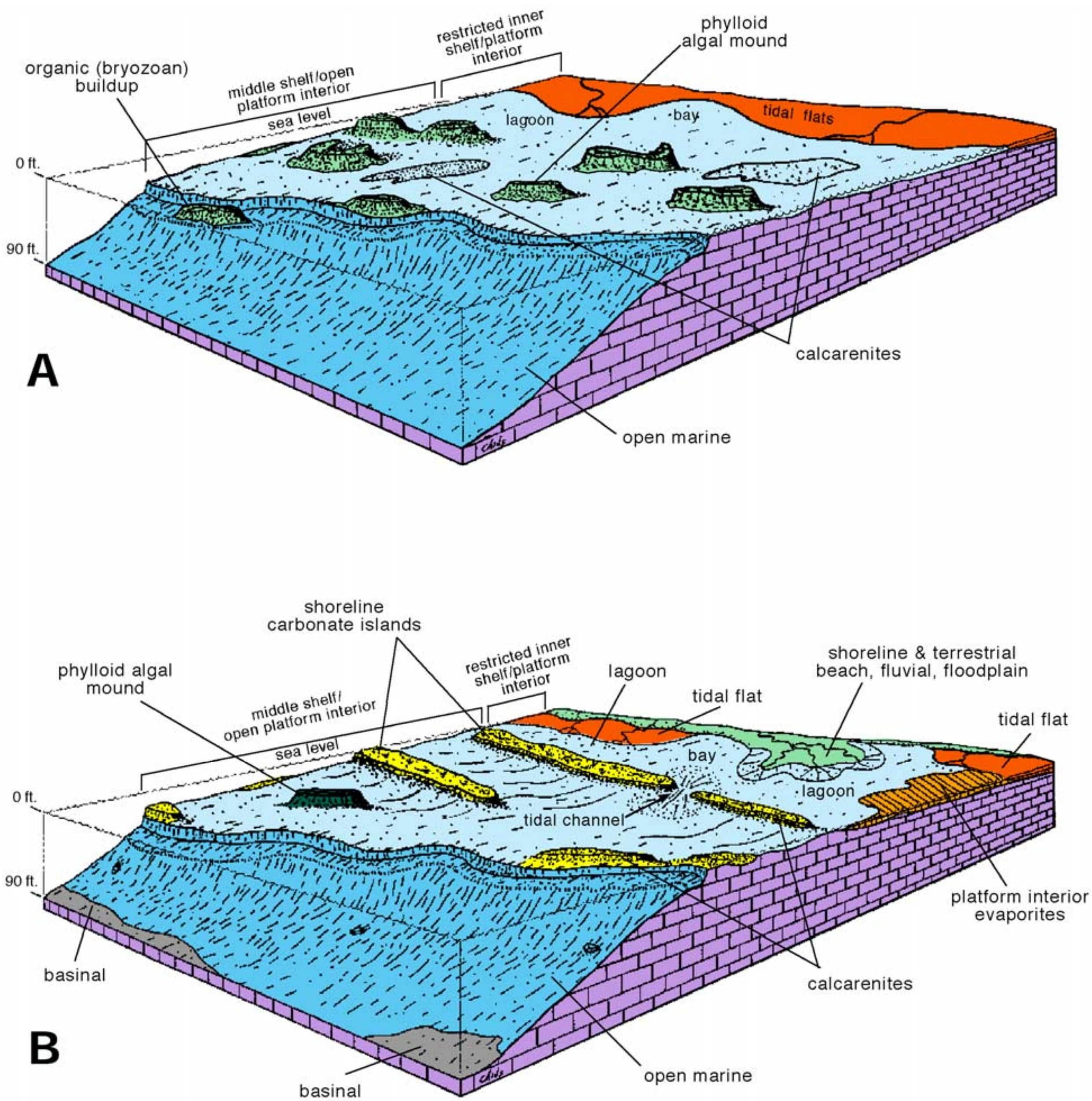


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

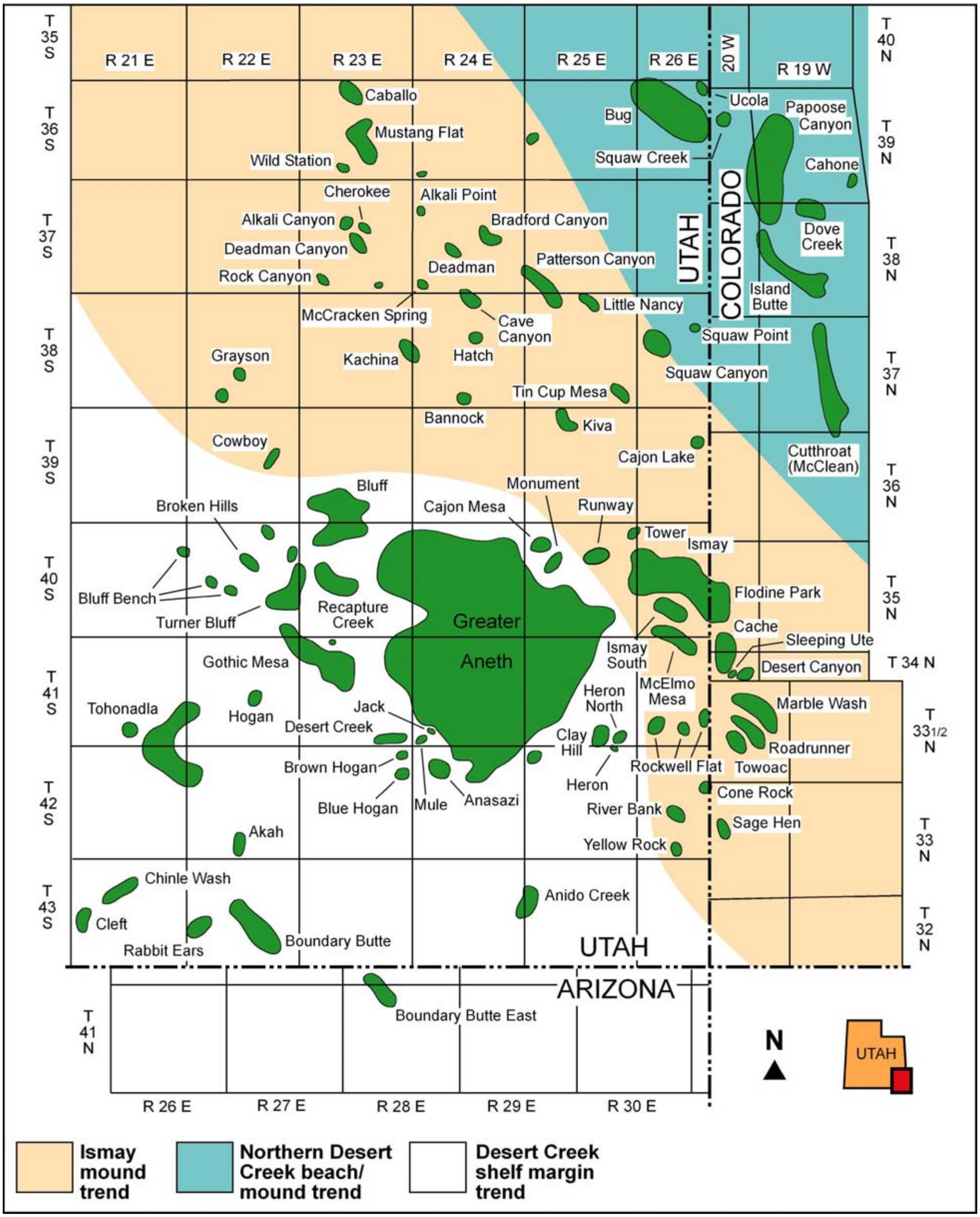


Figure 4. Map showing the project study area and fields within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

Facies Mapping Database

Regional geophysical well-logs, thickness relationships of important stratigraphic intervals, and facies types were combined with examination of cores throughout the Blanding sub-basin to provide a significant database for identifying potential targets for horizontal drilling within the small, heterogeneous, phylloid-algal buildups and associated facies in the upper Ismay and lower Desert Creek zones. The study area covers about 750 square miles (1,900 km^2) within the Blanding sub-basin of the Paradox Basin. The total number of wells drilled to the Paradox Formation within the study area is about 480 wells. We interpreted all available cores in the area: 41 wells in the upper part of the upper Ismay, 40 wells in the lower part of the upper Ismay, and 44 wells in the lower Desert Creek. Additionally, 82 geophysical well logs were interpreted from the upper Ismay and 38 from the Desert Creek.

Major Facies Mapped in the Upper Ismay and Lower Desert Creek Zones

Seven depositional facies interpreted from upper Ismay cores and four facies from lower Desert Creek cores have been recognized and mapped across the study area (plates 1 through 3). Mapping of these facies delineates prospective reservoir trends containing porous and productive buildups.

Upper Ismay (both the upper and lower parts as defined above) facies include open marine, middle shelf, inner shelf/tidal flat, bryozoan mounds, phylloid-algal mounds, quartz sand dunes, and anhydritic salinas. Lower Desert Creek facies include open marine, middle shelf, proto-mounds/collapse breccia, and phylloid-algal mounds.

Open Marine

Open-marine facies are found in both the Ismay and Desert Creek zones (plates 1 through 3 and figures 5 and 6). This facies consists of lime muds 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 with this facies act as barriers and baffles to fluid flow, having very little effective porosity and permeability.

Open-marine facies dominate the lower Desert Creek zone in the Blanding sub-basin where there is very little hydrocarbon potential (plate 3). However, this facies developed in different areas for both the upper part (northeastern and southern regions [plate 1]) and lower part (western to north-central regions [plate 2]) of the upper Ismay zone.

Middle Shelf

Middle-shelf facies are also found in both the Ismay and Desert Creek zones (figure 7). The most common depositional product of this facies is bioturbated lime to dolomitic mudstone with ubiquitous sub-horizontal, feeding burrows. 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.

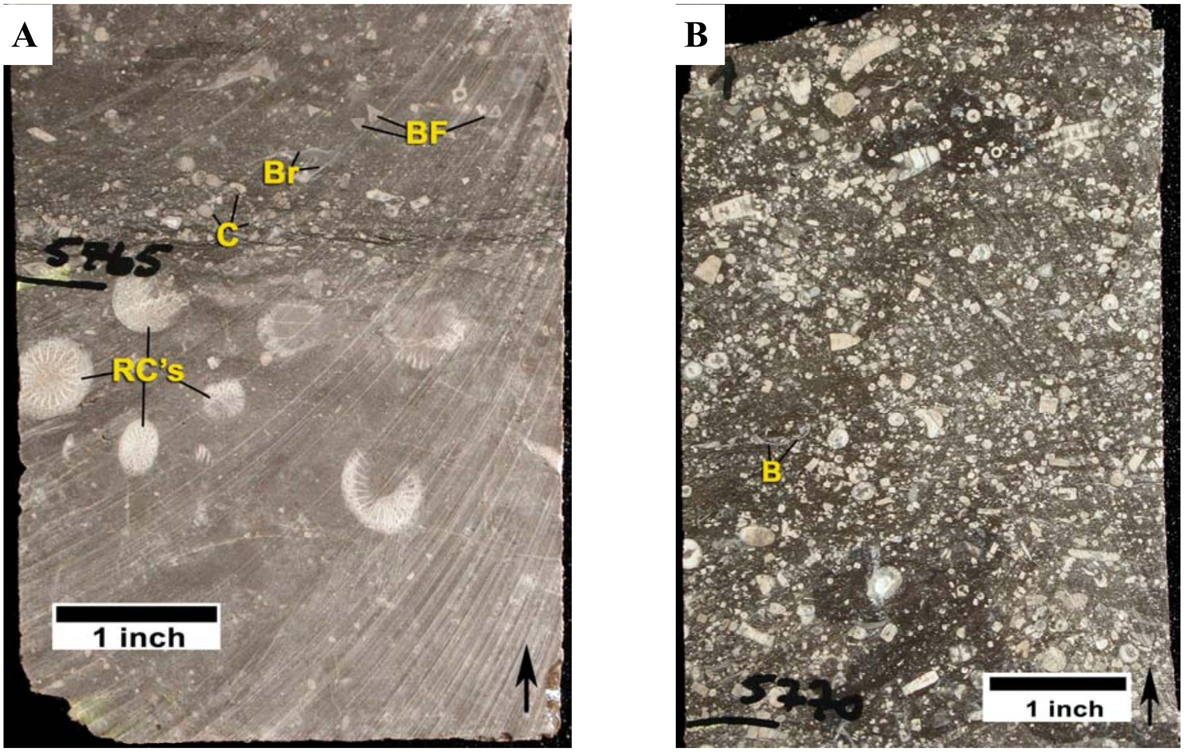
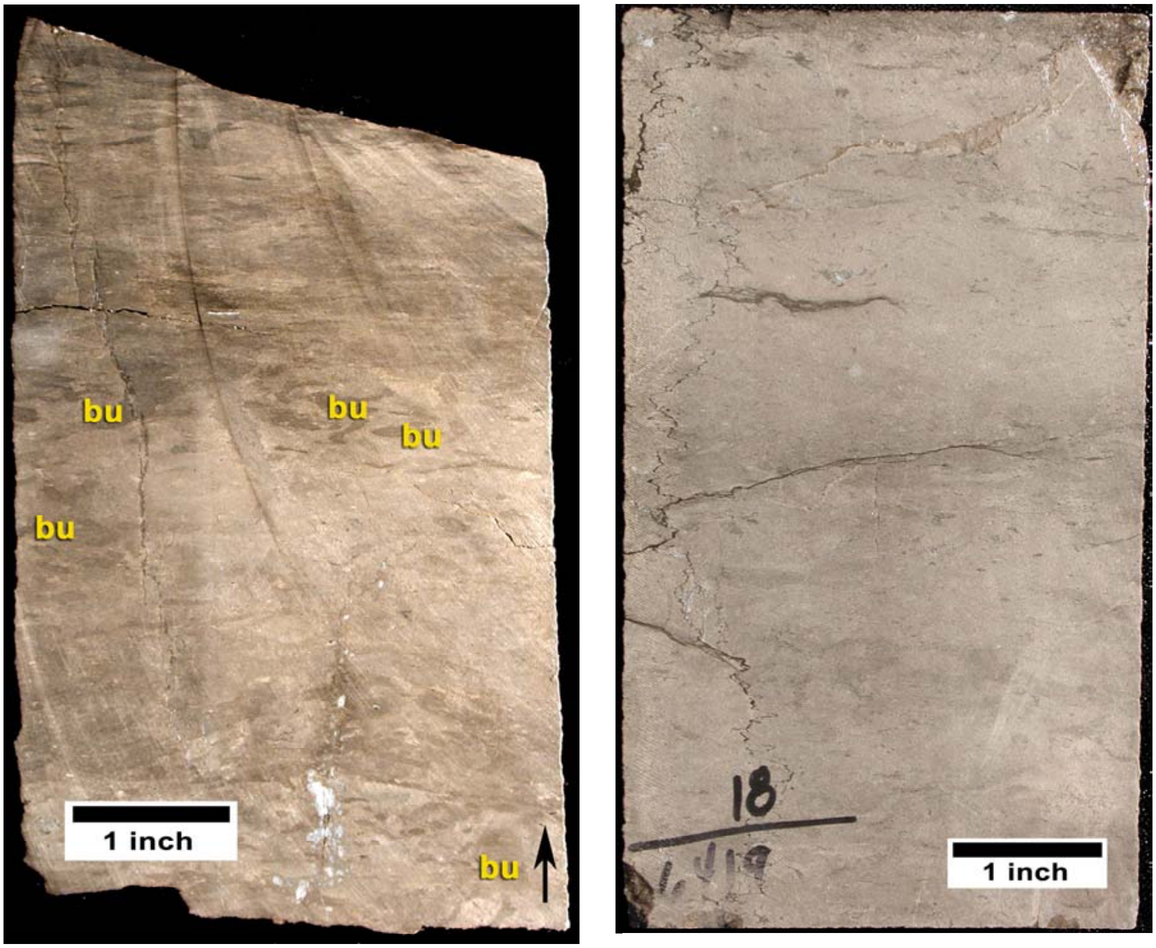


Figure 5. Typical, Ismay, open-marine facies from the No. 1-28 Cuthair well (section 28, T. 38 S., R. 22 E., Salt Lake Base Line [SLBL]). (A) Well-preserved rugose corals (RC), crinoids (C), brachiopods (Br), and benthic forams (BF); slabbed core from 5,765 feet. (B) Well-preserved, partially articulated crinoid stems and parts, as well as articulated thin-shelled bivalves (B); slabbed core from 5,770 feet.

Figure 6. Typical, Desert Creek, open-marine facies from the Scorpion No. 1 well (section 34, T. 36 S., R. 24 E., SLBL) containing dolomitized lime mud, and rugose corals and crinoids; slabbed core from 5,892 feet.



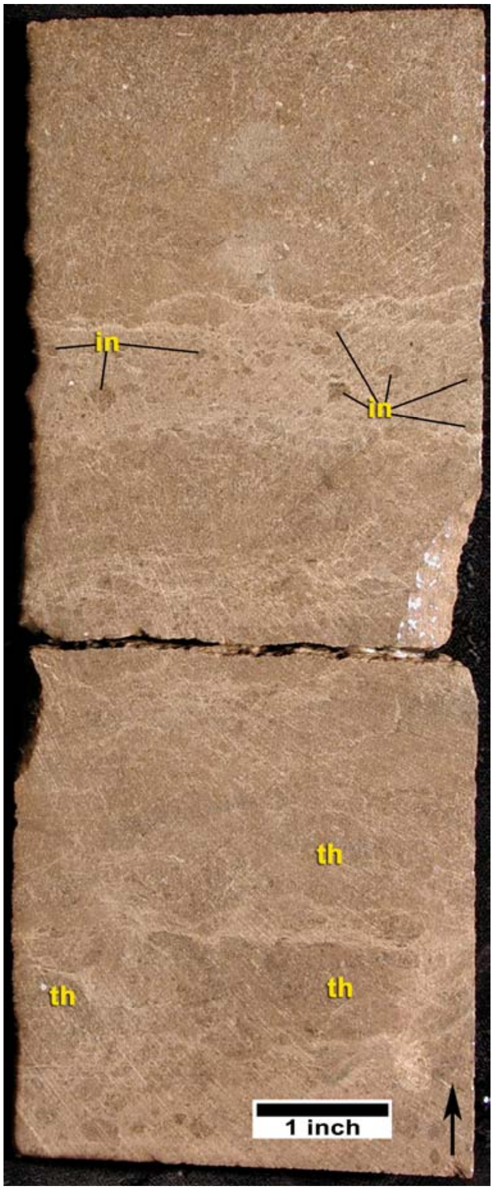
A B

Figure 7. Typical middle-shelf facies. (A) Ismay bioturbated lime mudstone containing compacted sub-horizontal feeding burrows (bu); Tank Canyon No. 1-9 well, section 9, T. 37 S., R. 24 E., SLBL, slabbed core from 5,412.5 feet. (B) Desert Creek burrowed dolomitic mudstone; Ucolo No. 1-32 well, section 32, T. 35 S., R. 26 E., SLBL, slabbed core from 6,418.7 feet.

Middle-shelf facies 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 (plates 1 through 3).

Inner Shelf/Tidal Flat

Inner shelf/tidal flat facies are found in the Ismay as dolomitized packstone and grainstone (figure 8). 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 facies.



A

B

Figure 8. Typical, Ismay, inner shelf/tidal flat facies. (A) 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, slabbed core from 5,460.5 feet. (B) Non-skeletal grainstone composed of ooids, coated grains, and peloids, with dark gray patches and columns composed of anhydrite-cemented sediments; Patterson No. 5 well, section 4, T. 38 S., R. 25 E., SLBL, slabbed core from 5,443.5 feet.

Inner shelf/tidal flat facies 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.

Bryozoan Mounds

Bryozoan mound facies are found in the Ismay zone as mesh-like networks of tubular and sheet-type (fenestrate) bryozoans (figure 9). These bryozoans provide the binding agent for lime mud-rich mounds. Crinoids and other open-marine fossils are common throughout these quiet-water buildups. 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.

Bryozoan mound facies developed in the relatively deeper water of the middle shelf. Thus far they are only recognized in the lower part of the upper Ismay, at and near Mustang Flat field (figure 4 and plate 2).

Proto-Mounds/Collapse Breccia

Proto-mounds/collapse breccia facies are found in the Desert Creek zone and represent the initial stage of a mound buildup or one that never fully developed (figure 10). They contain dolomitized and brecciated algal plates, marine cements, and internal sediments suggesting subareal exposure.

Proto-mounds/collapse breccia facies are usually near phylloid-algal mound facies 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 nearby fully developed mounds (plate 3).

Phylloid-Algal Mounds

Phylloid-algal mound facies are found in both the Ismay and Desert Creek zones and represent the dominant oil-producing reservoirs in the Paradox Formation (plates 1 through 3, and 11). Very large phylloid-algal plates of the codiacean green algae *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 11A). 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 11B). Desert Creek mounds are dolomitized, contain plates of the codiacean green algae *Kansasphyllum* (figure 11C), 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.

In the upper Ismay zone, most phylloid-algal mounds developed adjacent to widespread intra-shelf (anhydrite-filled) basins (plate 1 and 2). Porous Desert Creek mound facies, such as the reservoir for Bug field, appear to be linear shorelines that developed on the middle shelf (plate 3).

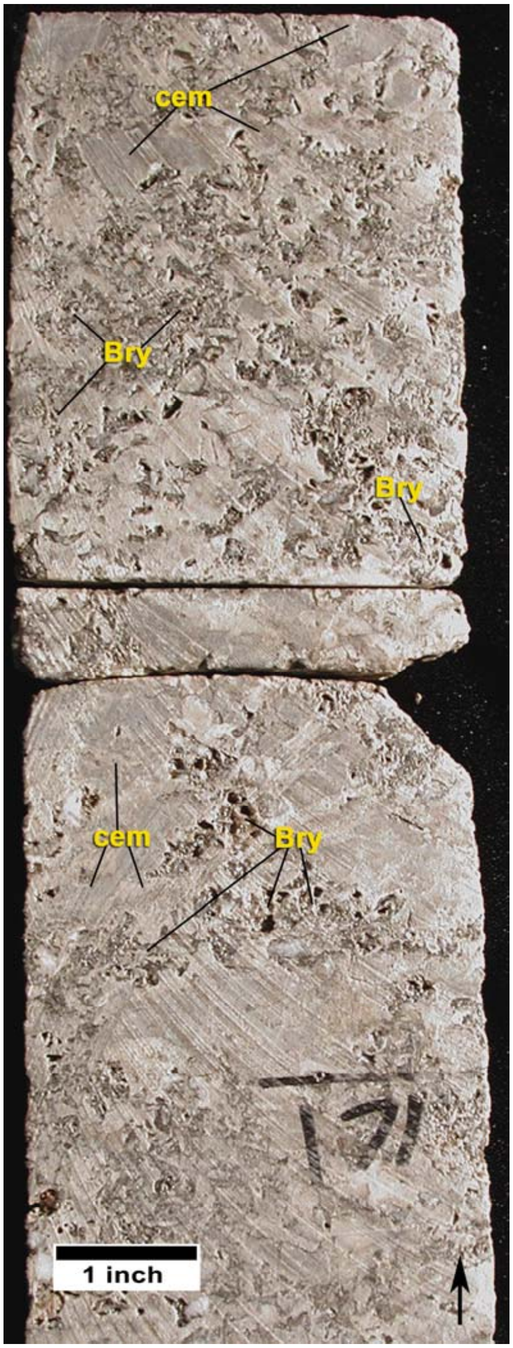
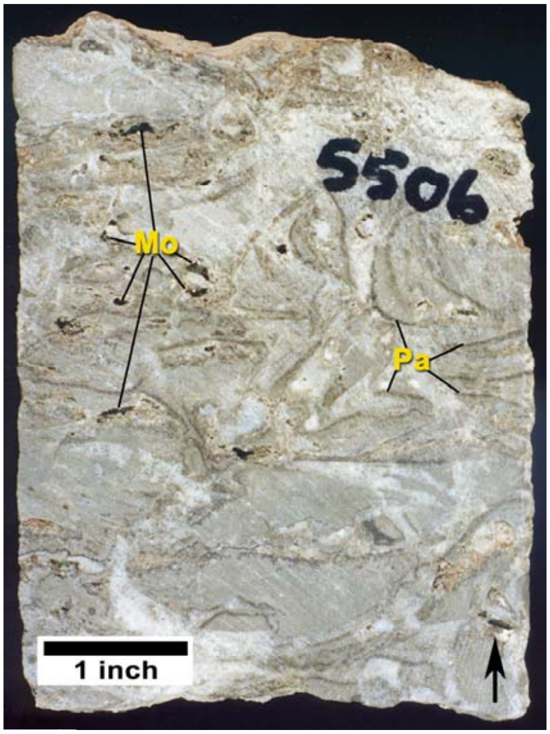


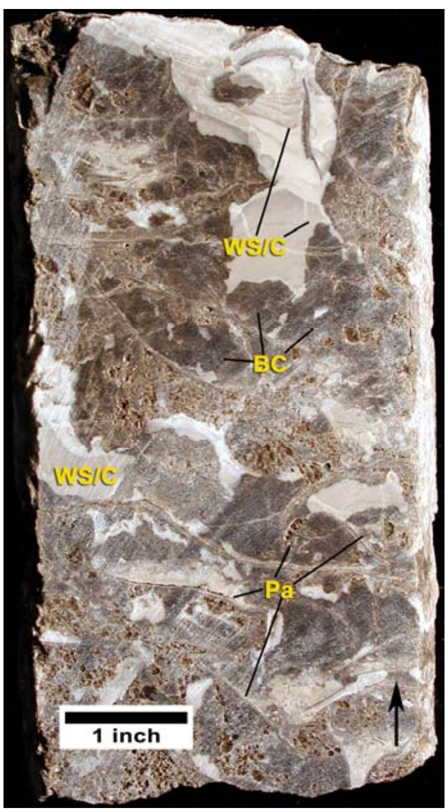
Figure 9. Typical, Ismay, bryozoan-mound facies from the Mustang No. 3 well (section 26, T. 36 S., R. 25 E., SLBL, slabbed core from 6,171 feet) containing large tubular bryozoans (Bry) and "lumps" of marine cement (cem). Occasional phylloid-algal plates are also present. This mound fabric is typical of higher energy, and possibly shallower water than the mud-dominated fabrics.

Figure 10. Typical, Desert Creek proto-mound/collapse breccia from the Ucolo No. 1 well (section 26, T. 38 S., R. 25 E., SLBL, slabbed core from 5,506 feet) showing dolomitized, broken algal plates, marine cement, and internal sediment. Note that very little porosity is preserved (white areas are anhydrite).



A

C



B

Figure 11. Typical Ismay and Desert Creek phylloid-algal mound facies. (A) Ismay bafflestone fabric in the Tin Cup Mesa No. 3-26 well (section 26, T. 38 S., R. 25 E., SLBL, slabbed core from 5,506 feet) 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. (B) Ismay bindstone (cementstone) from the Bonito No. 41-6-85 well (section 6, T. 38 S., R. 25 E., SLBL, slabbed core from 5,590.5 feet) 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. (C) Desert Creek mound from the May Bug No. 2 well (section 7, T. 36 S., R. 26 E., SLBL, slabbed core from 6,310 feet) composed of dolomitized algal plates of the genus Kansasphyllum (arrows).

Quartz Sand Dunes

Quartz, sand-dune facies are found in the Ismay as very fine grained, well-sorted quartzose sandstone that displays moderate- to high-angle cross-bedding (figure 12). The well-rounded nature of the individual quartz sand grains (visible in thin sections) is consistent with a possible eolian origin for these dunes, although the source of the sand is uncertain.

Quartz, sand-dune facies are present near Mustang Flat field and a few other isolated locations in the lower part of the upper Ismay zone (plate 2). This facies may also be present in the lower Ismay outcrop along the Honaker Trail in the San Juan River canyon near Goosenecks State Park, southern San Juan County, Utah (Pray and Wray, 1963).

Anhydritic Salinas

Anhydrite salina facies are found within locally thick accumulations in upper Ismay (upper and lower parts) intra-shelf basins (plates 1 and 2). Anhydrite growth forms include nodular-mosaic ("chicken-wire"), palmate, and banded anhydrite (figure 13). 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.

Regional facies mapping clearly defines anhydrite-filled, intra-shelf basins. Inner shelf/tidal flat and associated productive, phylloid-algal, mound-facies trends of the Ismay are present around the anhydritic salinas of intra-shelf basins (plates 1 and 2). Although not present in the lower Desert Creek zone in the Blanding sub-basin, the Desert Creek reservoir facies peripheral to Greater Aneth field to the south (figure 4) wrap around similar anhydrite-filled intra-shelf basins (Chidsey and others, 1996; Chidsey and Eby, 2000).

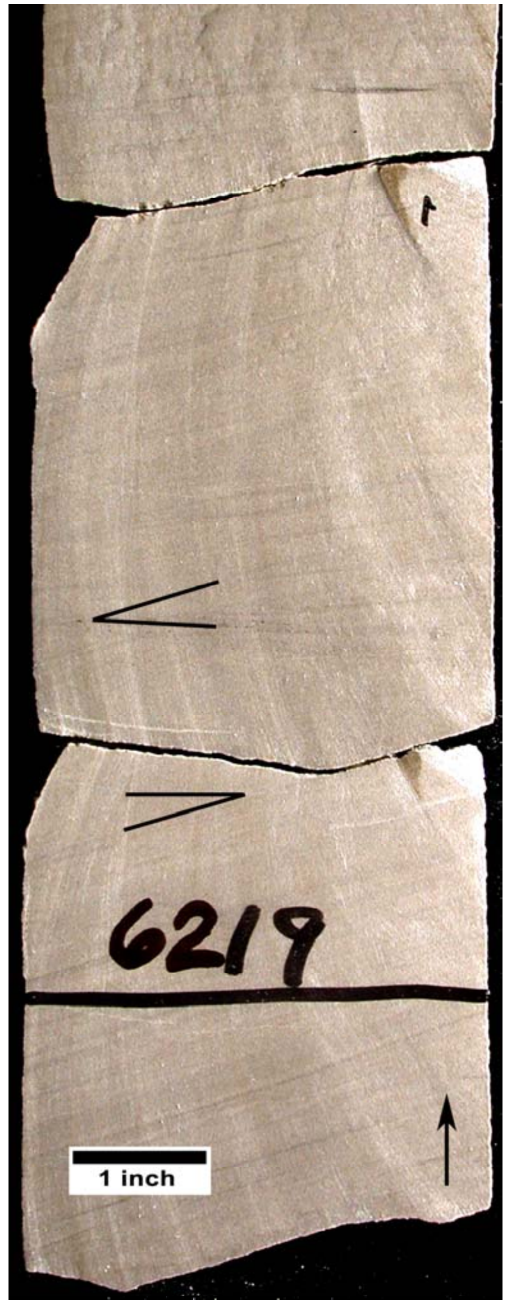


Figure 12. Typical upper Ismay (lower part) quartz sand dune facies from the Mustang No. 22-43 well (section 26, T. 36 S., R. 43 E. SLBL, slabbed core from 6,219 feet) showing high-angle cross-stratification within a 35-foot-thick sandstone encountered in wells of Mustang Flat field (figure 4).

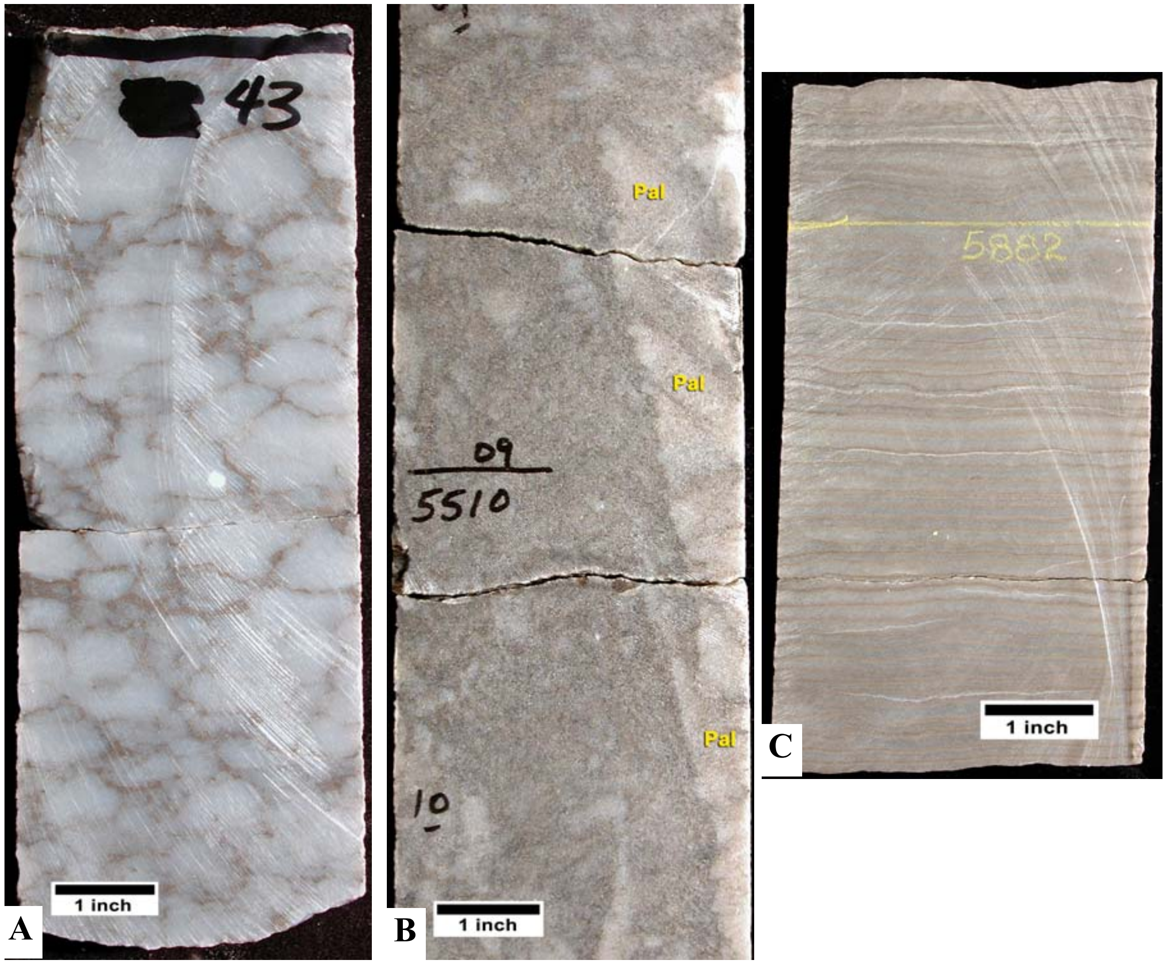


***Figure 13.** Anhydrite growth forms typically found in anhydrite salina facies of upper Ismay intra-shelf basins. (A) Nodular-mosaic ("chicken-wire") anhydrite; Tank Canyon No. 1-9 well, section 9, T. 37 S., R. 24 E. SLBL, slabbed core from 5,343 feet. (B) Large palmate crystals of anhydrite (Pal) 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 well, section 30, T. 38 S., R. 25 E., SLBL, slabbed core from 5,510 feet. (C) Thin (cm-scale), banded couplets of pure anhydrite (white to light gray) and dolomitic anhydrite (brown); Montezuma No. 41-17-74, section 17, T. 37 S., R. 24 E., SLBL, slabbed core from 5,882 feet.*

ACKNOWLEDGMENTS

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PLATES

Plate 1

Regional Facies

Upper Part - Upper Ismay Zone (Paradox Formation)

Deliverable 1.1.3 Regional Paradox Formation Facies Maps,
Blanding Sub-Basin, San Juan County, Utah

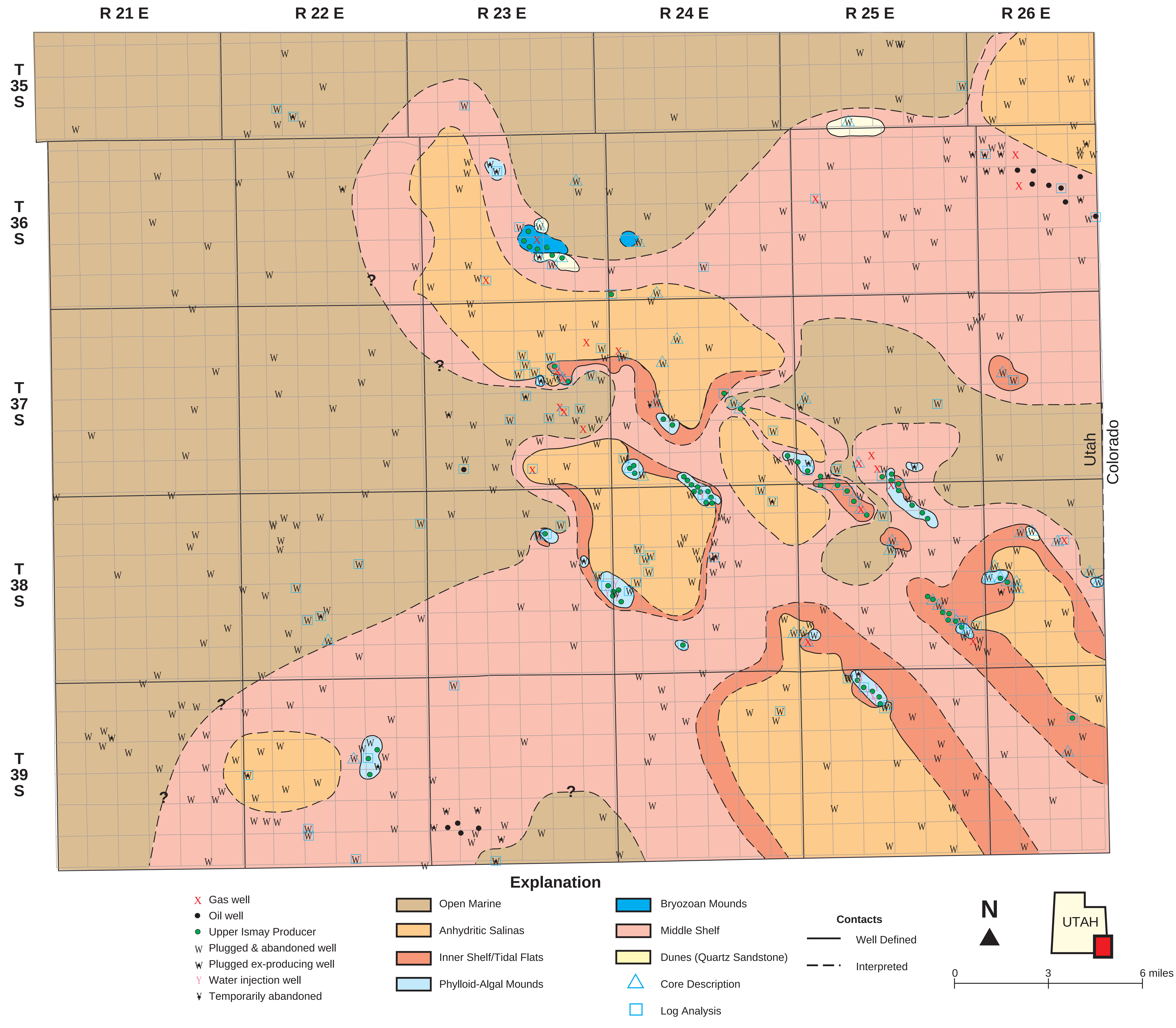


Plate 2

Regional Facies

Lower Part - Upper Ismay Zone (Paradox Formation)

**Deliverable 1.1.3 Regional Paradox Formation Facies Maps,
Blanding Sub-Basin, San Juan County, Utah**

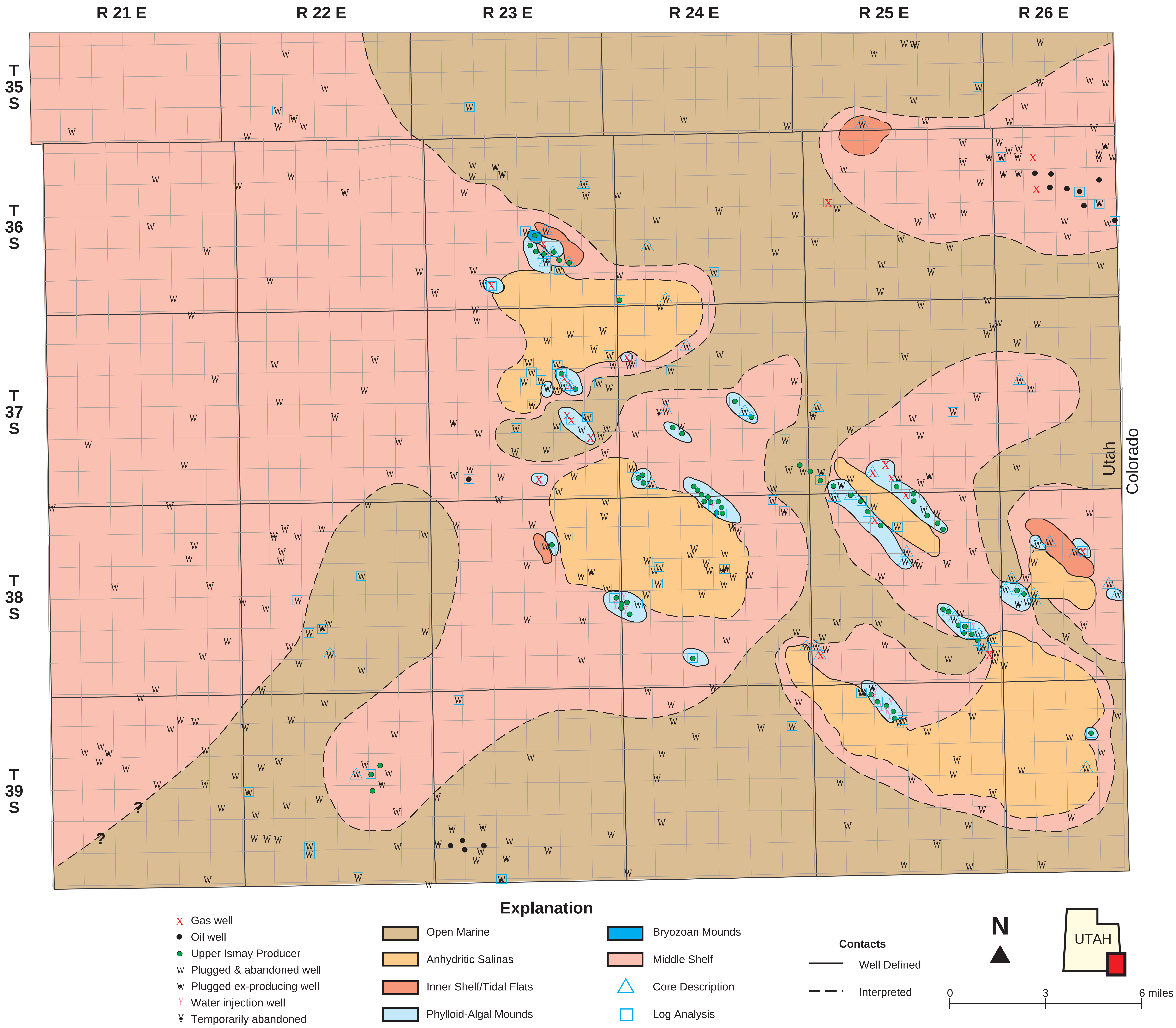
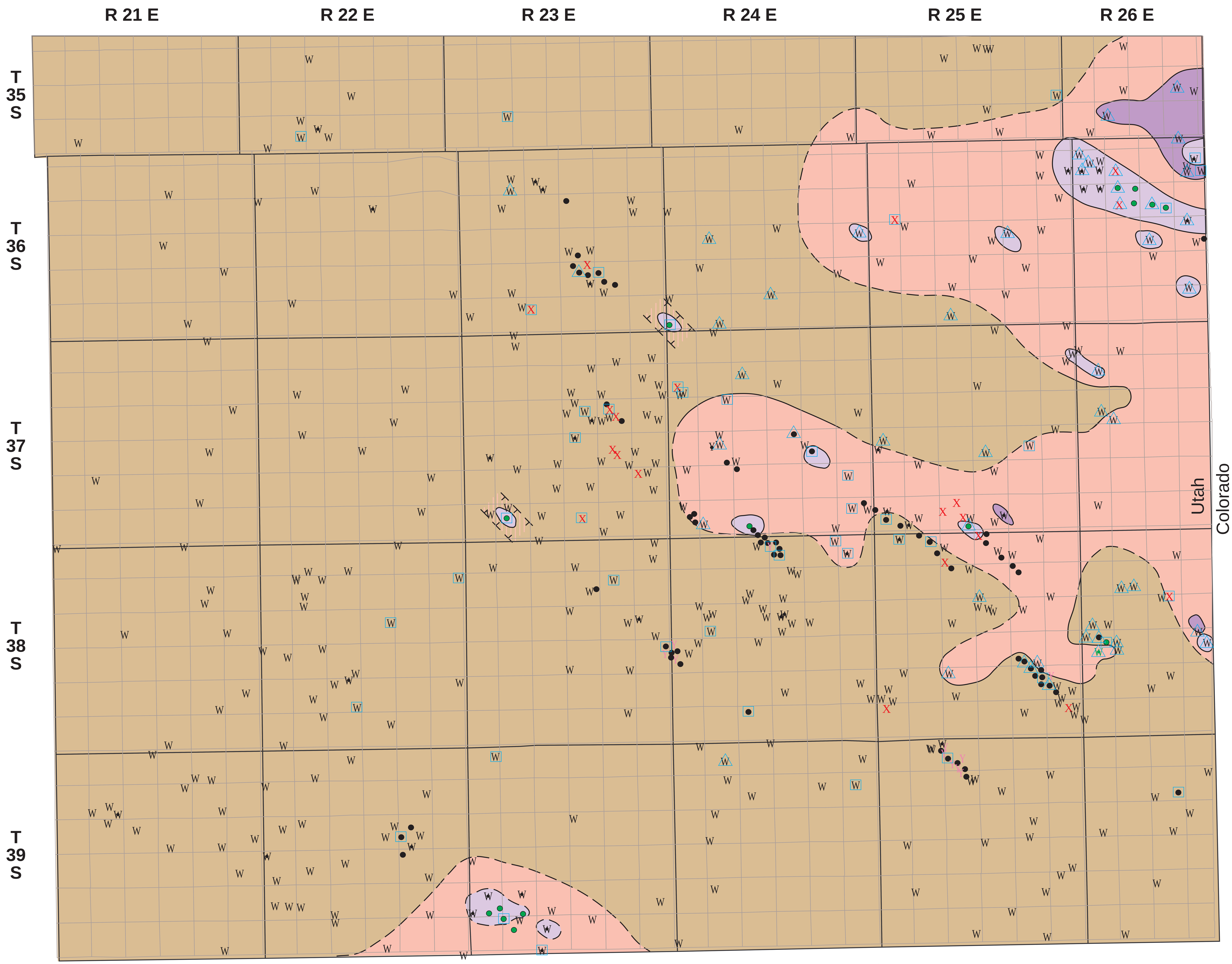


Plate 3

Regional Facies

Lower Desert Creek Zone (Paradox Formation)

**Deliverable 1.1.3 Regional Paradox Formation Facies Maps,
Blanding Sub-Basin, San Juan County, Utah**



Explanation

- Gas well
- Oil well
- Desert Creek Producer
- Plugged Desert Creek Producer
- Plugged & abandoned well
- Plugged ex-producing well
- Water injection well
- Temporarily abandoned

- Open Marine
- Middle Shelf
- Anhydrite-plugged Phylloid-Algal Mound
- Phylloid-Algal Mound
- Proto-mound/Collapsed Breccia
- Core Description
- Log Analysis

- Possible Collapse Feature with porosity

Contacts

- Well Defined
- Interpreted

N

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0 3 6 miles