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

(Contract No. DE-2600BC15128)

DELIVERABLE 1.2.1B THIN SECTION DESCRIPTIONS: LITTLE UTE AND SLEEPING UTE FIELDS, MONTEZUMA COUNTY, COLORADO

Submitted by

Utah Geological Survey Salt Lake City, Utah 84114 December 2003



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David E. Eby, Eby Petrography & Consulting, Inc. and Laura L. Wray, Colorado Geological Survey

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INTRODUCTION

Over 400 million barrels (64 million m^3) of oil have been produced from the shallowshelf 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 in Utah (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 m³) of oil will be left behind in these small fields because current development practices leave compartments of the heterogeneous reservoirs undrained. Through proper geological evaluation of the reservoirs, production may be increased by 20 to 50 percent through the drilling of low-cost single or multilateral horizontal legs from existing vertical development wells. In addition, horizontal drilling from existing wells minimizes surface disturbances and costs for field development, particularly in the environmentally sensitive areas of southeastern Utah and southwestern Colorado.

GEOLOGIC SETTING

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



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

The Paradox Basin can generally be divided into two areas: the Paradox fold and fault belt in the north, and the Blanding sub-basin in the south-southwest (figure 1). Most oil production comes from the Blanding sub-basin. The source of the oil is several black, organicrich shales within the Paradox Formation (Hite and others, 1984; Nuccio and Condon, 1996). The relatively undeformed Blanding sub-basin developed on a shallow-marine shelf which locally contained algal-mound and other carbonate buildups in a subtropical climate. The two main producing zones of the Paradox Formation are informally named the Ismay and the Desert Creek (figure 2). The Ismay zone is dominantly limestone comprising equant buildups of phylloid-algal material with locally variable small-scale subfacies (figure 3A) and capped by anhydrite. The Ismay produces oil from fields in the southern Blanding subbasin (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.



CASE-STUDY FIELDS

Two Colorado fields were selected for local-scale evaluation and geological characterization: Little Ute and Sleeping Ute in the Ismay trend (figure 4). This evaluation included data collection and thin section analysis of these fields as presented in this report.

This geological characterization focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within the fields. From these evaluations, untested or under-produced compartments can be identified as targets for horizontal drilling. The models resulting from the geological and reservoir characterization of these fields can be applied to similar fields in the basin (and other basins as well) where data might be limited.

Little Ute and Sleeping Ute fields are located in Montezuma County, Colorado (sections 3, 10, and 11, T. 34 N., R. 20 W. (figure 4). The producing reservoirs consist of phylloid-algal buildups in the Ismay zone flanked by bryozoan mounds and mound flank debris. These porous mounds, capped by impermeable anhydritic dolomite, produce primarily from porous phylloid-algal limestones, some of which have been dolomitized. The net reservoir thickness is 30 feet (9.1 m), which extends over approximately 640 acres (260 ha). Porosity ranges from 4 to 20 percent with 1 to 98 millidarcies (md) of permeability in vuggy and intercrystalline pore systems.



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



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

The first well drilled in the Little Ute/ Sleeping Ute study area was a dry hole, completed in 1959. The Calvert Drilling Company Desert Canyon No. 1 was drilled in the SW/4 of section 10, T. 34 N., R. 20 W., to a total depth of 5,938 feet (1,810 m) to the Gothic shale as a test of the Ismay and Desert Creek zones of the Paradox Formation. The well was plugged and abandoned on September 29, 1959, after a drill-stem test and four cores were taken in the Ismay and Desert Creek. The results of the drill-stem test, taken over the interval of 5,697 to 5,840 feet (1,736-1,780 m), were discouraging in that there was a very weak blow of air to the surface that died in 5 minutes and only 55 feet (17 m) of drilling mud was recovered. Somewhat more encouraging were the cores taken from 5,675 to 5,739 feet (1,730-1,749 m), 5,729 to 5,782 feet (1,746-1,762 m), 5,782 to 5,820 feet (1,762-1,774 m), and 5,880 to 5,938 feet (1,792-1,819 m). Over that entire interval, there were favorable reports of petroliferous odor, visible vuggy and intercrystalline porosity, and bleeding oil.

There are currently three producing wells and three dry holes in the Little Ute and Sleeping Ute study area proper. Well spacing is 80 acres (32 ha). The net reservoir thickness is 20 feet (6 m) over a 240-acre (97 ha) area. Porosity averages 15 percent and permeability is 0.01 to 2 md. Water saturation is 50 percent (Ghazal, 1978). Cumulative production from these three wells, plus the Desert Canyon No. 3 well that defined the Desert Canyon field, exceeds 325,000 barrels (51,675 m³) of oil and 750 million cubic feet (21 million m³) of gas.

RESERVOIR DIAGENETIC ANALYSIS BASED ON THIN SECTIONS

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Little Ute and Sleeping Ute fields can be indicators of reservoir flow capacity, storage capacity, and potential for horizontal drilling. In order to determine the diagenetic histories of the various Ismay reservoirs, thin sections of representative samples were selected from the conventional cores of each field for petrographic description (see figure 5 for well locations). Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. Each thin section was photographed with additional close-up photos of: (1) facies, (2) typical preserved primary and secondary pore types, (3) cements, (4) sedimentary structures, (5) fractures, and (6) pore plugging anhydrite and halite. Petrophysical data (porosity and permeability) were obtained from core plugs.

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

Facies

Six representative facies were identified from core and geophysical well correlation from the Little Ute and Sleeping Ute fields: (1) phylloid-algal mounds; (2) bryozoan mounds; (3) mound talus; (4) calcarenite shoals; (5) open-marine carbonates; and (6) lagoonal/restricted

Figure 5. Upper Ismay zone structural contour map, Little Ute, Sleeping Ute, and Desert Canyon fields, Montezuma County, Colorado.



shelf carbonates. In terms of cumulative production from the wells in Little Ute and Sleeping Ute fields, the phylloid-algal mound facies, developed in three separated intervals in the Little Ute No. 1 well, is the best reservoir in the area (figure 5).

Representative photomicrographs of these various facies display the nature and extent of the reservoir porosity and permeability. The phylloid-algal mound facies photomicrograph (figure 6) shows the stunning reservoir development as seen by the blue impregnated pores. Leaching of the carbonate constituents, with porosity enhancement from dolomitization, creates an excellent reservoir. By comparison, the reservoir capability of the bryozoan mound facies (figure 7) is limited due to the isolated pores that are restricted to minor corrosion and intraparticle spaces.

The mound talus facies, in general, is not a good reservoir as shown in figure 8. The porosity that is present is remnant interparticle and some solution porosity as shown in blue in figure 8. The lagoonal/restricted marine facies (figure 9) has excellent porosity developed in a dolomitic mudstone with limited and variable permeability.



Figure 6. Photomicrograph (plane light with white card technique) showing a phylloid-algal mound bafflestone with a partially dolomitized and leached limestone stained with Alizarin Red-S solution. This sample exhibits much higher porosity and permeability than the undolomitized examples. Micritized remnants of phylloid algal plate rims (in red) are surrounded by partially dolomitized lime muds (white rhombs) and open pores (in blue). Little Ute No. 1 well, 5,882.5 feet, porosity = 18.4 percent, permeability = 95.6 md



Figure 7. Photomicrograph (plane light) showing a bryozoan mound. This low-magnification micrograph shows poorly preserved remnants of bryozoan tubular clusters surrounded by vaguely peloidal lime muds. The large white masses in view are composed of this replacement anhydrite. Most of the porosity (in blue) is very isolated and restricted to minor corrosion and intraparticle spaces. Sleeping Ute No. 1 well, 5,599.3 feet, porosity = 2.5 percent, permeability = 1.30 md.

Figure 8. Photomicrograph (plane light) of mound talus showing elongate clasts of mud and fossil fragments that were probably derived from nearby bryozoan and phylloid-algal mounds. Remnant interparticle and modest solution porosity can be seen in blue. Sleeping Ute No. 1 well, 5,561.4 feet, porosity = 3.9 percent, permeability = 0.491 md.





Figure 9. Low-magnification photomicrograph (plane light) of lagoonal/restricted marine facies showing crystal casts (in white) of early evaporite minerals (now anhydrite) surrounded by a darkcolored, dolomitic mudstone with sponge spicules (the very small white specks). Note the vague peloid outlines and microporosity (in blue) within this sample. Little Ute No. 1 well, 5,837.8 feet, porosity = 20.5 percent, permeability = 2.87 md. The calcarenite shoal facies is one that, on geophysical well logs, appears to be a fair to good reservoir due to its porosity development. The problem, however, is that the intergranular and moldic porosity seen in figure 10 is isolated, and thus the permeability is extremely low.

Finally, the open-marine facies is replete with fossil fragments, some of which contain isolated moldic pores. Porosity such as is shown in figure 11 is actually quite good, but the lack of permeability that can connect these isolated pores results in a poor reservoir rock.

Figure 10. Photomicrograph (plane light) of high-energy shelf facies (calcarenite shoals) showing skeletal and aggregate grains within a highenergy grainstone. Among the typical grains of this facies are benthic for ams (including fusulinids), phylloid-algal plates, "hard" peloids or micritized skeletal grains, and grain aggregates. Isopachous marine cements and "dogtooth" meteoric spar cements are present. Little Ute No. 1 well, 5,940.5 feet, porosity = 4.6 percent, permeability = 0.018 md.





Figure 11. Photomicrograph (plane light) of open marine facies showing fossiliferous wackestone with part of a wellpreserved brachiopod shell as well as much smaller sponge spicules, echinoderm parts, and other bivalves. Note the vague peloidal fabric within the muds. Sleeping Ute No. 1 well, 5,636.6 feet, porosity = 8.0 percent, permeability = 0.080 md.

Pore Types

The Ismay facies contain a wide variety of pore types and associated reservoir characteristics. Interparticle porosity, shown in figure 12, contains pores that are remnants of the original interparticle pore system between the skeletal components in this grainstone. The paragenetic sequence of diagenesis suggests that most of the original pore space has been occluded by early marine cements, meteoric calcite spar, and minor anhydrite precipitation. The diagenetic overprint on what was originally an excellent reservoir rock renders the resultant sample poor due to lack of permeability between the isolated pores.

Figure 12. Photomicrograph (plane light with white card technique) of interparticle porosity. The scattered pores (in blue) visible in this micrograph are principally the remnants of primary interparticle space between the skeletal components of this grainstone. Early *marine cements, followed by probable* meteoric calcite spar and minor anhydrite (in white) have occluded most of the original interparticle Little Ute No. 1 well, porosity. 5,940.5 feet, porosity = 4.6 percent, permeability = 0.018 md.



Intraparticle porosity can create either good or poor reservoir rock, depending once again on the permeability network. Figure 13 shows good reservoir porosity, but a range in permeability that appears to be dependent upon the type of organisms in which the intraparticle porosity develops. This figure illustrates nicely that the phylloid-algal mound facies comprises superior reservoir characteristics compared to the bryozoan mound facies.

The phylloid-algal mound facies also contains examples of shelter porosity as seen in figure 14. Large pores develop under or between platy phylloid algal plates and/or curvilinear bivalve shells. Reservoir quality is degraded, however, when early cementation occludes these pores either partially or completely.

Early dissolution of skeletal grains and evaporite mineral crystals can also create moldic porosity, as seen in figure 15. These molds are large, but so isolated as to create very little permeability. Even extensive diagenetic dissolution that creates excellent porosity does not insure that a reservoir can be economically produced. Figure 16 shows large, open pores created by widespread dissolution of skeletal grains, carbonate clasts, and early carbonate cements. However, the permeability is ineffective in connecting this well-developed vuggy porosity.



Figure 13. Photomicrograph (plane light with white card technique) of interparticle porosity. Open pores (in blue) are shown here within the uncemented chambers of encrusting organisms surrounded by lime muds. This sample is from within a phylloidalgal mound core. Little Ute No. 1 well, 5,870.9 feet, porosity = 9.8 percent, permeability = 12.2 md.



Figure 14. Photomicrograph (plane light with white card technique) of shelter porosity. Most of the large pores (in blue) occurring between platy phylloid-algal plates and the curvilinear bivalve shells are sheltered from internal sediment fillings. These preserved primary pores are often lined with early cements, thus limiting permeability. Some of the original grains and muds in this sample are associated with a phylloid-algal mound core. Little Ute *No. 1 well, 5,946.3 feet, porosity = 3.9* percent, permeability = 0.881 md.

Figure 15. **Photomicrograph** (plane light) of moldic porosity. The isolated pores (in blue) are mostly from dissolved skeletal grains and early evaporite mineral crystals. These fossil molds and crystal are surrounded by dense lime muds. Sleeping Ute No. 1 well, 5,636.6 *feet,* = 8.0 *percent, permeability* = 0.080 md.





Figure 16. Photomicrograph (plane light with white card technique) of vuggy porosity. The oversized pores (in blue) shown here are solutionenlarged vugs. Early dissolution of skeletal grains, clasts and cements created these large, isolated pores. Little Ute No. 1 well, 5,946.3 feet, porosity = 3.9 percent, permeability = 0.881 md. Though not abundant in the Little Ute and Sleeping Ute fields, intercrystalline porosity, developed between dolomite microcrystals, can create excellent reservoir rock as seen in figure 17. The introduction of evaporites that replace grains and occlude porosity prevent this sample from having much higher permeabilities. An excellent example of effective intercrystalline porosity is seen in figure 18. Not surprisingly, this example is from the phylloid-algal mound facies and has excellent porosity and permeability developed between rhombic dolomite crystals, allowing large, well-connected pores.



Figure 17. Photomicrograph (plane light) of intercrystalline porosity. The extremely small pores (in blue) of this view mostly occur between dolomite microcrystals. Crystal casts of evaporite minerals (in white) have grown displacively or replaced the dolomitic mud sediment. Little Ute No. 1 well, 5,837.8 feet, porosity = 20.5 percent, permeability = 2.86 md.

Figure 18. Photomicrograph (plane light) of intercrystalline porosity. The large, wellconnected pores (in blue) in this view mostly occur between rhombic dolomite crystals. Some of the original grains and muds in this sample are associated with a phylloid-algal mound core. Little Ute No. 1 well, 5,882.5 feet, porosity = 18.4 percent, permeability = 95.6 md.



The final pore type seen in Little Ute and Sleeping Ute fields is microfractures, as displayed in figure 19. Reservoir quality is enhanced with extensive and abundant microfractures.



Figure 19. Photomicrograph (plane light) of microfractures. A pair of open microfractures (in blue) are illustrated here that cross lime muds within the sediments of a phylloid-algal mound interior. Recrystallized skeletal fragments (including phylloid-algal plates) are the white areas in this view. Little Ute No. 1 well, 5,919.2 feet, porosity = 8.0 percent, permeability = 0.398 md.

Mineralogy

Five distinct mineralogies are seen in Little Ute and Sleeping Ute fields. Simple limestone deposited as the calcite remains of phylloid-algal plates, marine fossils, and lime muds (figure 20), can have excellent porosity and permeability as a result of early dissolution by fresh waters. Dolomite, created during the diagenetic process in which organic mudstone is dolomitized (figure 21), can preserve high porosities and good effective permeabilities.



Figure 20. **Photomicrograph** (plane light with white card technique) of limestone where Alizarin Red-S staining shows the calcite composition of corroded remnants from phylloid-algal plates, marine fossils, and lime muds. Early dissolution by fresh waters has created some of the porosity (in Little Ute No. 1 well, blue). 5,882.5 feet, porosity = 18.4percent, permeability = 95.6 md.

Several mixed mineralogies are created and preserved as well. Anhydritic limestone, in which the original calcite fossils have been partially replaced by anhydrite, does not create a good reservoir (figure 22). In contrast, anhydritic dolomite, as seen in figure 23, has abundant microporosity but very little permeability.



Figure 21. Photomicrograph (plane light with white card technique) of dolomite where sponge spicule-bearing, organic mudstone has been replaced by very finely crystalline dolomite. Note the very small intercrystalline and micro-moldic pores (in blue). Little Ute No. 1 well, 5,837.8 feet, porosity = 20.5 percent, permeability = 2.87 md.

Figure 22. Low-magnification photomicrograph (crossed nicols) of anhydritic dolomite showing clusters of early evaporite minerals (now anhydrite) surrounded by a dark-colored, dense dolomitic mudstone. Sleeping Ute No. 1 well, 5,575.4 feet, porosity = 13.2 percent, permeability = 0.283 md.





Figure 23. Highm a g n i f i c a t i o n photomicrograph (plane light with white card technique) of the same sample in figure 31 showing the very small crystal size of the dolomite matrix in this mixed mineralogy sample. Note the microporosity (in blue) within this sample.

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