MAJOR OIL PLAYS IN UTAH AND VICINITY

QUARTERLY TECHNICAL PROGRESS REPORT

Reporting Period
Start Date: July 1, 2005
End Date: September 30, 2005

by
Thomas C. Chidsey, Jr., Principal Investigator
and
Craig D. Morgan
Utah Geological Survey

UTAH GEOLOGICAL SURVEY

December 2005

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. However, 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. The Utah Geological Survey believes this trend can be reversed 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 thirteenth quarter of the project (July 1 through September 30, 2005). This work included (1) gathering field data and analyzing best practices in the Mississippian Leadville Limestone, Paradox Basin play of Utah, and (2) technology transfer activities.

The Mississippian Leadville Limestone is a major oil and gas play in the Paradox Basin, having produced over 53 million bbls (8.4 million m^3) of oil. The Leadville is an open-marine, carbonate-shelf deposit. Most Leadville production is from the Paradox fold and fault belt in basement-involved structural traps with closure on both anticlines and faults. The Leadville has heterogeneous reservoir properties because of depositional facies differences, diagenetic effects (particularly dolomitization), and fracturing with varying porosity and permeability. Lisbon field, San Juan County, Utah accounts for most of the Leadville oil production in the Paradox Basin. Wells in Leadville fields were drilled with air or fresh-water mud to the top of the Pennsylvanian salt, after which a natural brine or salt-base mud was typically used to total depth. These wells were completed by perforating at four shots per foot and acid stimulation of porosity zones. A thick hydrocarbon column at Lisbon field contains a gas cap and oil ring. Associated gas was reinjected into the gas cap to maintain reservoir pressure and maximize the oil recovery.

Horizontal drilling technology was not readily available when Lisbon field and other Leadville fields were discovered and developed. If horizontal technology had been available, Leadville fields could have been developed with fewer wells (especially in environmentally sensitive areas), and would have resulted in a greater ultimate oil recovery. Lithologic variations due to facies changes, diagenetically increased porosity zones due to dolomitzation, and fractures create potential undrained compartments ideally suited for horizontal drilling in the Leadville-producing fields. Drilling techniques should include new wells, and horizontal, often multiple and stacked, laterals from existing vertical wells.

Technology transfer activities during this quarter consisted of exhibiting a booth display of project materials at the 2005 Rocky Mountain Section meeting of the American Association of Petroleum Geologists (AAPG), a presentation on the central Utah thrust belt Navajo Sandstone oil play, and publications. 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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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. However, 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. The overall objectives of this study are to (1) increase recoverable oil from existing field reservoirs, (2) add new discoveries, (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 thirteenth quarter of the project (July 1 through September 30, 2005). This work included (1) gathering field data and analyzing best practices in the Mississippian Leadville Limestone, Paradox Basin play of Utah, 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 Mississippian Leadville Limestone is a major oil and gas play in the Paradox Basin having produced over 53 million bbls (8.4 million m^3) of oil. The Leadville is an open-marine, carbonate-shelf deposit. Most Leadville production is from the Paradox fold and fault belt in basement-involved structural traps with closure on both anticlines and faults. The Leadville has heterogeneous reservoir properties because of depositional facies differences, diagenetic effects (particularly dolomitization), and fracturing with varying porosity and permeability. Lisbon field, San Juan County, Utah accounts for most of the Leadville oil production in the Paradox Basin. The Lisbon trap is an elongate, asymmetric, northwest-trending anticline bounded on the northeast flank by a major, basement-involved normal fault. Several minor, northeast-trending normal faults divide the Leadville reservoir into segments. The abandoned Big Flat field, Grand County, Utah, was the first Mississippian discovery in the Paradox Basin. The trap is a non-faulted, north-south-trending anticline.

Wells in these fields were drilled with air or fresh-water mud to the top of the Pennsylvanian Paradox Formation salt, after which a natural brine or salt-base mud was typically used to total depth. The wells were usually completed by perforating with four shots per foot, in Leadville high-quality porosity zones. The completion treatment included stimulation of perforated intervals with 15 percent hydrochloric acid.

A thick hydrocarbon column at Lisbon field contains a gas cap and oil ring. Associated, lean, processed, sour gas was reinjected into the gas cap to maintain reservoir pressure and maximize the oil recovery. Gas-sweetening, nitrogen-injection, and helium-recovery facilities were installed in 1992, and in 1993 the operator began gas cap blowdown and sale of residue gas.

Horizontal drilling technology was not readily available when Lisbon field and other Leadville fields were discovered and developed. If horizontal technology had been available, Leadville fields could have been developed with fewer wells (especially in environmentally sensitive areas), and would have resulted in a greater ultimate oil recovery. Lithologic variations due to facies changes, diagenetically increased porosity zones due to dolomitzation, and fractures create potential undrained compartments ideally suited for horizontal drilling in the Leadville-producing fields. Drilling techniques should include new wells, and horizontal, often multiple and stacked, laterals from existing vertical wells. Multiple laterals are recommended where separate, geologically distinct zones are present. Finally, a decision about drilling horizontally in Leadville fields should also be based on the reservoir depth, regulatory requirements for spacing, type of application, and surface location to avoid topographic features.

Technology transfer activities during this quarter consisted of exhibiting a booth display of project materials and a presentation on the central Utah thrust belt Navajo Sandstone oil play at the 2005 Rocky Mountain Section Meeting of the American Association of Petroleum Geologists (AAPG) in Jackson, Wyoming. Numerous interviews with the news media were also given on the Utah thrust Navajo Sandstone play. 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. 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, 2005). However, the 13.7 million bbls (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 (Utah Division of Oil, Gas and Mining, 2002). Proven reserves are relatively high, at 241 million bbls (38.3 million m^3) (Energy Information Administration, 2003). With higher oil prices now prevailing, secondary and tertiary recovery techniques should boost future production rates and ultimate recovery from known fields.

Utah's drilling history has fluctuated greatly due to discoveries, oil price trends, and changing exploration targets. During the boom period of the early 1980s, activity peaked at over 500 wells per year. Sustained high petroleum prices are likely to provide 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.

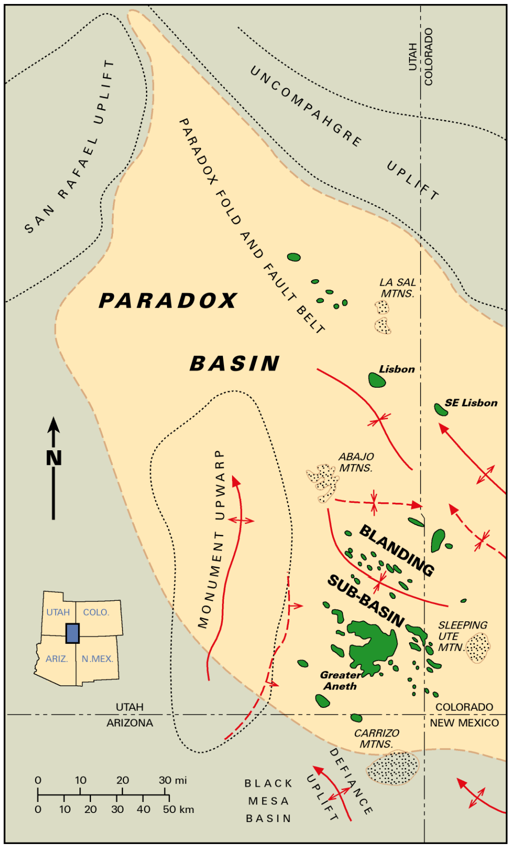
The primary goal of this study is to increase recoverable oil reserves from existing field reservoirs and new discoveries by providing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming (figure 1). These 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 thirteenth quarter of the project (July 1 through September 30, 2005). This work included (1) gathering field data and analyzing best practices in the Mississippian Leadville Limestone Paradox Basin play, and (2) technology transfer activities.

Project Benefits

The overall goal of this multi-year project is enhanced petroleum production in the Rocky Mountain region. Specifically, the project goal will benefit from the following:

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



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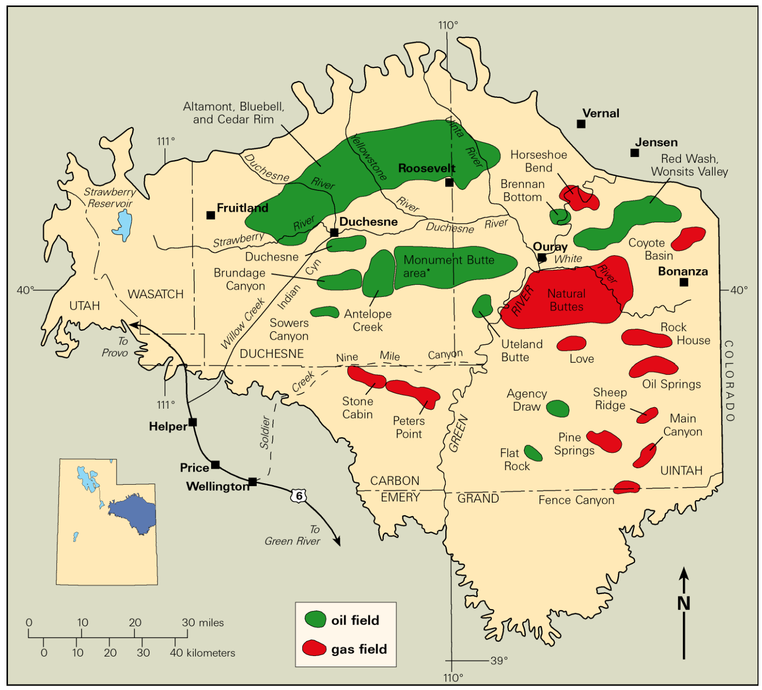

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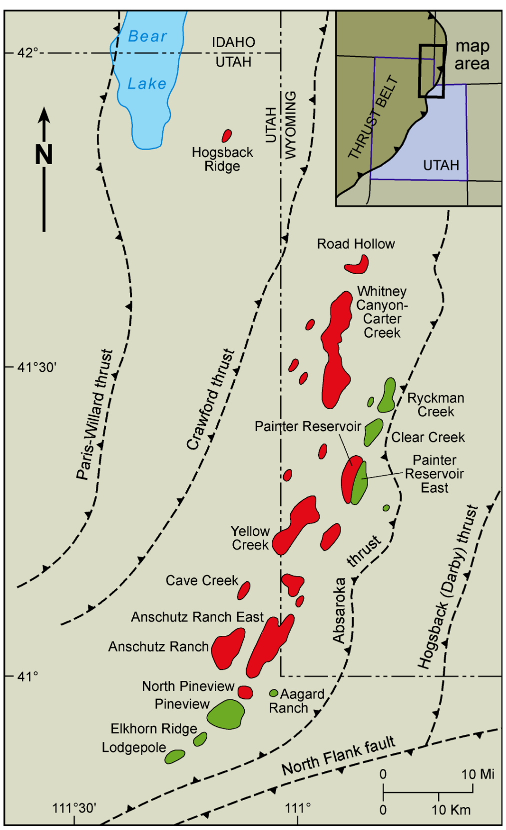

C

Figure 1. Major oil-producing provinces of Utah and vicinity. A - Oil and gas fields in the Paradox Basin of Utah and Colorado. 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.

(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.

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.

BEST PRACTICES FOR THE MISSISSIPPIAN LEADVILLE LIMESTONE, PARADOX BASIN PLAY - DISCUSSION AND RESULTS

Introduction

Data were collected from the files of the Utah Division of Oil, Gas and Mining, where there is a wealth of publicly available information, and various publications for fields in the Utah portion of the Paradox Basin. This information includes structure maps and cross sections, production and pressure data, completion reports, drilling and development plans, and testimony given at spacing hearings and other hearings before the Utah Division of Oil, Gas and Mining. The purpose of this data collection is to help determine the best drilling, completion, and secondary/tertiary recovery techniques for these and similar fields in the Paradox Basin.

Two significant practices were or could be employed in the later development of these fields to enhance the ultimate recovery of oil: (1) reinjection of produced gas for pressure maintenance, and (2) horizontal drilling.

Paradox Basin Overview

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1A). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The 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). Each area contains oil and gas fields with structural, stratigraphic, or combination traps formed on discrete, often seismically defined, closures.

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, 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. A series 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 southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from 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 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, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). 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 flowage, dissolution and collapse, and (3) regional uplift (Doelling, 2000).

Leadville Limestone, Paradox Basin Play Description

The Mississippian Leadville Limestone is one of two major oil and gas plays in the Paradox Basin, the other being the Pennsylvanian Paradox Formation. Most Leadville production is from the Paradox fold and fault belt (figure 2). The Leadville Limestone has

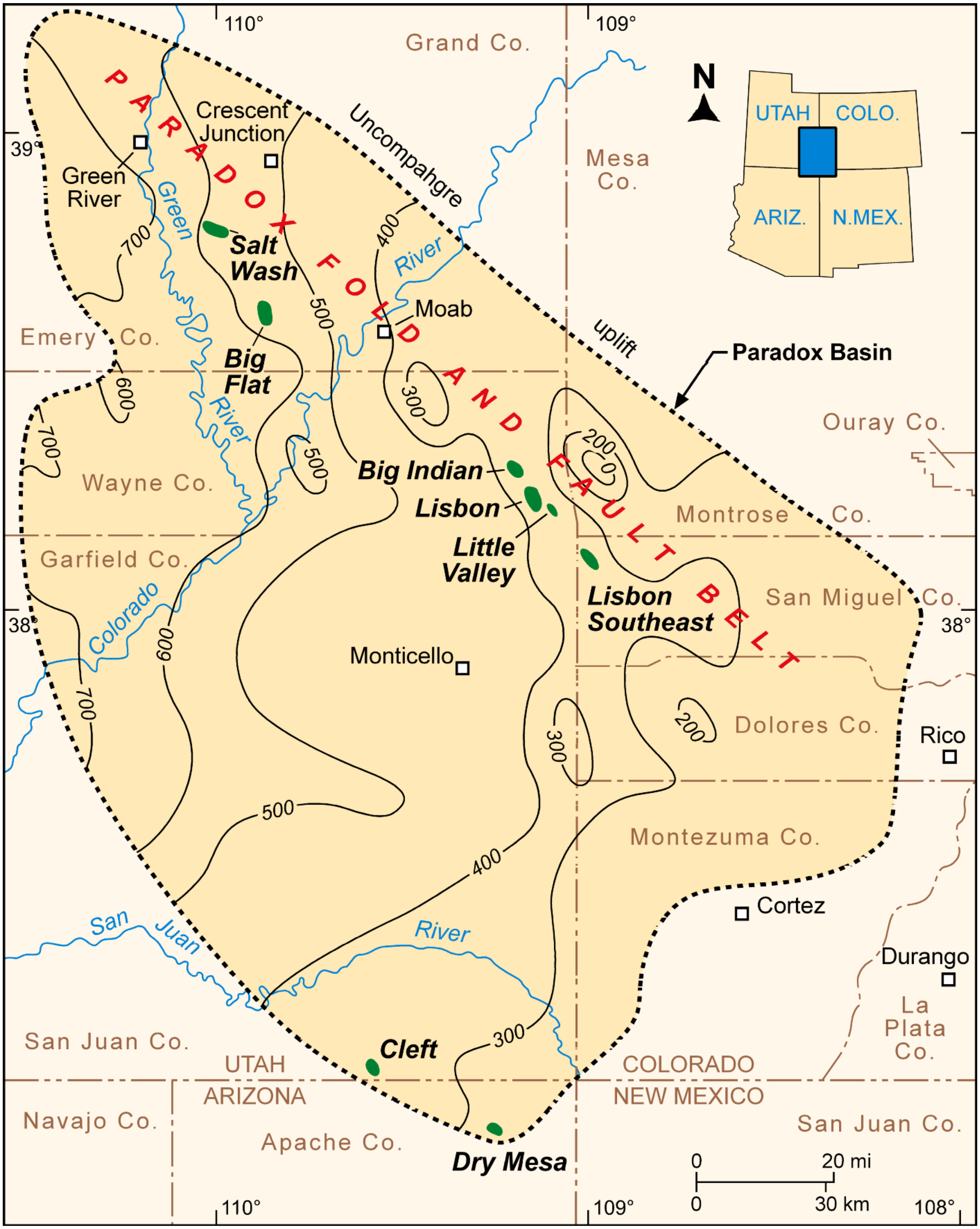

Figure 2. Location of fields that produce oil (green) from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963). The Leadville Limestone, Paradox Basin play area is dotted. Modified from Morgan (1993).

produced over 53 million bbls (8.4 million m^3) of oil and 845 billion cubic feet of gas (BCFG) (23.9 billion m^3) from the six fields in the northern Paradox Basin of Utah and Colorado (Utah Division of Oil, Gas and Mining, 2005; Colorado Oil and Gas Conservation Commission records). However, much of the gas included in the production figures is cycled gas used in the past for pressure maintenance at Lisbon field, Utah. This 7500-mi^2 (19,400 km^2) area is relatively unexplored; only about 100 wells penetrate the Leadville (less than one well per township), thus the potential for new discoveries remains great.

The play outline represents the maximum extent of petroleum potential in the geographical area as defined by producing reservoirs, hydrocarbon shows, and untested hypotheses (figure 2). The attractiveness of the Leadville Limestone Paradox Basin play (and other Paradox Basin plays) to the petroleum industry depends on the likelihood of successful development, reserve potential, pipeline access, drilling costs, oil and gas prices, and perhaps most significantly in the Paradox Basin, environmental concerns. When evaluating these criteria, certain aspects of the Leadville play may meet the exploration guidelines of major oil companies while other aspects meet the development guidelines of small, independent companies.

The Leadville Limestone is an open-marine, carbonate-shelf deposit. Local depositional environments included shallow-marine, subtidal, supratidal, and intertidal (Fouret, 1982, 1996). Solution breccia and karstified surfaces are common. Most oil and gas produced from the Leadville is found in basement-involved structural traps with closure on both anticlines and faults. The seals for the Leadville producing zones are the overlying clastic beds of the Molas Formation and evaporite beds within the Paradox Formation, both Pennsylvanian in age. Hydrocarbons in Leadville reservoirs were likely generated from source rocks in the Paradox Formation. Hydrocarbons were then expelled and subsequently migrated into traps, primarily along fault planes and fractures.

The Leadville Limestone has heterogeneous reservoir properties because of depositional facies with varying porosity and permeability, diagenetic effects, and fracturing. The early diagenetic history of the Leadville sediments, including some dolomitization (finely crystalline) and leaching of skeletal grains, resulted in low-porosity and/or low-permeablility rocks. Most of the porosity and permeability associated with Leadville hydrocarbon production at Lisbon field was developed during later, deep subsurface dolomitization (coarsely crystalline replacement and saddle [hydrothermal?] dolomite) and dissolution.

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults. Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 2) are found on sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 2), northwest of the Lisbon area, are found on unfaulted, east-west- and north-south-trending anticlines, respectively. The unfaulted structures probably developed from movement on deep, basement-involved faults that do not rise to the level of the Leadville. These and other faults affecting the Leadville probably reflect the reactivation of preexisting, Precambrian-age faults during the Laramide orogeny or later. As examples of both types of structural traps, the best practices of Lisbon and Big Flat fields are described in the following sections.

Lisbon Field, San Juan County, Utah

Field Synopsis

Lisbon field, San Juan County, Utah (figure 2) accounts for most of the Leadville oil production in the Paradox Basin. The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 3). Several minor, northeast-trending normal faults divide the Leadville reservoir into segments. Producing units contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes autobrecciation, karst development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6 percent in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an

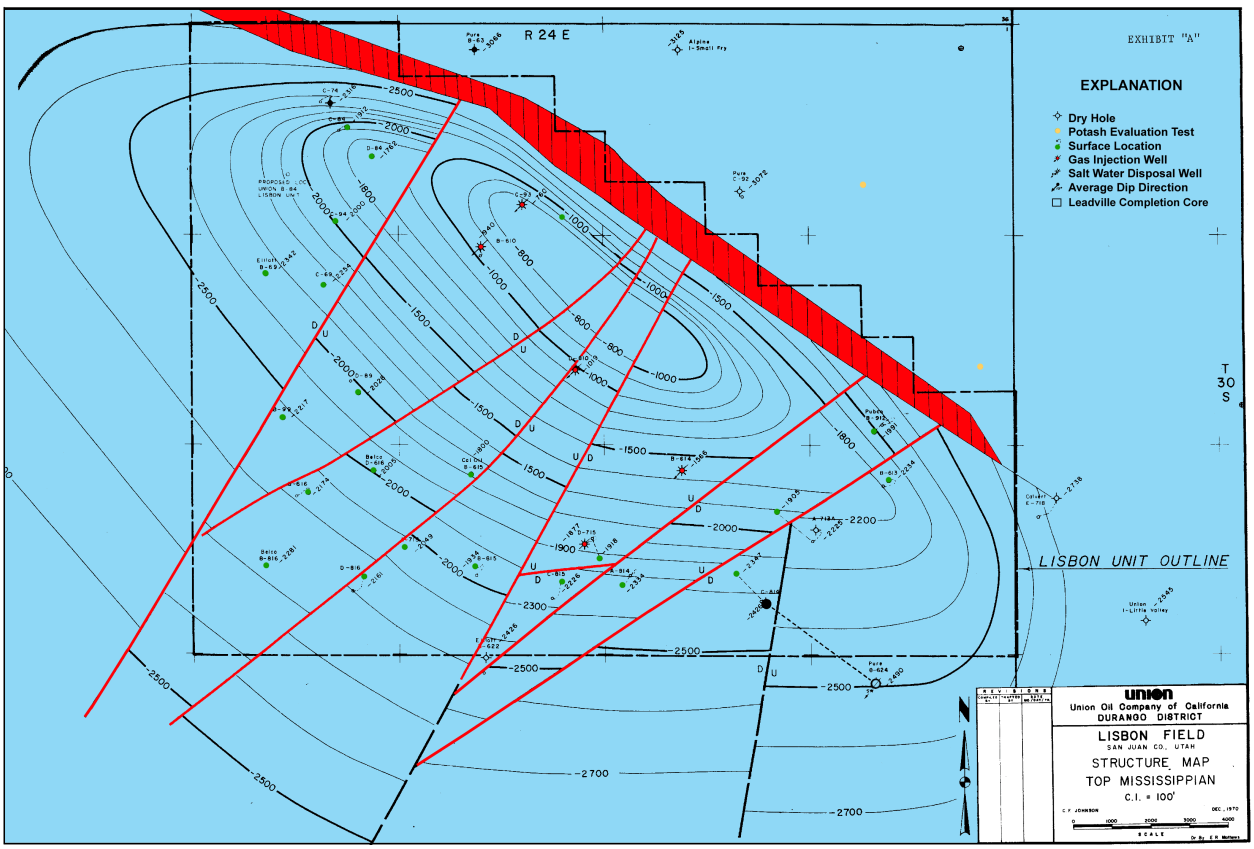

***Figure 3.** Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah. Contour interval = 500 feet, datum = mean sea level. The field is bounded on its northeast flank by a major, basement-involved normal fault (in red) with greater than 2500 feet of displacement. Note the multiple, northeast-trending faults that divide the Leadville reservoir into several segments. Some of the best producing wells are located close to these faults. Modified from C.F. Johnson, Union Oil Company of California files (1970); courtesy of Tom Brown, Inc.*

expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 153 to 189ºF (67-87ºC). The produced associated gas contains various hydrocarbon fractions as well as carbon dioxide, hydrogen sulfide, and helium (Stowe, 1972).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., Salt Lake Base Line and Meridian (SLBL&M) (figure 3), with an initial flowing potential (IFP) of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (MCFGPD) (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (psi) (20,560 kPa) (Clark, 1978).

There are currently 22 producing (or shut-in wells), 11 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of July 1, 2005, was 51,129,974 bbls of oil (8,129,666 m^3), 779.3 BCFG (22.1 BCMG) (cycled gas), and 49,936,145 bbls of water (7,939,847 m^3) (Utah Division of Oil, Gas and Mining, 2005).

Best Practices

Pressure maintenance and Lisbon gas plant: Lisbon field encompasses a large area with significant structural closure. As a result, Lisbon has a thick hydrocarbon column, which includes a gas cap and oil ring. A gas plant (figure 4) was built at Lisbon field in 1962, and 60 MMCFGPD (1.7 MMCMGPD) of associated sour (hydrogen sulfide) gas was reinjected into the gas cap to maintain reservoir pressure and maximize the oil recovery. Natural gas liquids recovery facilities (figure 4) were added in 1966, and for 27 years lean, processed, sour gas was recycled into the reservoir. Gas-sweetening, nitrogen-injection, and helium-recovery facilities were installed in 1992, and in 1993 the operator began gas cap blowdown and sale of residue gas. A detailed discussion of the Lisbon gas plant was published by Jones and others (2004a, 2004b).

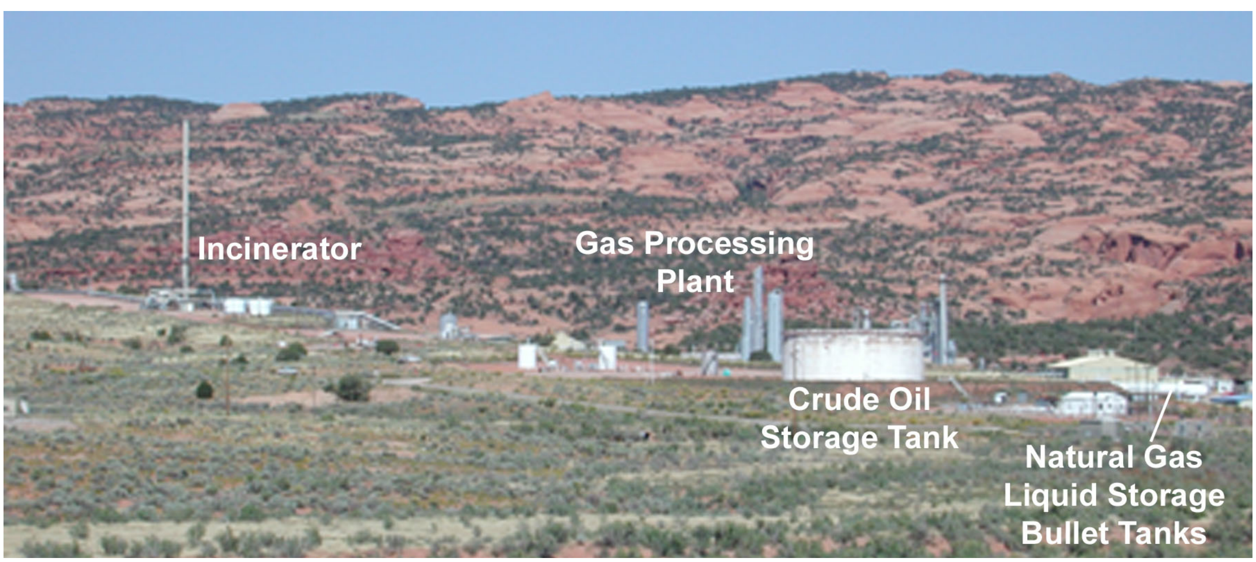

Figure 4. Lisbon field gas processing plant, oil and natural gas liquid storage tanks, and incinerator (one of two).

Drilling and completion: The Leadville Limestone is at drill depths from 7500 to 9500 feet (2300-2900 m) at Lisbon field. Wells in the field were typically drilled to a depth of 10 to 70 feet (3-23 m) where a conductor was set; the diameter varied from 13.375 to 20 inches (34-51 cm). Surface casing ranging in diameter from 9.675 to 10.75 inches (24-27 cm) was set from 300 to 4317 feet (90-1316 m), but most were set at 700 to 1200 feet 210-370 m). The wells were drilled to total depth and 5.5- to 7-inch (14-18 cm) diameter casing was set. The wells were drilled with fresh-water mud to the top of the Paradox Formation salt, after which a natural brine or salt-base mud was typically used to total depth.

The wells were completed by perforating high-quality porosity intervals in the Leadville Limestone with four shots per foot (occasionally at two shots per foot). The gross perforated interval ranged from 6 to 394 feet (2-121 m); most intervals were less than 200 feet (60 m) and the average gross perforated interval was 125 feet (38 m) (figure 5). The net perforated interval ranged from 6 to 394 feet (6-121 m); most were from 6 to 50 feet (2-15 m), with an average net perforated interval of 72 feet (22 m) (figure 6). The typical completion treatment was to stimulate the perforated intervals with 15 percent hydrochloric (HCl) acid. Treatment volumes ranged from 0 to 1167 gallons of acid per foot (gal/ft) (0-14,504 L/m) of perforation, most were 0 to 150 gal/ft (0-1864 L/m) with an average of 149 gal/ft (1852 L/m) (figure 7).

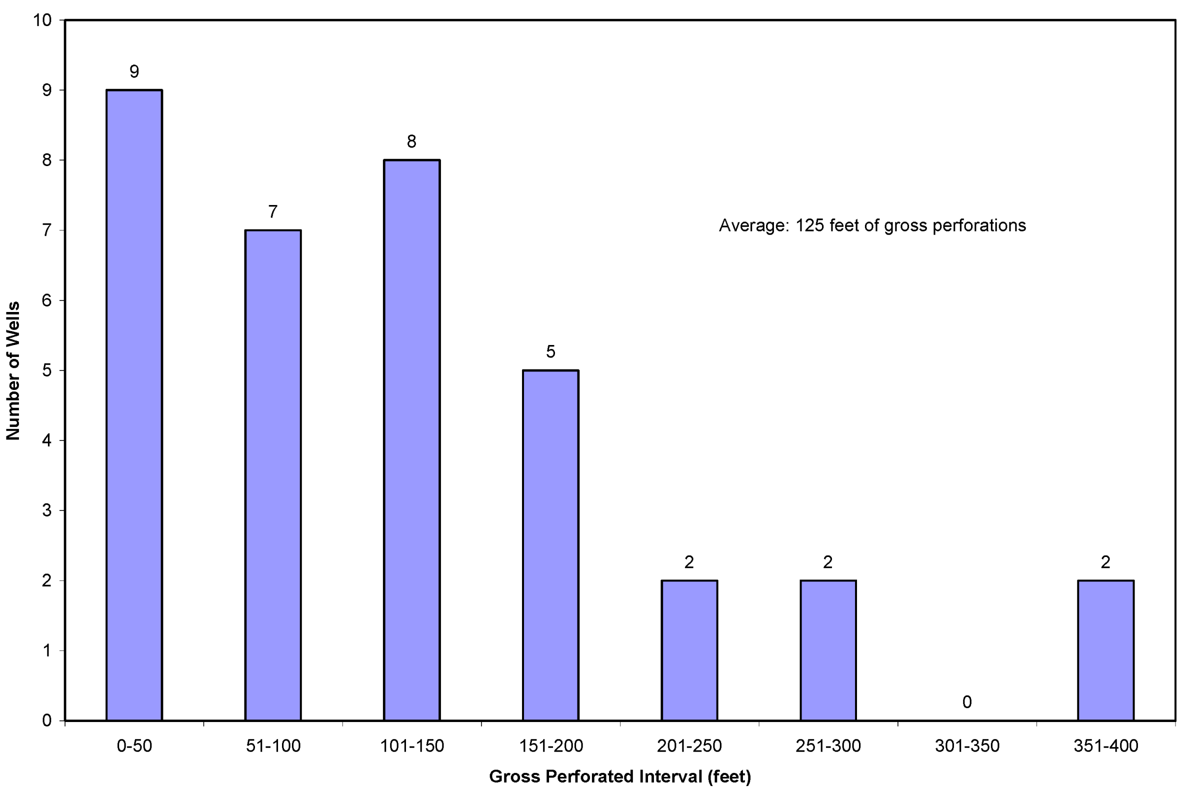

Figure 5. Thickness of gross perforated intervals in Lisbon field wells, in feet.

In addition to the wellhead and tank batteries, the typical producing well site includes dehydrators, heated separators (heater/treaters), double-walled emergency pit tanks, and solar-powered flow meters for monitoring production data remotely (figure 8).

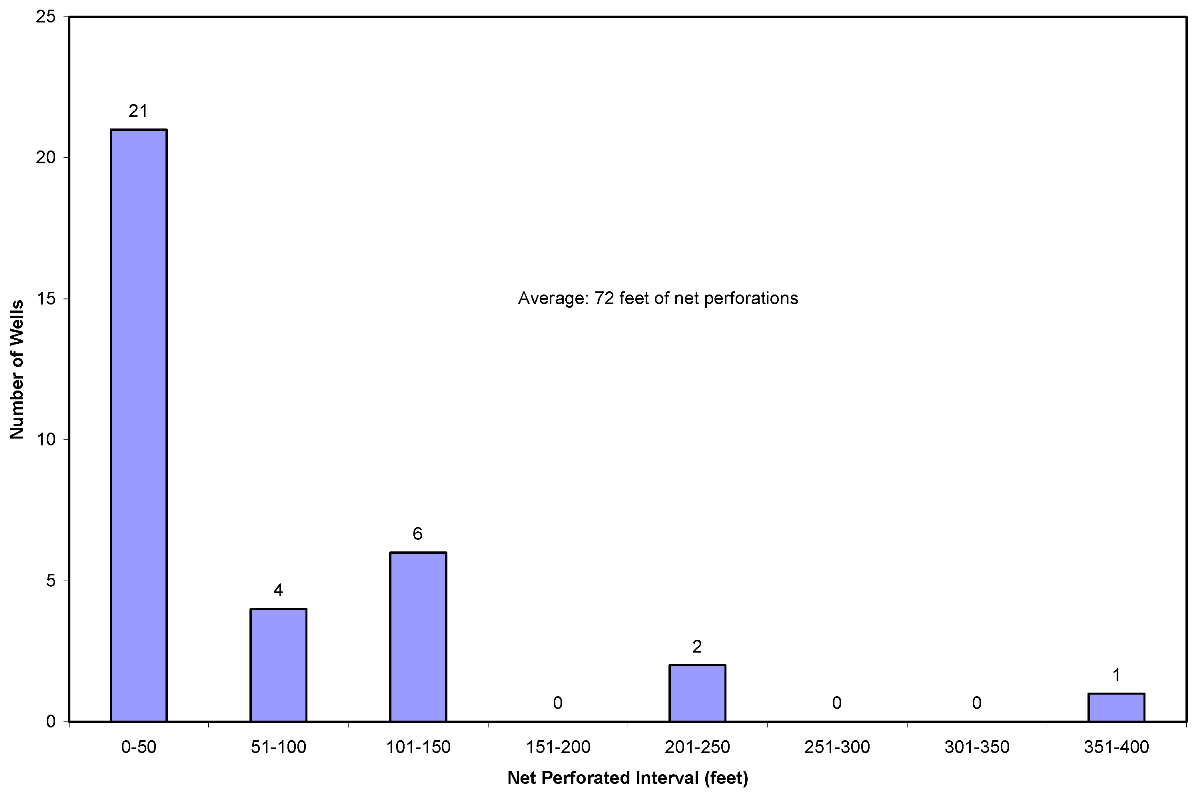

Figure 6. Thickness of net perforated intervals in Lisbon field wells, in feet.

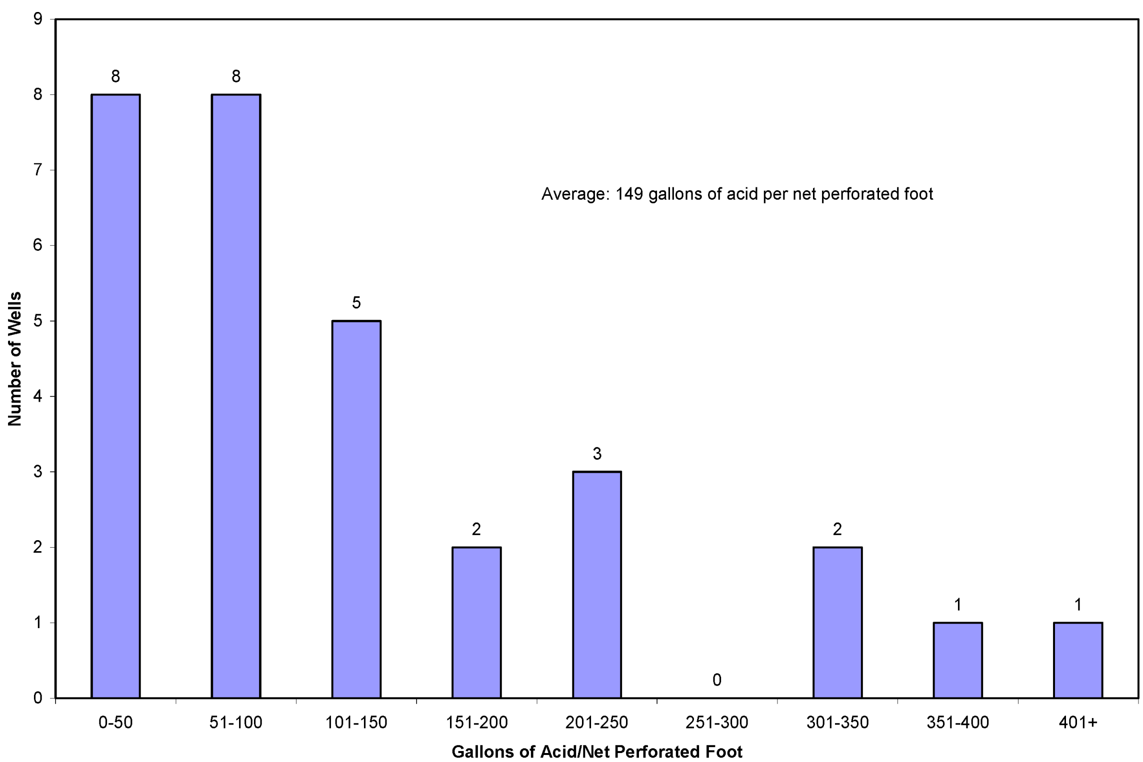

Figure 7. Gallons of acid per foot of perforation used to stimulate Lisbon field wells.

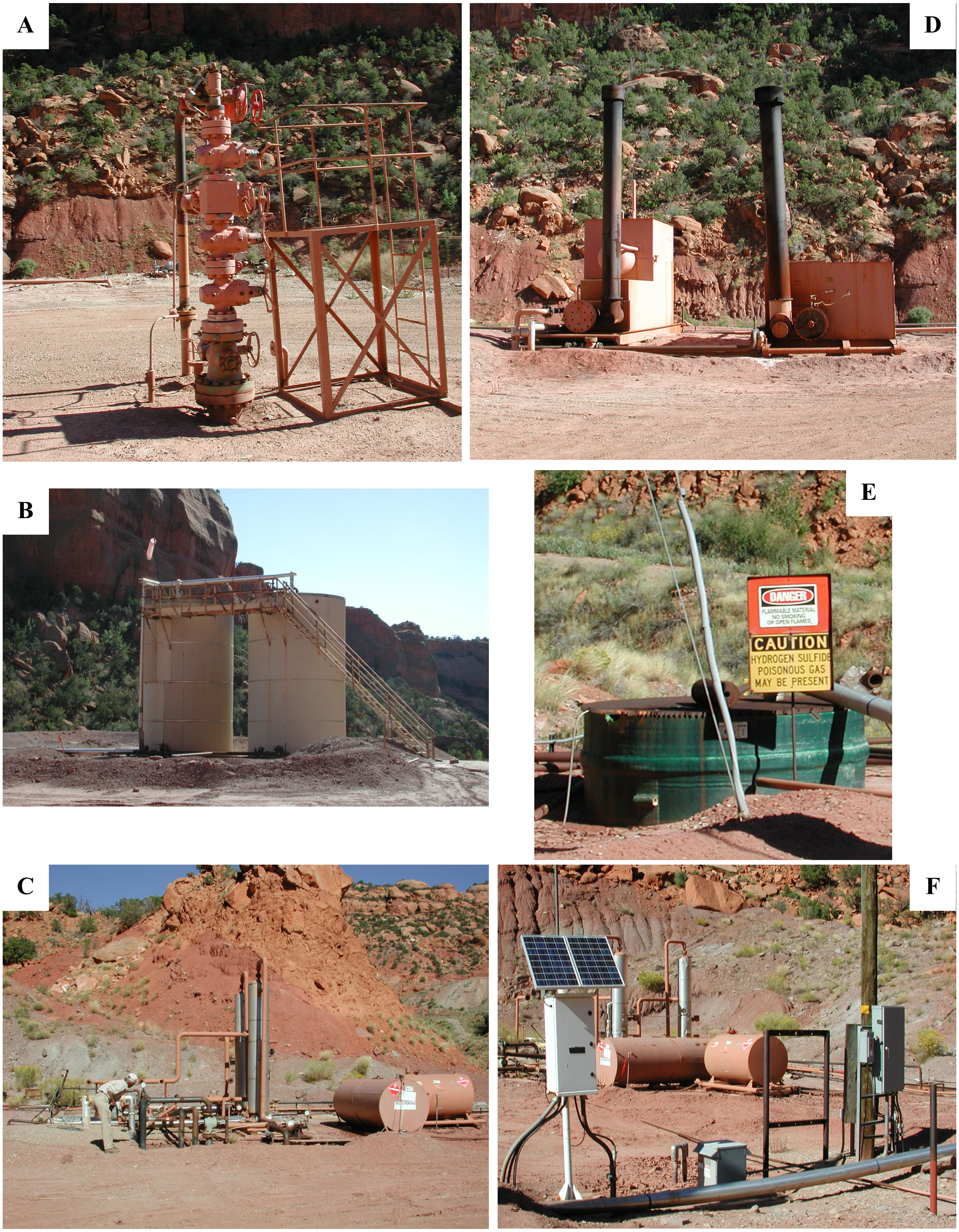

***Figure 8.** Typical Lisbon well site including: A – wellhead, B - tank batteries, C – dehydrators with chemical storage tank for methanol, D - heated separators (heater/treaters), E - double-walled emergency pit tanks, and F - solar-powered flow meters.*

Big Flat Field, Grand County, Utah

Field Synopsis

Big Flat field, Grand County, Utah, was the first Mississippian discovery in the Paradox Basin (figure 2). The trap is a north-south-trending anticline with 276 feet (84 m) of structural closure (figure 9) that produced from Leadville limestone and dolomite (Smith, 1978). The net reservoir thickness is 30 feet (10 m), which extends over a 480-acre (190 ha) area. Porosity ranges from 4 to 14 percent in vuggy and intercrystalline pore systems that are enhanced by vertical fractures. Permeability varies and is dependent, therefore, on the extent of fracture development. The drive mechanism is water drive with an inert gas cap and the initial water saturation was 30 to 50 percent (Smith, 1978). The field now produces oil from horizontal wells in the Cane Creek shale of the Pennsylvanian Paradox Formation, on a separate structure north of the original, abandoned Leadville feature.

Big Flat field was discovered in 1957, with the completion of the Pure Oil Company No. 1 Big Flat Unit well (figure 9), SW1/4SE1/4 section 14, T. 26 S., R. 19 E., SLBL&M; IFP was 319 BOPD (51 m^3/d). The original Leadville reservoir field pressure was 2450 psi (16,900 kPa) (Smith, 1978).

The Leadville reservoir was abandoned in 1968. Cumulative Leadville production was 83,469 bbls of oil (13,272 m^3), 52.4 billion BCFG (1.5 BCMG), and 41,950 bbls of water (6670 million m^3) from three wells from 1957 through 1967 (Stowe, 1972).

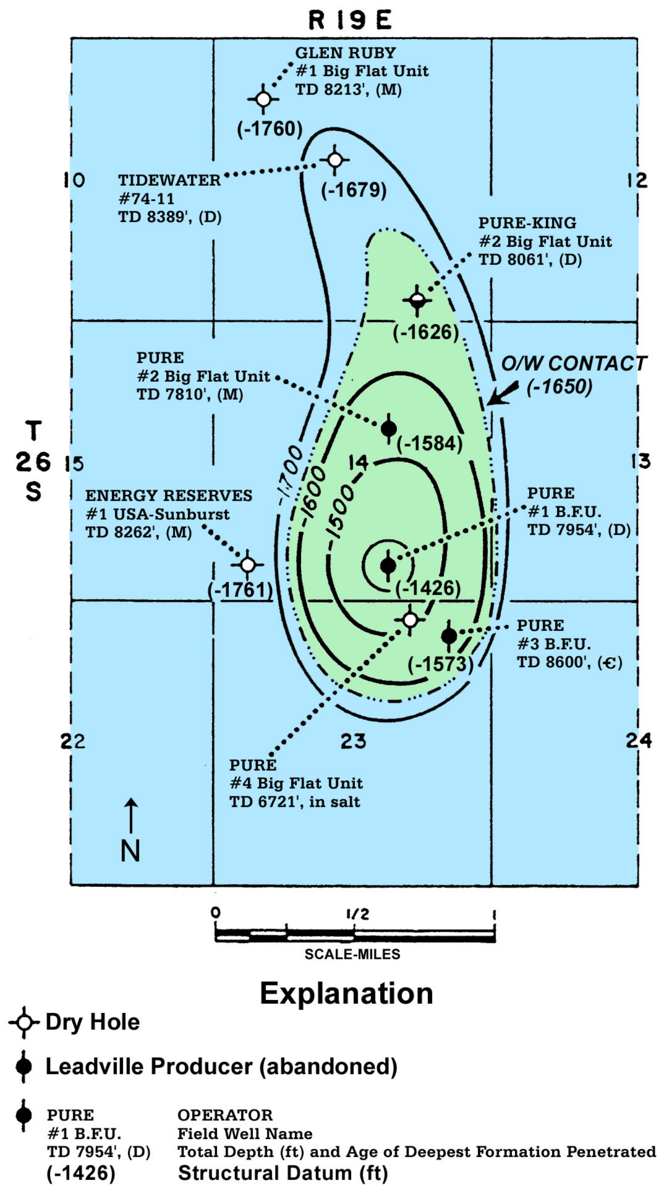

Figure 9. Top of structure of the Leadville Limestone, Big Flat field, Grand County, Utah. Contour interval = 100 feet, datum = mean sea level. Modified from Smith (1978).

Best Practices

The drilling and completion techniques for Big Flat field are older and represent a much smaller data set than provided from Lisbon field, but are not significantly different. Big Flat field did not have a gas cap and there were no attempts to maintain reservoir pressure or increase recovery through secondary or tertiary methods.

The Leadville Limestone is at drill depths from 7500 to 7800 feet (2300-2400 m) at Big Flat field. Wells in the field were typically drilled to a depth of 10 to 30 feet (3-10 m) where a conductor was set; the diameter varied from 16 to 20 inches (41-51 cm). Surface casing 13.375 inches (34 cm) in diameter, was set from 480 to 1000 feet (150-300 m). An intermediate, 9.675-inch (24 cm) diameter casing string was set into the top of the Paradox Formation salt with 7-inch (18 cm) diameter casing set to total depth. The wells were drilled with air or fresh-water mud to the top of the Paradox Formation salt, after which a natural brine or salt-base mud was typically used to total depth.

The wells were completed by perforating high-quality porosity intervals in the Leadville Limestone with four shots per foot (occasionally at two shots per foot). The gross and net perforated interval ranged from 12 to 52 feet (4-16 m). The average gross perforated interval was 33 feet (10 m) and the average net perforated interval was 27 feet (8 m). The oil column was much smaller at Big Flat field compared to Lisbon field; as a result, the gross and net perforated intervals are very similar. The typical completion treatment was to stimulate the perforated intervals with 15 percent HCl acid. Treatment volumes ranged from 10 to 417 gal/ft (124-5283 L/m), with an average of 163 gal/ft (2026 L/m).

Horizontal Drilling

Introduction

Three factors create reservoir heterogeneity within productive zones in the Leadville Limestone: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification and various stages of dolomitization), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow. Untested compartments created by these conditions may be ideally suited for, as yet to be attempted, horizontal drilling techniques.

Horizontal drilling, developed primarily in the 1990s, is now a common, economical technique to increase oil production and reserves. Advances in downhole motors, flexible drill pipe, and measurement-while-drilling (MWD) technology have resulted in improved success and reduced drilling costs. Drilling horizontally (1) improves well/reservoir productivity, (2) increases well drainage area and reservoir exposure, particularly critical if the reservoir is fractured or thin (figure 10A, B, and C), (3) delays interface breakthrough (coning) (figure 10D), (4) improves sweep efficiency/ultimate recovery, (5) accelerates well payoff and rate of return, (6) reduces inertial (turbulence) pressure losses, (7) accesses remote and isolated zones, (8) improves reservoir characterization, and (9) exploits gravity drainage mechanism effectively (Kikani, 1993; Stark, 2003).

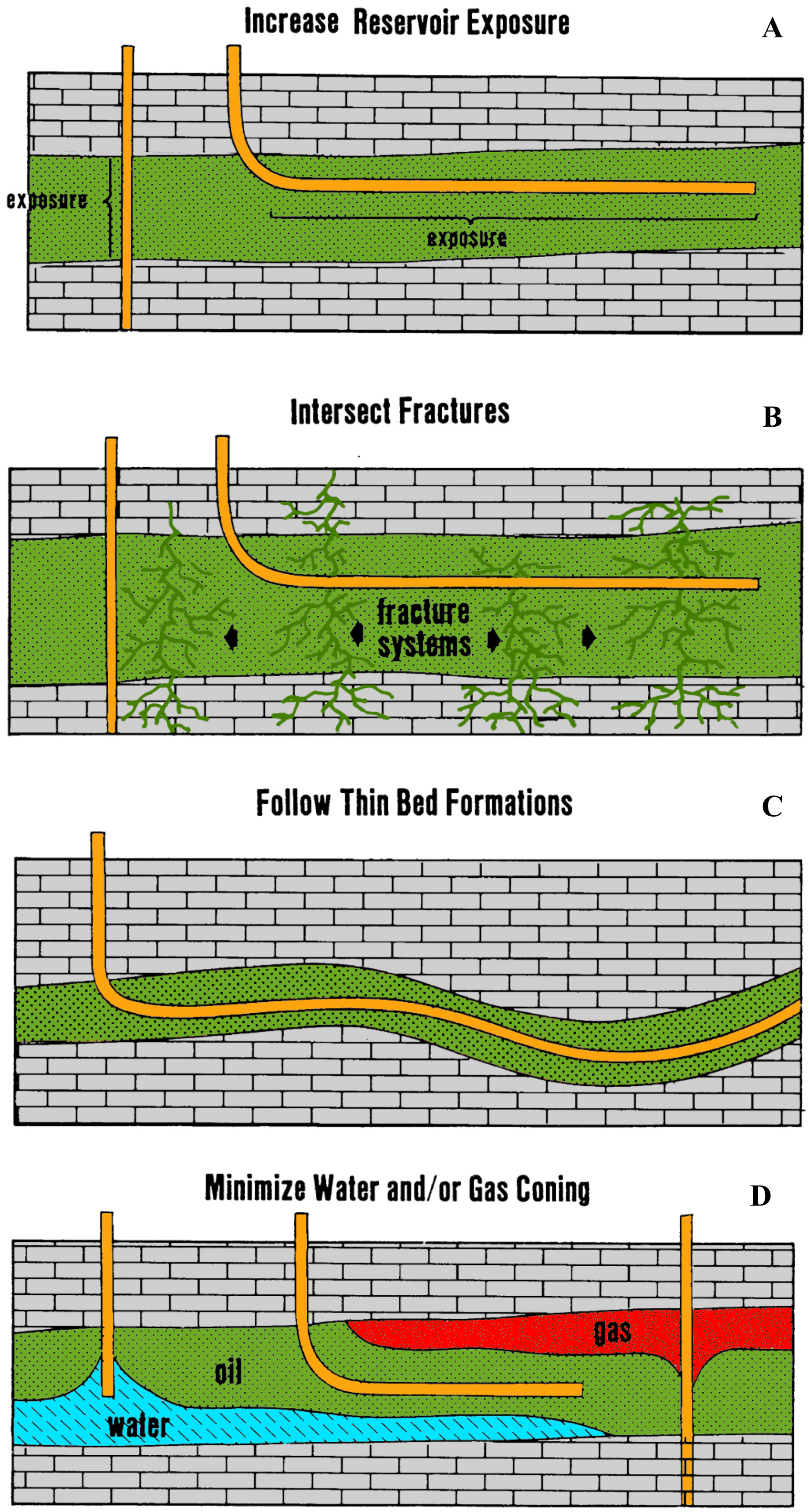

Figure 10. Reservoir conditions favorable for horizontal drilling (modified from Kikani, 1993).

Types of Horizontal Wells Applicable to the Leadville Limestone

Horizontal wells are categorized by their radius of curvature: ultra-short radius, short radius, medium radius, and long radius (figure 11). The decision for drilling a particular category in Leadville fields, and elsewhere, is based on the reservoir depth, regulatory requirements for spacing, type of application, and surface location to avoid topographic features (Kikani, 1993).

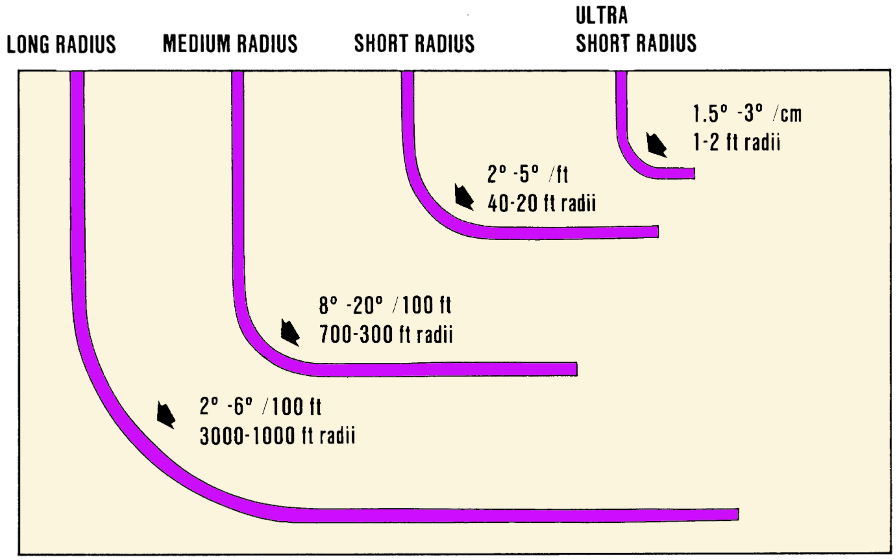

Figure 11. Radius of curvature and the angle building ranges for various horizontal well profiles (modified from Kikani, 1993).

There are advantages and disadvantages for long/medium-radius and short/ultra short-radius horizontal wells. Short/ultra short-radius horizontal wells provide a more precise vertical placement of horizontal drains than long/medium-radius wells. They are best for small leases, less expensive if drilled from an existing well, and there is less risk than long/medium-radius wells because the kickoff is usually below fluid contacts and there is good isolation between fluid zones. The disadvantages of short/ultra short-radius wells are the need for customized drilling equipment. There is usually a short horizontal drain hole with only an open-hole completion. Short/ultra short-radius horizontal wells are usually not logged or cored.

The advantages of long/medium-radius horizontal wells include the fact that they use conventional drilling equipment, accommodate normal-size MWD tools, can use down-hole motor and steerable systems, and cover over 3000 feet (1000 m) of horizontal length. They also allow conventional logging, coring, and casing and completion. The disadvantages of long/ medium-radius wells are that they are less accurate on depth and cost more than short/ultra short-radius wells.

Drilling Techniques

Drilling techniques may include new wells and horizontal, often multiple, laterals from existing vertical wells, preferred in environmentally sensitive areas. Multilaterals exiting a single wellbore (figure 12) have gained wide acceptance (Chambers, 1998). They are required where two, separate, geologically distinct zones are present. Multiple laterals can also be used where canyons and other rugged terrain are an issue. These laterals may be horizontal or deviated to reach different bottom hole locations. The laterals are drilled from the main

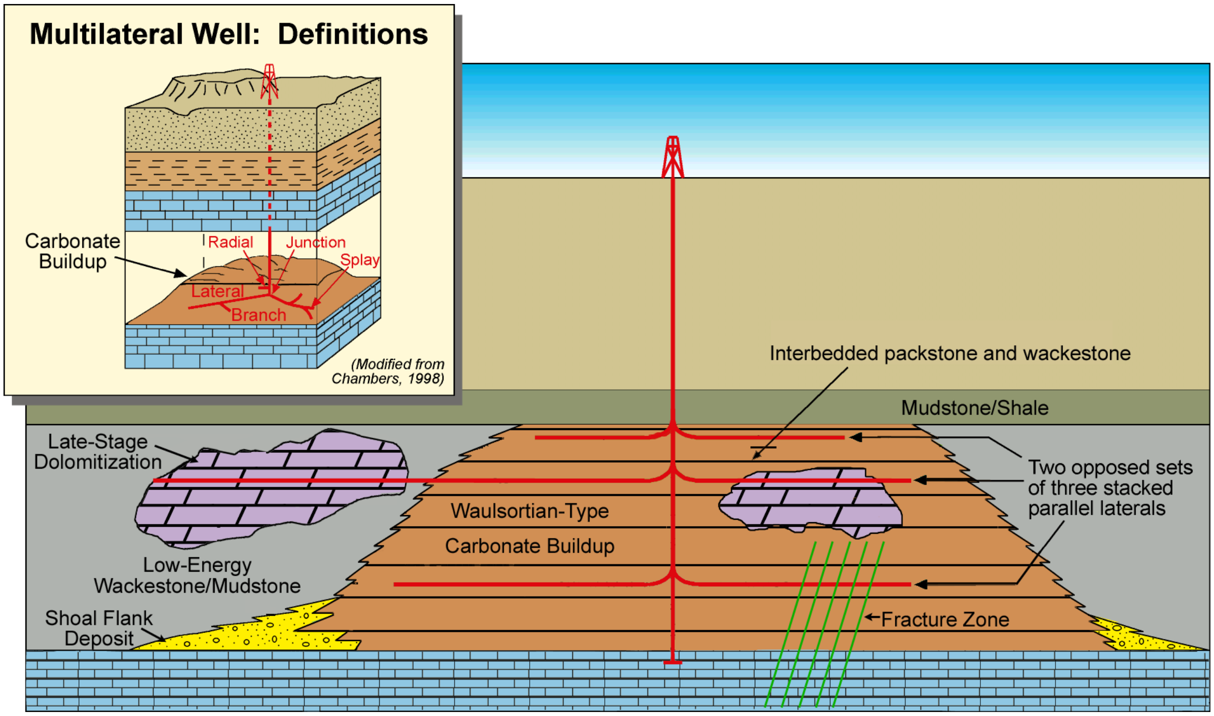

Figure 12. Schematic diagram of drilling targets in a Mississippian Waulsortian mound facies by multilateral (horizontal) legs from an existing field well.

wellbore. Branches are drilled from a horizontal lateral into the horizontal plane. Splays (fish hooks or herringbone) are drilled from a horizontal lateral in the vertical plane. A dual lateral is a multilateral well with two laterals. Laterals may be opposed to each other or stacked. Multilaterals are drilled for cost-saving reasons, or reservoir production reasons associated with improved drainage or injection. They provide a means for increasing wellbore contact with the pay zones, and target untapped reservoir compartments. Problems may include casing collapse in horizontal laterals and scale caused by certain water chemistries; the latter requires a scale-inhibitor program.

The depth of horizontal wells must be controlled to be above and parallel to the low-proved oil or oil/water contacts. These contacts may have moved upward during the production history of the field so determining their exact elevation is a key component in drilling plans. Accurate determination of dip and strike of the complex producing structures is also critical to planning horizontal drilling operations. Sophisticated MWD techniques are applied to steer up and down the structure or particular facies within the target zone.

Logging and production tests in horizontal wells typically use coiled tubing units or pipe conveyed logging. Most horizontal wells are completed open hole, with slotted/pre-perforated liners, or cemented (Kikani, 1993).

Horizontal Drilling Based on Leadville Facies, Diagenesis, and Fractures

Identification and correlation of depositional facies and diagenetic trends in individual Leadville reservoirs are critical to understanding the effect of these parameters on production rates and paths of petroleum movement. Depositional facies are targeted where, for example, multiple carbonate buildups can be penetrated with two opposed sets of stacked, parallel horizontal laterals. Good porosity zones associated with late-stage, secondary dolomite could be drained with radially stacked, horizontal laterals and splays.

The fracture patterns observed in outcrop and structural orientation can be applied to planning directions and lengths of horizontal wells in Leadville reservoirs. In addition, borehole studies and Formation MicroImager or other fracture-identification geophysical well logs should be used to plan horizontal drilling programs. Horizontal wells are generally drilled perpendicular to the dominant orientation of open fractures.

TECHNOLOGY TRANSFER

The Utah Geological Survey (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 September 1, 2005. Project activities, results, and recommendations were presented at this meeting.

Project materials, plans, and objectives were displayed at the UGS booth during the AAPG Rocky Mountain Section Meeting on September 24-26, 2005, in Jackson, Wyoming. Four UGS scientists staffed the display booth at this event. Project displays will be included as part of the UGS booth at professional and other public meetings throughout the duration of the project.

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.

Project Publications

Chidsey, T.C., Jr., and Morgan, C.D., 2005, Major oil plays in Utah and vicinity – quarterly technical progress report for the period April 1 to June 30, 2005: U.S. Department of Energy, DOE/FC26-02NT15133-12, 61 p.

Sprinkel, D.A., and Chidsey, T.C., Jr., 2005, Exploration history and petroleum geology of the central Utah thrust belt [abs.]: American Association of Petroleum Geologists, Rocky Mountain Section Meeting Official Program, p. 49.

Presentation

The following presentation was made during the reporting period as part of the technology transfer activities:

"Exploration History and Petroleum Geology of the Central Utah Thrust " by Douglas A. Sprinkel and Thomas C. Chidsey, Jr., at the AAPG Rocky Mountain Section Meeting, Jackson, Wyoming, September 26, 2005. The exploration history, petroleum geology, oil source and migration, the Covenant field discovery, and potential of the central Utah thrust belt Navajo Sandstone oil play were part of the presentation.

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 and Wyoming. Oil plays are specific geographic areas having petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors.

2. The Mississippian Leadville Limestone is a major oil and gas play in the Paradox Basin having produced over 53 million bbls (8.4 million m^3) of oil. The Leadville is an open-marine, carbonate-shelf deposit. Most Leadville production is from the Paradox fold

and fault belt in basement-involved structural traps with closure on both anticlines and faults. The Leadville has heterogeneous reservoir properties because of depositional facies differences, diagenetic effects (particularly dolomitization), and fracturing with varying porosity and permeability.

3. Lisbon field, San Juan County, Utah accounts for most of the Leadville oil production in the Paradox Basin. The Lisbon trap is an elongate, asymmetric, northwest-trending anticline bounded on the northeast flank by a major, basement-involved normal fault. Several minor, northeast-trending normal faults divide the Leadville reservoir into segments. Big Flat field, Grand County, Utah, was the first Mississippian discovery in the Paradox Basin. The trap is a non-faulted, north-south-trending anticline. The Leadville reservoir was abandoned in 1968 after producing just over 83,000 bbls of oil (13,000 m^3) from three wells.

4. Lisbon field has a thick hydrocarbon column, which contains a gas cap and oil ring. Associated, lean, processed, sour gas was reinjected into the gas cap to maintain reservoir pressure and maximize the oil recovery. Gas-sweetening, nitrogen-injection, and helium-recovery facilities were installed in 1992, and in 1993 the operator began gas cap blowdown and sale of residue gas. Big Flat field did not have a gas cap and there were no attempts to maintain reservoir pressure or increase recovery through secondary or tertiary methods.

5. Best practices included drilling wells with air or fresh-water mud to the top of the Paradox Formation salt, after which a natural brine or salt-base mud was typically used to total depth. The wells were completed by usually perforating, at four shots per foot, porosity zones in the Leadville Limestone. The typical completion treatment included stimulation of perforated intervals with 15 percent HCl acid.

6. Horizontal drilling technology was not readily available when Lisbon field and other Leadville fields were discovered and developed. Horizontal drilling programs have successfully extended the productive lives of other Utah fields, even if they are at an advanced stage of depletion. If horizontal technology had been available, Leadville fields could have been developed with fewer wells (especially in environmentally sensitive areas), and would have resulted in a greater ultimate oil recovery.

7. Lithologic variations due to facies changes, diagenetically increased porosity zones due to dolomitzation, and fractures create potential undrained compartments ideally suited for horizontal drilling in the Leadville-producing fields. Drilling techniques should include new wells and horizontal, often multiple and stacked, laterals from existing vertical wells. Multiple laterals are recommended where separate, geologically distinct zones are present. Horizontal wells should generally be drilled perpendicular to the dominant orientation of open fractures, and above and parallel to the low-proved oil or oil/water contacts. Finally, a decision about drilling horizontally in Leadville fields should also be based on the reservoir depth, regulatory requirements for spacing, type of application, and surface location to avoid topographic features.

ACKNOWLEDGMENTS

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James Parker, Sharon Wakefield, and Cheryl Gustin of the UGS prepared the figures. Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David Tabet and Robert Ressetar of the UGS.

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