# MAJOR OIL PLAYS IN UTAH AND VICINITY

## QUARTERLY TECHNICAL PROGRESS REPORT

**Reporting Period**
**Start Date: January 1, 2005**
**End Date: March 31, 2005**

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

UTAH GEOLOGICAL SURVEY

## April 2005

Contract No. DE-FC26-02NT15133

Submitting Organization: Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100
Salt Lake City, Utah 84114-6100
Ph.: (801) 537-3300/Fax: (801) 537-3400

Rhonda Jacobs, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
1 West 3rd Street
Tulsa, OK 74103-3532

# DISCLAIMER

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# ABSTRACT

Utah oil fields have produced over 1.2 billion barrels (191 million $m^3$) of oil and remaining proved reserves are 241 million barrels (38.3 million $m^3$). 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 eleventh quarter of the project (January 1 through March 31, 2005). This work included (1) describing the Mississippian Leadville Limestone Paradox Basin play, and (2) technology transfer activities.

The Mississippian Leadville Limestone, a shallow, open marine, carbonate-shelf deposit, is a major oil and gas reservoir in the Utah/Colorado Paradox Basin, having produced over 53 million barrels (8.4 million $m^3$) of oil and 845 billion cubic feet (23.9 billion $m^3$) of gas. Most Leadville production is from the Paradox fold and fault belt 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 and 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.

New prospective drilling targets in the Leadville Limestone Paradox Basin play should be delineated using high-quality, two- and three-dimensional seismic data, forward modeling/visualization tools, well control, dipmeter information, and surface geologic maps to access trap geometry. Relatively low-cost surface geochemical surveys, hydrodynamic analysis, and epifluorescence techniques may identify potential Leadville hydrocarbon migration patterns and oil-prone areas.

As part of technology transfer activities during this quarter, project team members joined Utah Stake Holders Board Members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah. A presentation on the central Utah thrust belt, Jurassic Navajo Sandstone oil play was made to the Sevier County (Utah) Commissioners. 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 remaining proved reserves are 241 million barrels (38.3 million $m^3$). 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 eleventh quarter of the project (January 1 through March 31, 2005). This work included (1) describing the Mississippian Leadville Limestone Paradox Basin play, 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 reservoir in the Utah/Colorado Paradox Basin, having produced over 53 million barrels (8.4 million $m^3$) of oil and 845 billion cubic feet (23.9 billion $m^3$) of gas. Most Leadville production is from the Paradox fold and fault belt.

The Leadville Limestone is a shallow, open marine, carbonate-shelf deposit. Local depositional environments included shallow-marine, subtidal, supratidal, and intertidal. 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. Identification and correlation of depositional facies in individual Leadville reservoirs is critical to understanding their effect on production rates and paths of petroleum movement. 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.

Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields are found on sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields, 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, Precambrain-age faults during the Laramide orogeny or later.

New prospective drilling targets in the Leadville Limestone Paradox Basin play should be delineated using high-quality, two- and three-dimensional seismic data, forward modeling/visualization tools, well control, dipmeter information, and surface geologic maps to access trap geometry. Relatively low-cost surface geochemical surveys, hydrodynamic analysis, and epifluorescence techniques may identify potential Leadville hydrocarbon migration patterns and oil-prone areas. Determination of the timing of structural development, petroleum migration, entrapment, and fill and spill histories is critical to successful exploration.

As part of technology transfer activities during this quarter, the project team joined Utah Stake Holder Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah. Project team members published a quarterly report detailing project progress and results. A presentation on the central Utah thrust belt, Jurassic Navajo Sandstone oil play was made to the Sevier County (Utah) Commissioners. The project home page was updated on the Utah Geological Survey Web site.

# 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, 2004). 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.

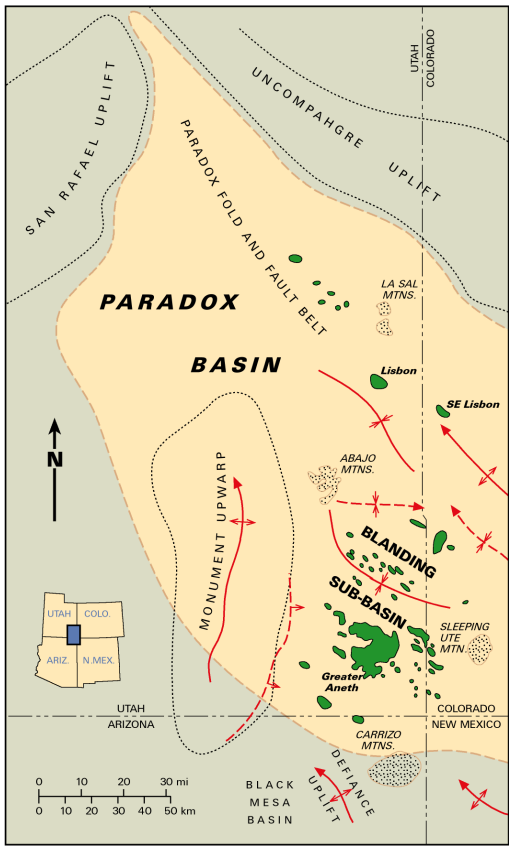
This report covers research activities for the eleventh quarter of the project (January 1 through March 31, 2005). This work included (1) describing the Mississippian Leadville Limestone Paradox Basin play, and (2) technology transfer activities.

## Project Benefits

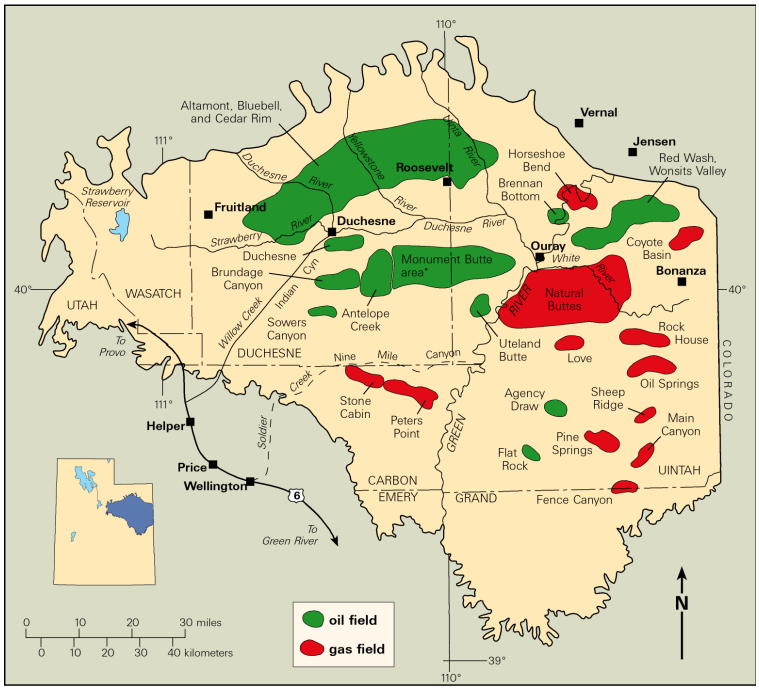
The overall goal of this multi-year project is enhanced petroleum production in the Rocky Mountain region. Specifically, the project goal will benefit from the following projects:

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

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




A

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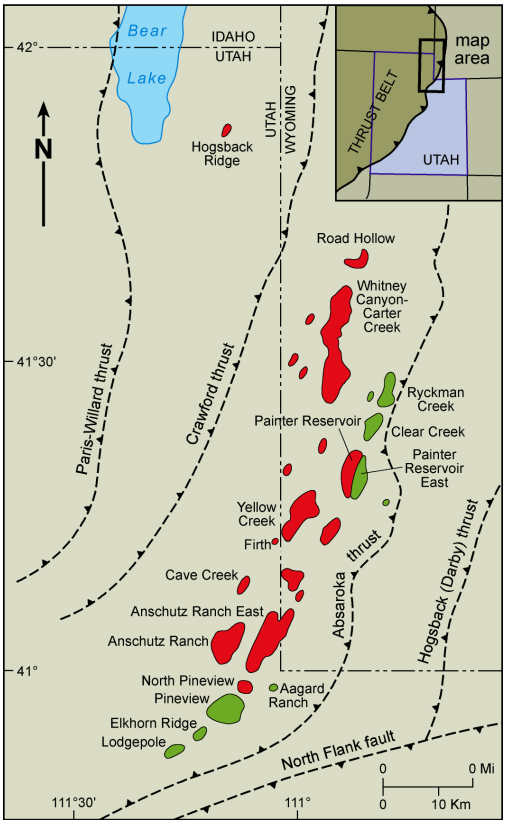



C

***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.***

(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 identified basins or 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 to reduce development costs and risk, and allow limited energy investment dollars to be used more productively, 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.

# MISSISSIPPIAN LEADVILLE LIMESTONE PARADOX BASIN PLAY – DISCUSSION AND RESULTS

## 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 (figure 2). Most Leadville production is from the Paradox fold and fault belt (figure 3). The Leadville Limestone has produced over 53 million barrels (8.4 million $m^3$) of oil and 845 billion cubic feet (BCF [23.9 billion $m^3$]) of gas from the six fields in the northern Paradox Basin of Utah and Colorado (Utah Division of Oil, Gas and Mining, 2004; Colorado Oil and Gas Conservation Commission records). However, much 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. Geologic data for individual fields in the play are summarized in table 1.

The play outline represents the maximum extent of petroleum potential in the geographical area as defined by producing reservoirs, hydrocarbon shows, and untested hypotheses. The attractiveness of the 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.

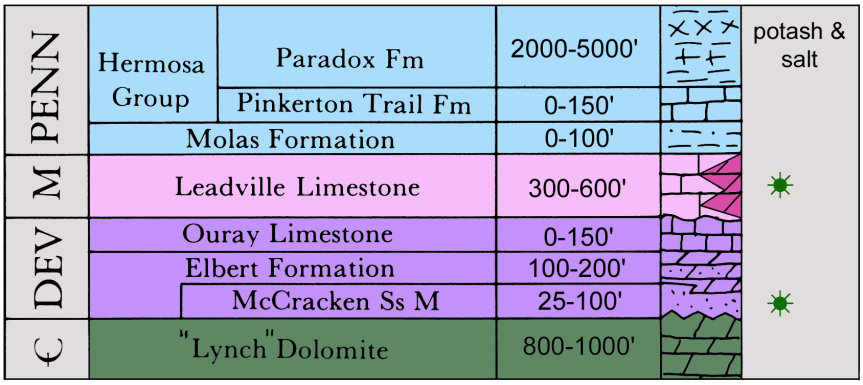



*Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).*

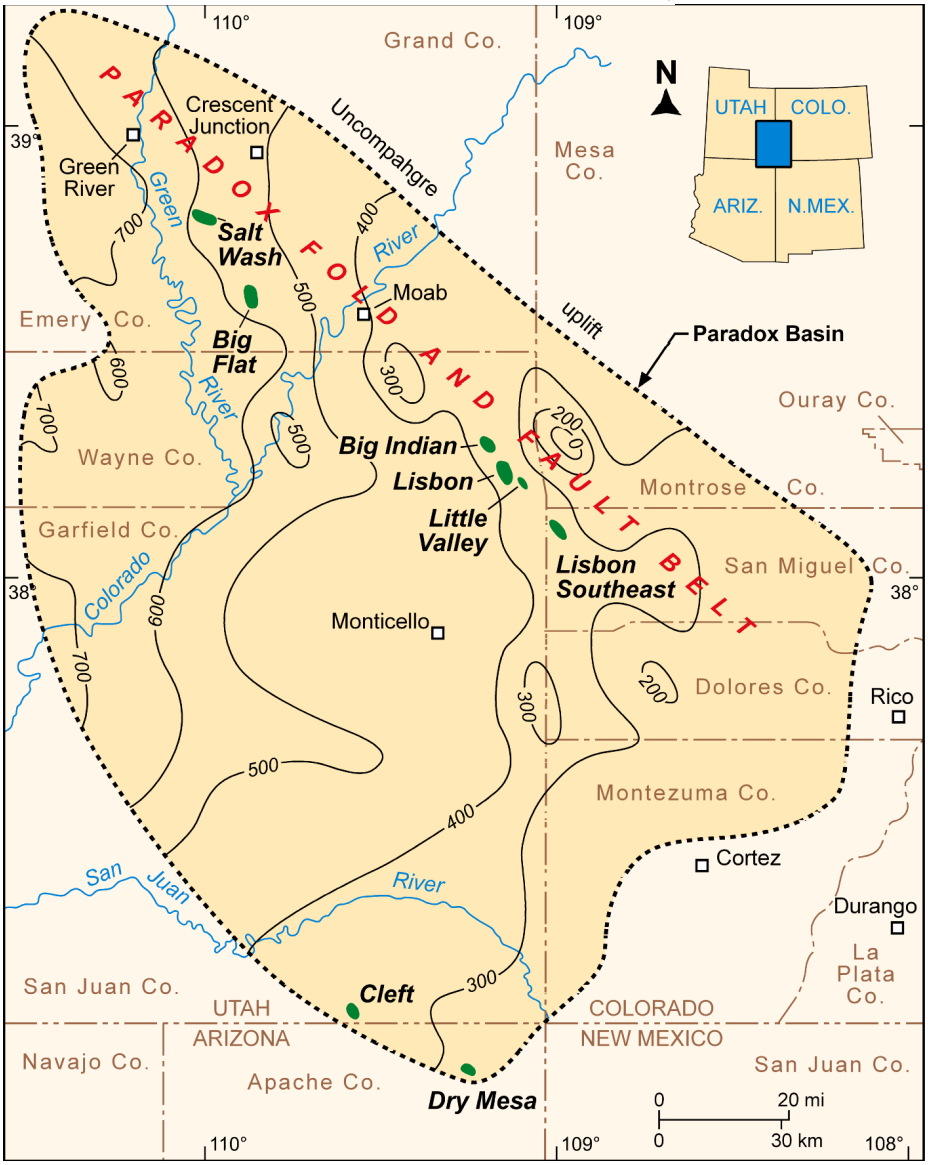



*Figure 3. Location of fields that produce oil (green) from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963). The Leadville Limestone Paradox Basin play area is dotted. Modified from Morgan (1993).*

*Table 1. Geologic, reservoir, and production data for fields in the Mississippian Leadville Limestone Paradox Basin play. Data compiled from Stowe (1972), Cargile (1978), Clark (1978), Latch (1978a, 1978b), Norton (1978), Smith (1978), Parker (1981), Morgan (1993), Smouse (1993a, 1993b), Utah Division of Oil, Gas and Mining (2004), and Colorado Oil & Gas Conservation Commission (verbal communication, April 2005).*

| State | County | Field | Discovery Date | Active Producers | Abandoned Producers | Acres | Spacing (acres) | Pay (feet) | Porosity (%) | Permeability (mD) | Temp. (°F) | Initial Reservoir Pressure (psi) | Average Monthly Production | | Cumulative Production | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | Oil (bbl) | Gas (MCF) | Oil (bbl) | Gas (BCF) |
| Colorado | San Miguel | Lisbon Southeast | 1960 | 5 | 1 | 800 | 640 | 50 | 8 | 10 | NA | 2340 | 313 | 50,295 | 164,922 | 16.2 |
| Utah | San Juan | Big Flat | 1957 | 0 | 3 | 480 | 80 | 30 | 9 | variable | 125 | 2450 | 0 | 0 | 83,469 | 0.05 |
| Utah | San Juan | Big Indian | 1961 | 1 | 0 | 640 | 640 | 72 | 6 | 3-10 | 148 | 3240 | 0 | 0 | 178,160 | 26.4 |
| Utah | San Juan | Lisbon | 1960 | 22 | 13 | 5120 | 320 | 225 | 6 | 22 | 127 | 2982 | 2917 | 1,114,919* | 51,045,833 | 773.6* |
| Utah | San Juan | Little Valley | 1961 | 1 | 2 | 660 | 160 | 100 | 6 | 6-10 | 127 | 3043 | 0 | 0 | 137,848 | 17.3 |
| Utah | Grand | Salt Wash | 1961 | 7 | 4 | 920 | 160 | 19 | 8 | NA | 143 | 4075 | 793 | 42 | 1,563,865 | 11.7 |

NA = Not available
*Includes cycled gas

## Depositional Environment

The Mississippian (late Kinderhookian through Osagean to early Meramecian time) Leadville Limestone is a shallow, open marine, carbonate-shelf deposit (figure 4). Local depositional environments included shallow-marine, subtidal, supratidal, and intertidal (Fouret, 1982, 1996). The western part of the Paradox fold and fault belt includes a regional, reflux-dolomitized, interior bank facies containing Waulsortian mounds (Welsh and Bissell, 1979) - local, mud-supported buildups involving growth of "algae" (Wilson, 1975; Ahr, 1989; Fouret, 1982, 1996).

During Late Mississippian time, the entire carbonate platform in southeastern Utah and southwestern Colorado was subjected to subaerial erosion resulting in formation of a lateritic regolith (Welsh and Bissell, 1979). This regolith and associated carbonate dissolution is an important factor in Leadville reservoir potential (figure 5). Solution breccia and karstified surfaces are common, including possible local development of cavernous zones (Fouret, 1982, 1996).

Periodic movement along northwest-trending basement faults affected deposition of the Leadville Limestone. Crinoid banks or mounds, the primary reservoir facies, accumulated in shallow-water environments on upthrown fault blocks or other paleotopographic highs. In areas of greatest paleorelief, the Leadville is completely missing as a result of non-deposition or subsequent erosion (Baars, 1966).

There are four Leadville depositional facies based on cores from Lisbon field (figure 3): open marine, shoal flank, restricted marine, and middle shelf. Open-marine facies are represented by crinoidal banks or shoals and Waulsortian-type buildups (figure 4). This facies represents a high-energy environment with well-circulated, normal-marine salinity water in a subtidal setting. Water depths ranged from 5 to 45 feet (1.5-14 m). Waulsortian buildups or mud mounds developed exclusively during the Mississippian in many parts of the world (Wilson, 1975). They are steep-sloped tabular, knoll, or sheet forms composed of several generations of mud deposited in a subtidal setting (Fouret, 1982, 1996; Lees and Miller, 1995) (figure 4). Crinoids and sheet-like fenestrate byrozoans, in the form of thickets, are associated with the deeper parts of the mud mounds and are indicative of well-circulated, normal-marine salinity. This facies represents a low- to moderate-energy environment. Water depths ranged from 60 to 90 feet (20-30 m).

Shoal-flank facies are associated with both crinoid bank/shoal and Waulsortian-type buildup facies (figure 4). This facies represents a moderate-energy environment, again with well-circulated, normal-marine salinity water in a subtidal setting. Water depths ranged from 60 to 90 feet (20-30 m).

Restricted-marine facies are represented by "hard" peloid and oolitic shoals that developed as a result of regularly agitated, shallow-marine processes on the shelf (figure 4). Like crinoidal banks and Waulsortian-type buildups, hard peloid and oolitic shoals are common throughout Leadville deposition, especially on paleotopographic highs. This facies represents a moderate- to high-energy environment, with moderately well-circulated water in an intertidal setting. The water probably had slightly elevated salinity compared to the other facies. Sediment deposition and modification probably occurred in water depths ranging from near zero to 20 feet (6 m).

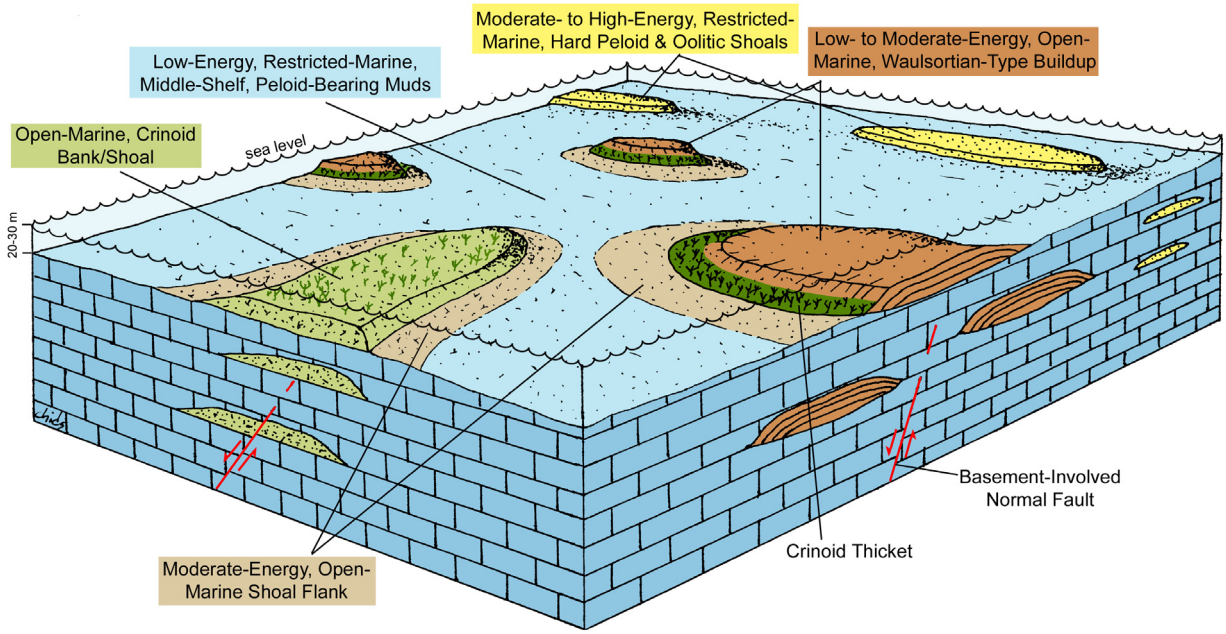



***Figure 4. Block diagram displaying major depositional facies, as determined from core, for the Mississippian Leadville Limestone.***

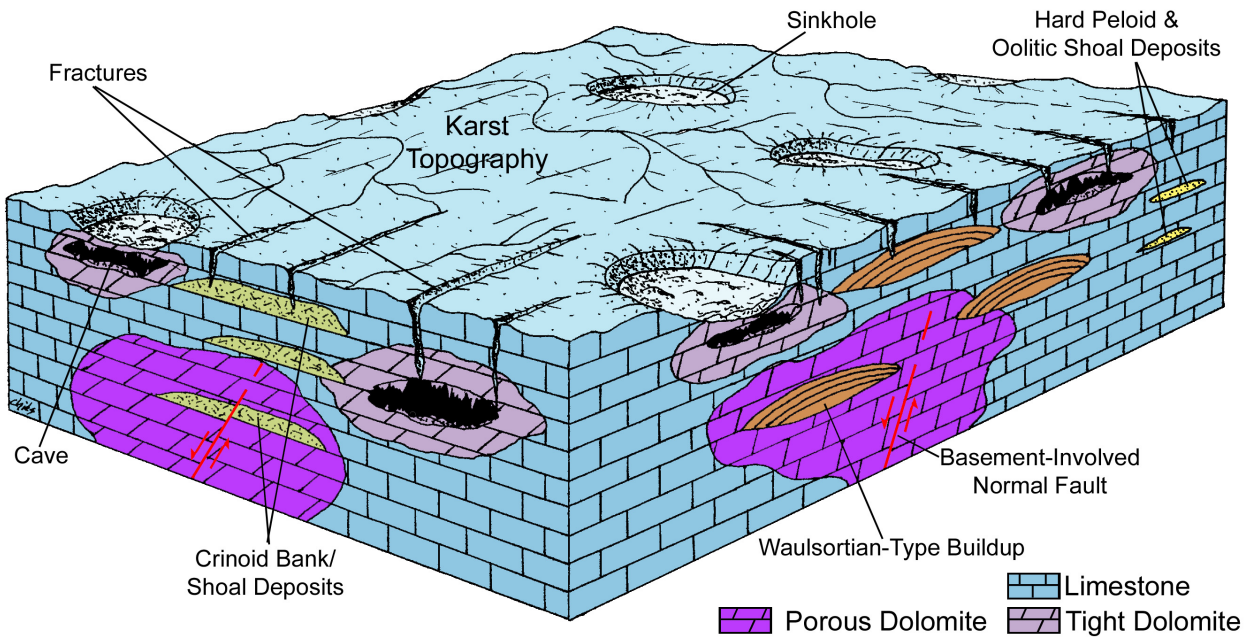



***Figure 5. Block diagram displaying post-Leadville karst and fracture overprint.***

Middle-shelf facies covered extensive areas across the shallow shelf. This facies represents a low-energy, often restricted-marine environment (figure 4). Mud and some sand were deposited in a subtidal (burrowed), inter-buildup/shoal setting. Water depths ranged from 60 to 90 feet (20-30 m).

## Stratigraphy and Thickness

The Leadville Limestone is typically 300 to 600 feet (100-200 m) thick in the play area (Hintze, 1993). However, the Leadville thins from more than 700 feet (230 m) in the northwest corner of the Paradox Basin to less than 200 feet (70 m) in the southeast corner (Morgan, 1993) (figure 3). Thinning is a result of both depositional onlap onto the Mississippian cratonic shelf and erosion. The Leadville is divided into two informal members, a dolomitic lower member and a limestone and dolomite upper member, separated by an intraformational discomformity (Fouret, 1982, 1996). Each unit has a subtle but distinct characteristic geophysical log response (figure 6).

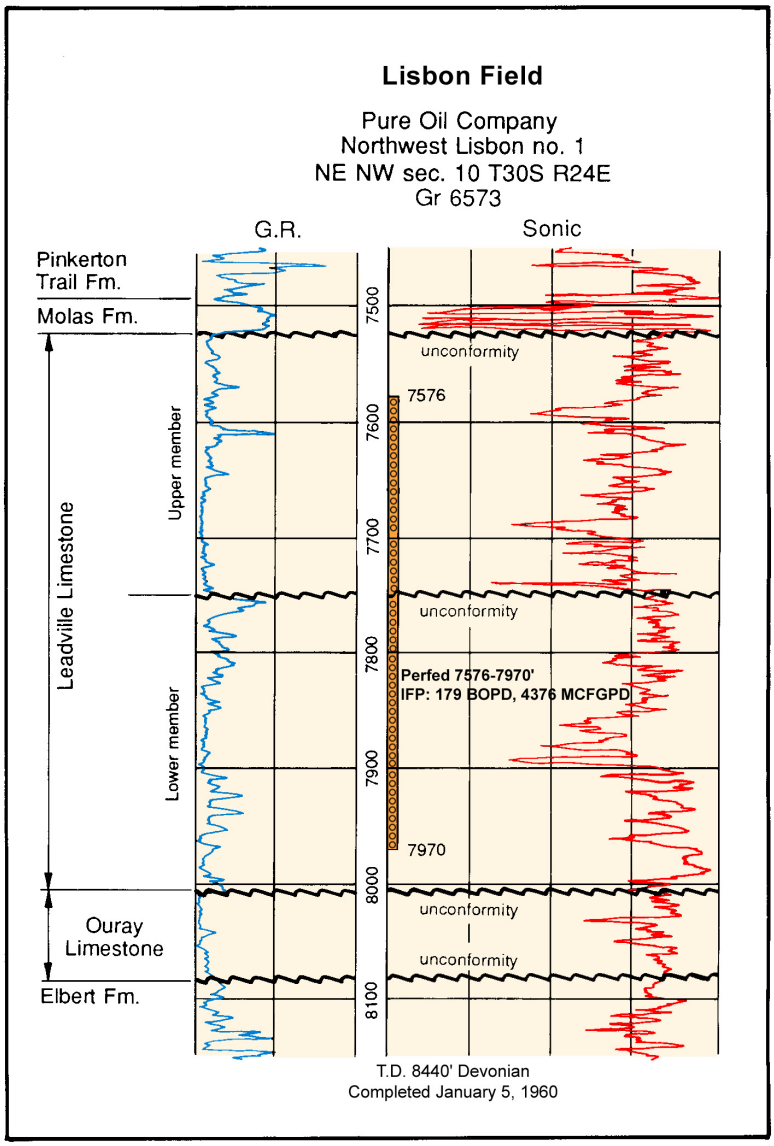



***Figure 6. Typical gamma ray-sonic log of the Leadville Limestone, Lisbon field discovery well, San Juan County, Utah. Producing (perforated) interval between depths of 7576 and 7070 feet. See figures 1 and 3 for location of Lisbon field.***

The Leadville Limestone is overlain by the Pennsylvanian Molas Formation and underlain by the Devonian Ouray Limestone (figures 2 and 6). Average depth to the Leadville in Paradox Basin fields is 8760 feet (2920 m).

**Lithology**

The depositional fabrics of crinoidal banks and shoals include grainstone and packstone (figure 7A). Rocks representing crinoidal banks and shoals typically contain the following diagnostic constituents: dominately crinoids and rugose corals, and lesser amounts of broken fenestrate bryozoans, brachiopods, ostracods, and endothyroid forams as skeletal debris. Low to medium cross-bedding is common. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains, followed by dolomitization, has occurred.

The depositional fabrics of the Waulsortian-type buildups include mud-supported boundstone, packstone, and wackestone (figure 7B). Rocks representing Waulsortian-type buildups typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, and associated skeletal debris, and *stromatactis*. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability, especially after dolomitization.

The depositional fabrics of the shoal-flank facies include peloidal/skeletal packstone and wackestone (figure 8A). Bedding is generally absent in cores. Rocks representing this facies typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, brachiopods, and associated skeletal debris, and talus, depositional breccia, and conglomerate (Fouret, 1982, 1996). Rock units having shoal-flank facies constitute a limited reservoir potential, having little effective porosity and permeability.

The depositional fabrics of the restricted-marine facies include grainstone and packstone (figure 8B). Rocks representing this facies typically contain the following diagnostic constituents: ooids, coated grains, and hard pelloids. Fossils are relatively rare. Rock units having restricted-marine facies constitute good reservoir potential. Remnants of visible interparticle and moldic porosity may be present in this facies. Dolomitization significantly increases the reservoir quality of this facies.

The depositional fabrics of the middle-shelf facies include wackestone and mudstone (figure 8C). The most common is bioturbated lime to dolomitic mudstone with sub-horizontal feeding burrows. Rocks representing this facies typically contain the following diagnostic constituents: soft pellet muds, “soft” peloids, grain aggregates, crinoids and associated skeletal debris, and fusulinids. Rock units having middle-shelf facies generally act as barriers and baffles to fluid flow, having very little effective porosity and permeability. There are few megafossils and little visible matrix porosity, with the exception of an occasional moldic pore. However, recognizing this facies is important because low-energy carbonates of the middle shelf form the substrate for the development of the higher energy crinoid banks, oolitic/hard peloid shoals, and Waulsortian-type buildups (figure 4). The middle-shelf facies can contain reservoir-quality rocks if dolomitized.

Fractures in the Leadville Limestone are an important reservoir component. They are associated with folding and faulting or collapse related to karst processes.

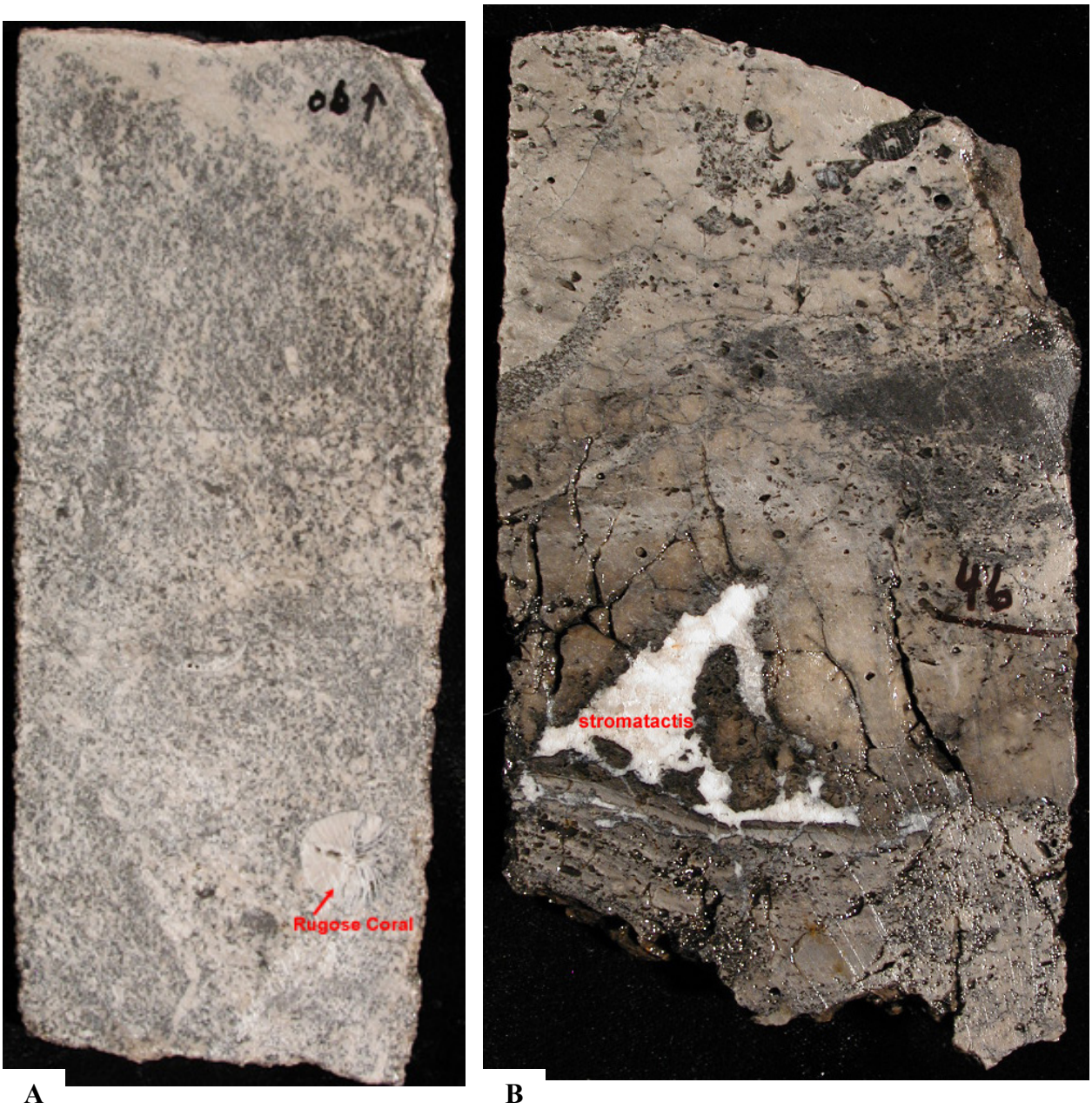



***Figure 7. Typical Leadville Limestone depositional fabrics from Lisbon field, San Juan County, Utah. A - Crinoidal/skeletal grainstone/packstones representing high-energy, open-marine shoal facies; slabbed core from 8506.5 feet, Lisbon No. B-816 well. B - Peloidal/ skeletal packstone/wackestones representing moderate- to low-energy, open-marine, Waulsortian-type buildup facies; slabbed core from 8646 feet, Lisbon No. B-816 well.***




***Figure 8. Typical Leadville Limestone depositional fabrics from Lisbon field, San Juan County, Utah. A - Peloidal/skeletal packstone/wackestone representing moderate-energy, open-marine, shoal-flank facies; slabbed core from 8521 feet, Lisbon No. B-816 well. B - Peloidal grainstone/packstone representing moderate-energy, restricted-marine, "hard" peloid shoal facies; slabbed core from 8463 feet, Lisbon No. B-816 well. C - Skeletal/"soft" peloidal wackestone/ mudstone representing low-energy, restricted-marine, middle-shelf facies; slabbed core from 8549 feet, Lisbon No. B-816 well.***

## Hydrocarbon Source and Seals

Hydrocarbons in Leadville Limestone reservoirs were likely generated from source rocks in the Pennsylvanian Paradox Formation (figure 2). Organic-rich informal units, such as the Cane Creek, Chimney Rock, and Gothic shales, are well established source rocks for oil produced from the Paradox Formation itself (Hite and others, 1984; Nuccio and Condon, 1996). These rocks are composed of black, sapropelic shale and shaley dolomite, deposited in quiet water under anaerobic bottom conditions (Morgan, 1993). The average total organic carbon (TOC) content of the black shale in Cane Creek shale is 15 percent with some samples containing up to 28 percent (Grummon, 1993). The Chimney Rock shale has from 1 to 3 percent TOC and a mean vitrinite reflectance ($R_o$ mean) of 1.3 to 2.5. The Gothic shale has from 1.5 to near 4 percent TOC and an $R_o$ mean of 0.8 to 1.2 (Hite and others, 1984; Peterson, 1992). Other, deeper shale facies in the Paradox Formation contain as much as 13 percent TOC (Hite and others, 1984). Peterson (1992) calculates a cumulative thickness of more than a 1000 feet (330 m) of organic-rich rocks in the Paradox.

Hydrocarbon generation occurred during maximum burial in the Late Cretaceous and early Tertiary. Hydrocarbons were then expelled and subsequently migrated, primarily along fault planes, into carrier beds or structures where the Leadville Limestone was juxtaposed directly against Pennsylvanian source rocks. Fracture systems developed along fault systems may have provided secondary migration routes. Oil generated from non-Pennsylvanian source rocks require long-distance migration.

The seals for the Leadville producing zones are the overlying clastic beds of the Pennsylvanian Molas Formation (figure 2). Hydrocarbons in the Leadville are further sealed by evaporite (salt and anhydrite) beds within the overlying Pennsylvanian Paradox Formation.

## Structure and Trapping Mechanisms

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 (figure 9). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are found on sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), 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, Precambrain-age faults during the Laramide orogeny or later. As examples of both types of structural traps, Big Flat and Lisbon fields are briefly described below.

**Big Flat field:** Big Flat field, Grand County, Utah, was the first Mississippian discovery in the Paradox Basin (figure 3). The trap is a doubly plunging anticline with 276 feet (84 m) of structural closure (figure 10) 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. The field now produces oil from horizontal wells in the Cane Creek shale of the Paradox Formation, on a separate structure north of the original, abandoned Leadville feature.

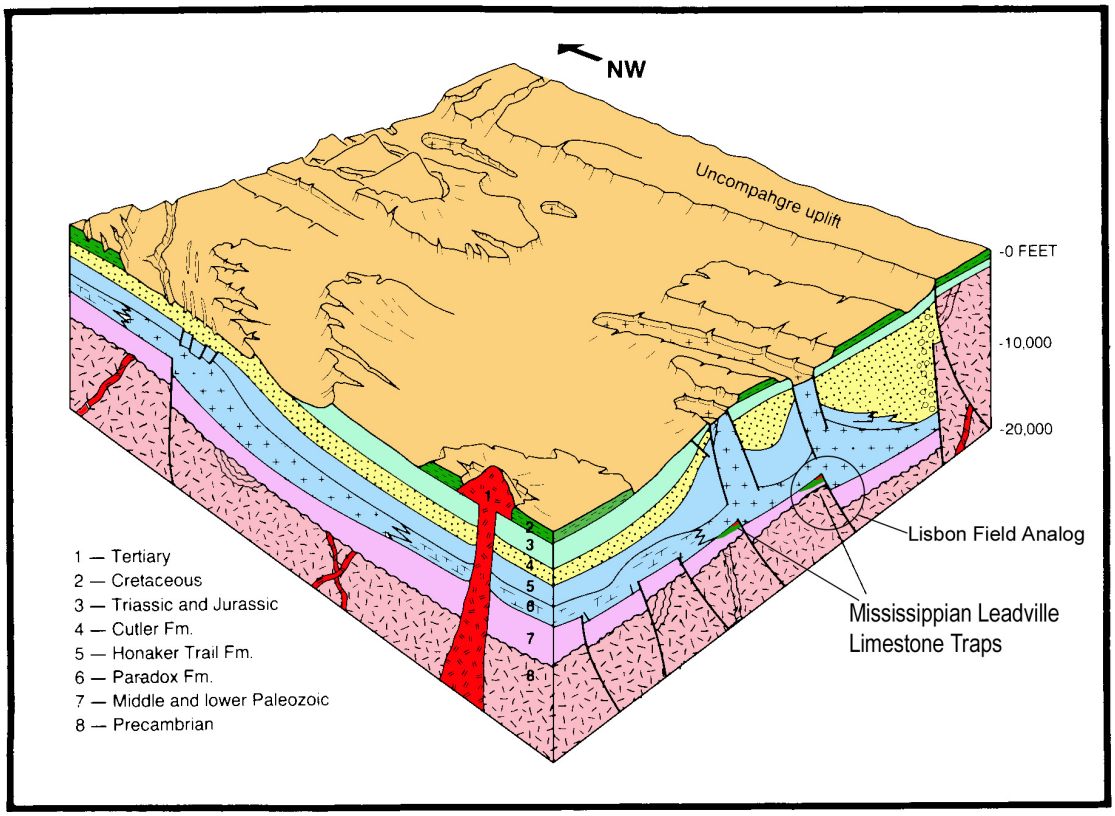
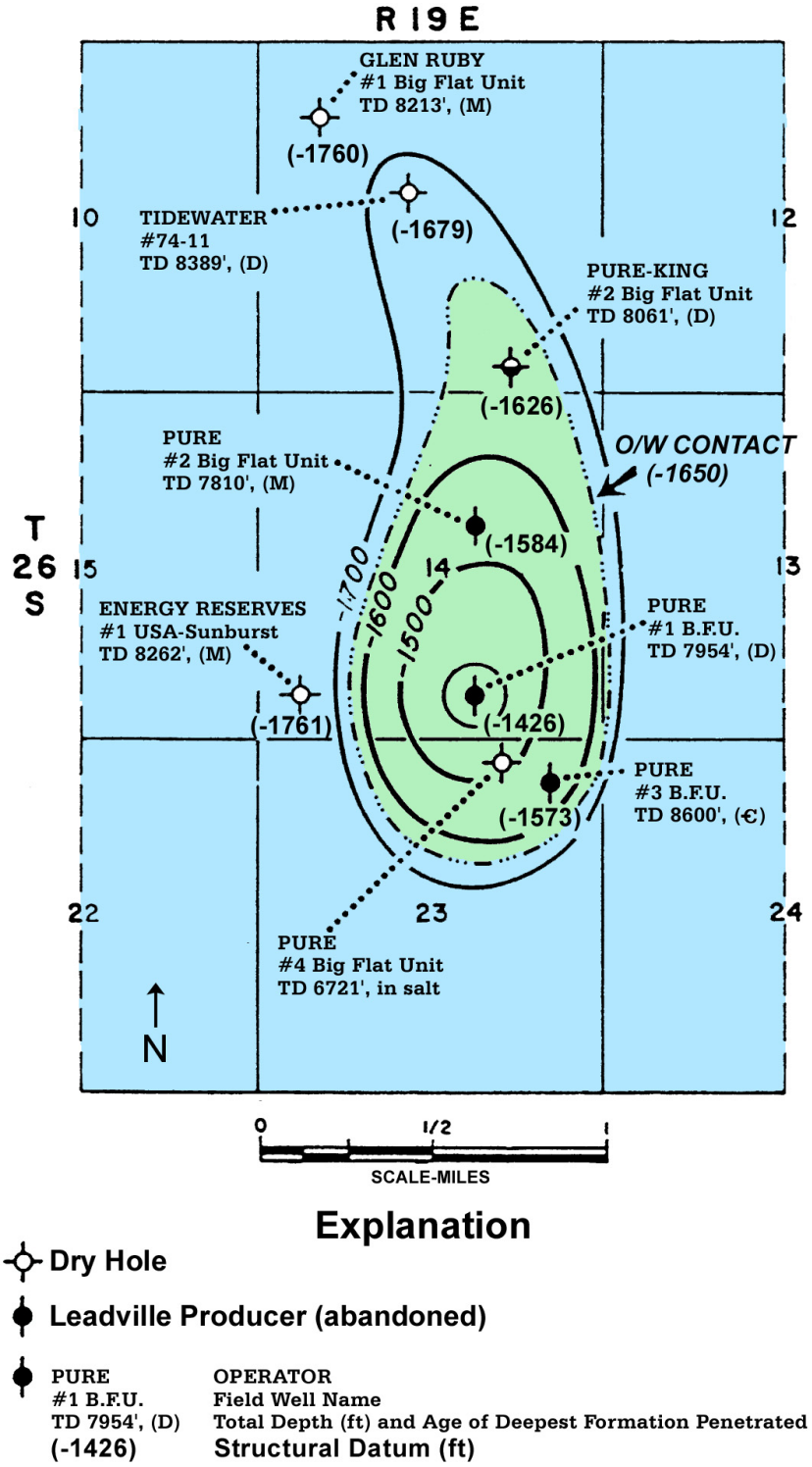



***Figure 9. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).***

**Lisbon field:** Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. The 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) (figures 11 and 12). Several minor, northeast-trending normal faults dissect the Leadville reservoir into segments. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993a).

## Reservoir Properties

The Leadville Limestone has heterogeneous reservoir properties because of (1) depositional facies with varying porosity and permeability, (2) diagenetic effects, and (3) fracturing. Identification and correlation of depositional facies in individual Leadville reservoirs is critical to understanding their effect on production rates and paths of petroleum movement. Natural fractures also affect permeability, and control hydrocarbon production and injection fluid pathways. Leadville reservoir porosity ranges from 4 to 21 percent with typical porosity averaging 6 to 8 percent (Morgan, 1993). Permeability is variable, generally ranging from 3 to 10 millidarcies (mD). At Lisbon field, San Juan County, Utah (figure 3), the permeability ranges from less than 1 to 1100 mD, averaging 22 mD (Smouse, 1993a).




## Explanation

Dry Hole

Leadville Producer (abandoned)

| | |
|---|---|
| PURE | OPERATOR |
| #1 B.F.U. | Field Well Name |
| TD 7954', (D) | Total Depth (ft) and Age of Deepest Formation Penetrated |
| (-1426) | Structural Datum (ft) |

*Figure 10. 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).*

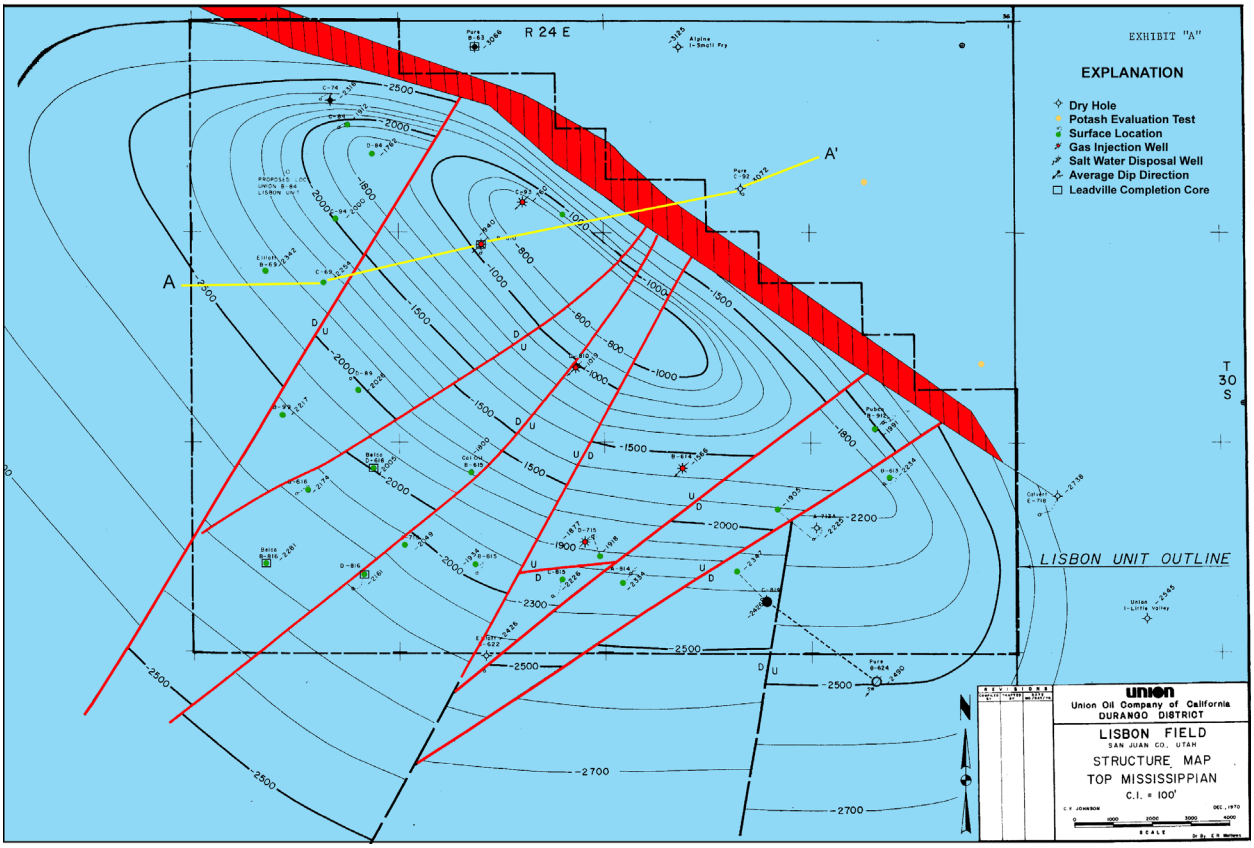



***Figure 11. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah. Contour interval = 500 feet, datum = mean sea level. The field is bounded on its northeast flank by a major, basement-involved normal fault (in red) with greater than 2500 feet of displacement. Note the multiple, northeast-trending faults that dissect 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. Cross section A-A' shown on figure 12.***

The early diagenetic history of the Leadville sediments, including some dolomitization (finely crystalline) (figure 4) and leaching of skeletal grains (figure 13A), resulted in low-porosity and/or low-permeablility rocks. Most of the porosity and permeability associated with hydrocarbon production at Lisbon field, for example, was developed during later, deep subsurface dolomitization (coarsely crystalline replacement and saddle [hydrothermal?] dolomite) and dissolution (figures 5 and 13B). Predating or concomitant with saddle dolomite formation are pervasive leaching episodes that cross-cut the carbonate host rocks with dissolution resulting in late vugs as well as extensive microporosity. Pyrobitumen appears to coat most intercrystalline dolomite as well as dissolution pores associated with the late dolomite. Extensive solution-enlarged fractures and autobreccias are also common (figure 14A). Sediment-filled cavities are relatively common throughout the upper third of the Leadville in Lisbon field (figure 14B). These cavities or cracks were related to karstification of the exposed Leadville (figure 5). Infilling of the cavities by detrital carbonate and siliciclastic sediments occurred before the deposition of the Pennsylvanian Molas Formation.

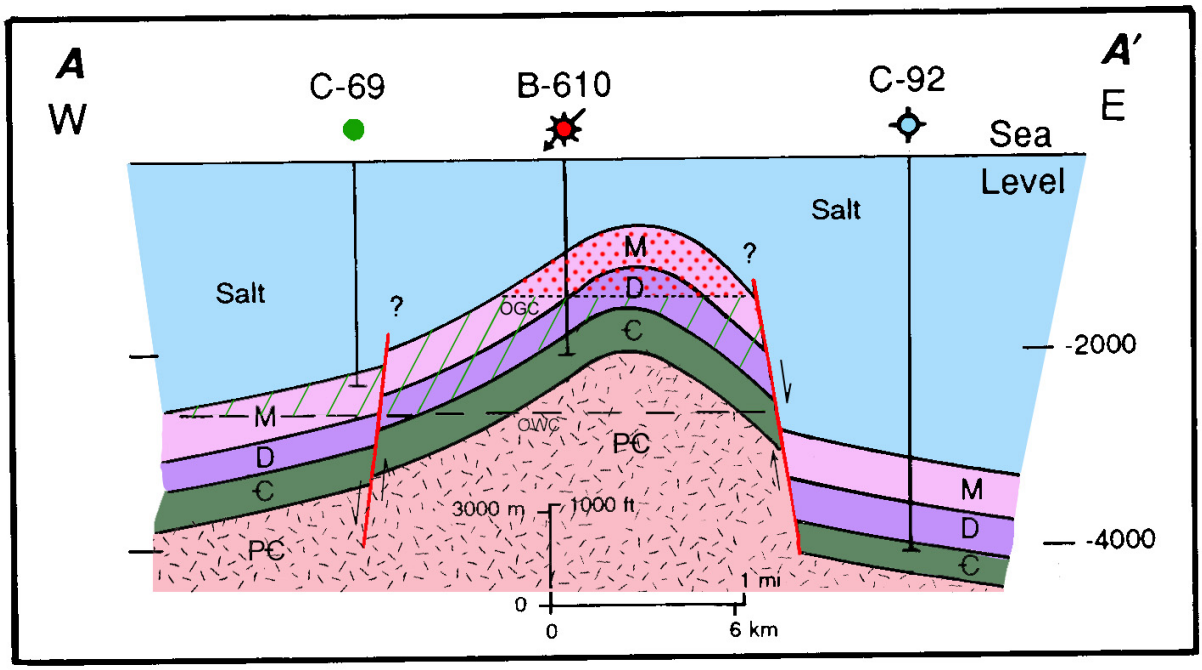



*Figure 12. Schematic east-west cross section through Lisbon field. Line of section shown on figure 11. Note the juxtaposition of the Mississippian section against the Pennsylvanian section which includes evaporites (salt) and organic-rich shale.*

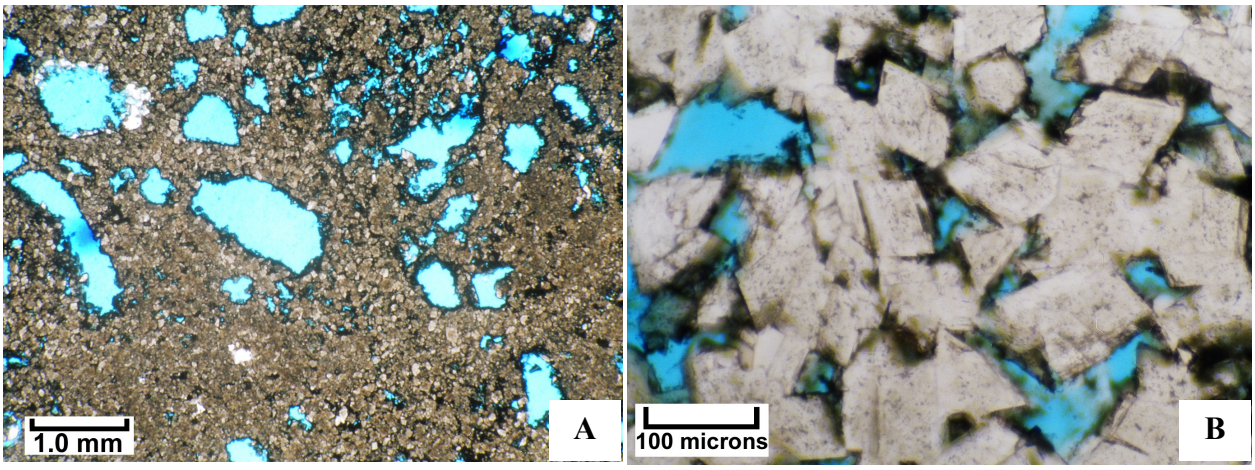



*Figure 13. Leadville Limestone diagenetic characteristics from Lisbon field, San Juan County, Utah. A - Representative photomicrograph (plane light) of the tight, finely crystalline dolomite with isolated grain molds. Most of this fabric-selective dolomite formed early in the diagenetic history of the skeletal/peloid sediment. B - Representative photomicrograph (plane light) of the coarser, replacement dolomite (both euhedral rhombs and occasional "saddle" overgrowths). The black (opaque) areas are the result of pyrobitumen films. From Lisbon No. D-816 well, 8433 feet; porosity = 2 percent, permeability <0.1 mD.*

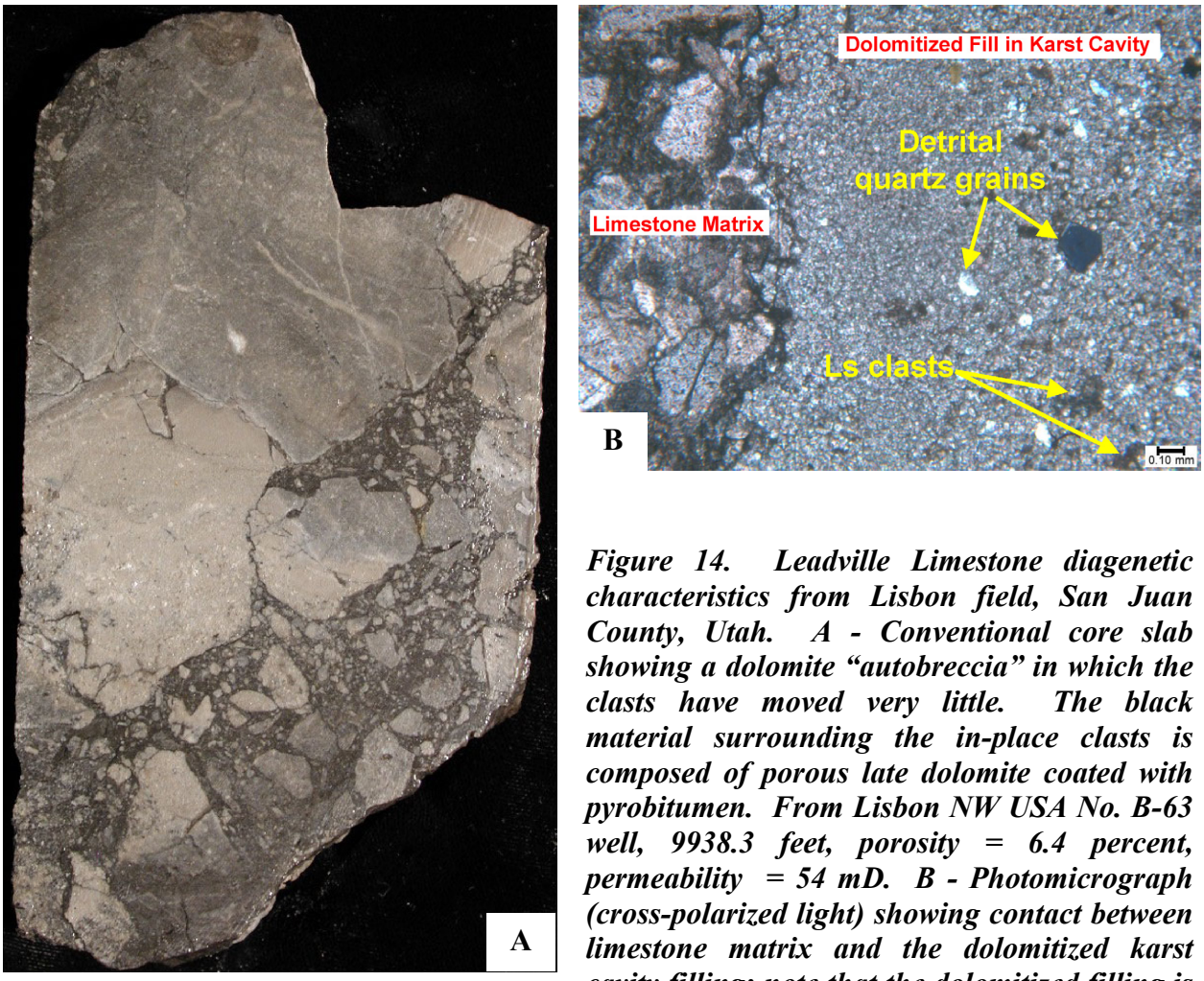



***Figure 14. Leadville Limestone diagenetic characteristics from Lisbon field, San Juan County, Utah. A - Conventional core slab showing a dolomite "autobreccia" in which the clasts have moved very little. The black material surrounding the in-place clasts is composed of porous late dolomite coated with pyrobitumen. From Lisbon NW USA No. B-63 well, 9938.3 feet, porosity = 6.4 percent, permeability = 54 mD. B - Photomicrograph (cross-polarized light) showing contact between limestone matrix and the dolomitized karst cavity filling; note that the dolomitized filling is composed of very fine crystals with detrital quartz grains and small carbonate clasts. From Lisbon No. D-616 well, 8308 to 8309 feet, porosity = 1.2 percent, permeability = 11.1 mD.***

Leadville net-pay thickness is also variable, depending on diagenesis and fracturing, and ranges from 19 to 225 feet (6-75 m). The average Leadville reservoir temperature is 134ºF 57ºC). Water saturations range from 25 to 50 percent, salinities range from 20,000 to 1830 parts per million, and resistivities ($R_w$) range from 0.059 to 0.103 ohm-m at 68ºF (20ºC). Initial reservoir pressures average about 3022 pounds per square inch (20,840 kPa). The reservoir drive mechanisms include gas expansion, water drive, and gravity drainage.

Reservoir data for individual fields in the Mississippian Leadville Limestone Paradox Basin play are summarized in table 1. For details see Stowe (1972), Cargile (1978), Clark (1978), Latch (1978a, 1978b), Norton (1978), Smith (1978), Parker (1981), Morgan (1993), Smouse (1993a, 1993b), Gwynn (1995), Utah Division of Oil, Gas and Mining (2004), and Colorado Oil & Gas Conservation Commission (verbal communication, April 2005).

## Oil and Gas Characteristics

In major reservoirs, the produced Leadville oil and condensate are rich, volatile crudes. The API gravity of the oil ranges from 41º to 54º; the gas-oil ratio ranges between 50 and 3150 cubic feet/bbl. The API gravity of the condensate ranges from 60º to 66º. Oil colors vary from brownish green to yellow/amber to red, and condensate can be light green to yellow to red. The viscosity of the crude oil ranges from 32 to 55 seconds at 100ºF (38ºC); the viscosity of the condensate is less than 32 seconds at 100ºF (38ºC). The pour point of the crude oil ranges from 40 to 85ºF (4-29ºC). The average weight percent sulfur and nitrogen of produced Leadville hydrocarbon liquids are 0.13 and 0.005, respectively (Stowe, 1972).

Leadville reservoirs produce associated gas that is variable in composition. Associated gas produced at Lisbon field contains 40 percent methane, 9 percent ethane, 7 percent propane, 2 percent butane, 1 percent pentane, 0.5 percent hexane and higher fractions, 13 percent nitrogen, 27 percent carbon dioxide, and 1 percent helium. The gas heating value averages 892 British thermal units/cubic foot (Btu/$ft^3$); the specific gravity averages 1.046. Associated gas produced at Salt Wash field contains 13 percent methane, 3 percent ethane, 3 percent propane, 3 percent butane, 1 percent pentane, 0.5 percent hexane and higher fractions, 71 percent nitrogen, 3 percent carbon dioxide, and 1.5 percent helium. The gas heating value averages 443 Btu/$ft^3$; the specific gravity averages 1.005 (Moore and Sigler, 1987).

Leadville reservoirs produce nonassociated gas that is relatively uniform in composition: 64 percent methane, 5 percent ethane, 2 percent propane, 1 percent butane, 0.3 percent pentane, 0.4 percent hexane and higher fractions, 13 percent nitrogen, 13 percent carbon dioxide, and 0.7 percent helium. The gas heating values average 864 Btu/$ft^3$; the specific gravity averages 0.813 (Moore and Sigler, 1987). Gas produced from the reservoirs in the Leadville Limestone Paradox Basin contains only a trace of hydrogen sulfide.

## Production

Three fields in the Leadville Limestone Paradox Basin play have produced crude oil and associated gas. Big Flat, Lisbon, and Salt Wash fields (figure 3) have combined to produce nearly 53 million bbls of oil (MMBO [8.4 MMCMO]) and 785 BCF (22.2 BCM) of gas from the Leadville (Utah Division of Oil, Gas and Mining, 2004) (table 1). There are currently 29 active producers and 20 abandoned Leadville producers in these three fields (table 1).

Three fields in the Leadville Limestone Paradox Basin play have produced condensate and nonassociated gas. Big Indian, Lisbon Southeast, and Little Valley fields (figure 3) have combined to produce 480,930 bbls of condensate (76,468 $m^3$) and 59.9 BCF (1.70 BCM) of gas from the Leadville (Utah Division of Oil, Gas and Mining, 2004; Colorado Oil & Gas Conservation Commission, verbal communication, April 2005) (table 1). There are currently seven active producers and three abandoned producers in these three fields (table 1).

In 2004, the monthly production from the Leadville Limestone averaged 3022 bbls of oil (and condensate) (481 $m^3$) and 1.17 BCF (0.03 BCM) of gas (Utah Division of Oil, Gas and Mining, 2004; Colorado Oil & Gas Conservation Commission, verbal communication, April 2005). Production peaked in the mid to late 1960s, and has generally declined since then.

## Exploration Methods

Leadville-producing fields were discovered in the late 1950s and early 1960s using surface geologic mapping, subsurface geology, and seismic data. New prospective drilling targets in the Leadville Limestone Paradox Basin play should be delineated using high-quality two-dimensional (2-D) and three-dimensional (3-D) seismic data, 2-D and 3-D forward modeling/visualization tools, well control, dipmeter information, high-quality surface geologic maps, and detailed analyses of structural geometry. Several techniques can be used to determine the timing of structural development, petroleum migration, and entrapment, and to decipher fill and spill histories. These techniques include illite age analysis, apatite fission track analysis, and use of fluid inclusions (Meneses-Rocha and Yurewicz, 1999).

Exploring for petroleum in the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive 3-D seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult, particularly for independents that have limited funds. Relatively low-cost, field surface exploration technologies may identify potential Leadville drilling targets. Mapping the middle Paleozoic hydrodynamic pressure regime may determine hydrocarbon migration directions. Geochemical surveys (using microbial, soil, gas, iodine, and trace elements) can locate surface geochemical anomalies, and maybe especially useful in environmentally sensitive areas where the potential for ground disturbance may preclude other methods of exploration.

Surface geochemical surveys have recently been shown in the Michigan and Williston Basins to help identify areas of poorly drained or by-passed oil in pinnacle reef fields (Wood and others, 2001, 2002). The microbial surveys are based on the concept that the types of microbes living in the soil vary according to their food source. Some microbes thrive on light hydrocarbons (methane through butane). Samples are collected 8 inches (20 cm) below the ground surface, then cultured in a laboratory and the microbe population counted. If certain microbes are present, then it is assumed that the corresponding gases that they consume are present; ethane, propane, and butane in soil are considered to have originated from oil and gas accumulations. Thus, the presence of microbes that feed on these gases is an indication that hydrocarbons have migrated from depth. Absorbed soil gas is detected using gas chromatography-mass spectrometry and produces similar results as the microbial analysis. Iodine and trace elements are also detected using gas chromatography-mass spectrometry.

Regional facies mapping (from studying cores, geophysical well logs, outcrop and modern analogs) and identifying potential oil-prone areas based on shows (using low-cost epifluorescence techniques) also establish areas for Leadville exploration. The epifluorescence analysis of Leadville oil compared to epifluorescence in the cores and cuttings from Lisbon field will create a Leadville epifluorescence standard. The standard can be used to map Leadville oil migration patterns (no hydrocarbons, hydrocarbons passed through, hydrocarbons present but not mobile, hydrocarbons mobile).

These techniques can help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation.

# TECHNOLOGY TRANSFER

The Utah Geological Survey (UGS) is the Principal Investigator and prime contractor for the PUMPII project. 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 will also provide field and reservoir data, especially data pertaining to best practices. During the quarter, project team members joined Utah Stake Holders Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah, on March 8, 2005. Project activities, results, and recommendations were presented at this meeting.

## Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Utah Geology/Oil, Coal, and Energy*, which describes the UGS/DOE cooperative studies (PUMPII, Paradox Basin [two projects], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The PUMPII project page, http://geology.utah.gov/emp/pump/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) quarterly technical progress reports.

## Presentation

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

"The Jurassic Navajo Sandstone Central Utah Thrust Belt Exploration Play, Sevier County, Utah" by Thomas C. Chidsey, Jr., Richfield, Utah, March 1, 2005, to the Sevier County Commissioners and Community & Economic Development Director. The petroleum geology of the central Utah thrust belt play, the recent oil discovery of Covenant field, play potential, and the economic impact on the county were part of the presentation.

## Project Publication

Chidsey, T.C., Jr., and Sprinkel, D.A., 2005, Major oil plays in Utah and vicinity – quarterly annual technical progress report for the period October 1 to December 31, 2004: U.S. Department of Energy, DOE/FC26-02NT15133-10, 44 p.

## CONCLUSIONS AND RECOMMENDATIONS

1. A combination of depositional and structural events created the right conditions for oil generation and trapping in the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado 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 barrels (8.4 million $m^3$) of oil and 845 billion cubic feet (BCF [23.9 billion $m^3$]) of gas. Most Leadville production is from the Paradox fold and fault belt. The Leadville is a shallow, open marine, carbonate-shelf deposit. Local depositional environments included shallow-marine, subtidal, supratidal, and intertidal. 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 Pennsylvanian Molas Formation and evaporite (salt and anhydrite) beds within the Pennsylvanian Paradox Formation.

3. Hydrocarbons in Leadville Limestone reservoirs were likely generated from source rocks in the Pennsylvanian Paradox Formation. Hydrocarbon generation occurred during maximum burial in the Late Cretaceous and early Tertiary. Hydrocarbons were then generated, expelled, and subsequently migrated into traps, primarily along fault planes and fractures.

4. The Leadville Limestone has heterogeneous reservoir properties because of depositional facies with varying porosity and permeability, diagenetic effects, and fracturing. Identification and correlation of depositional facies in individual Leadville reservoirs is critical to understanding their effect on production rates and paths of petroleum movement. 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 hydrocarbon production at Lisbon field was developed during later, deep subsurface dolomitization (coarsely crystalline replacement and saddle [hydrothermal?] dolomite) and dissolution.

5. 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 are found on sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields, 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, Precambrain-age faults during the Laramide orogeny or later.

6. In major reservoirs, the produced Leadville oil and condensate are rich, volatile crudes. Leadville reservoirs produce associated gas that is variable in composition; nonassociated gas is relatively uniform in composition.

7. New prospective drilling targets in the Leadville Limestone Paradox Basin play are delineated using high-quality 2-D and 3-D seismic data, 2-D and 3-D forward modeling/visualization tools, well control, dipmeter information, and surface geologic maps to assess trap geometry. Relatively low-cost surface geochemical surveys, hydrodynamic analysis, and epifluorescence techniques may identify potential Leadville hydrocarbon migration patterns and oil-prone areas. Determination of the timing of structural development, petroleum migration, entrapment, and fill and spill histories is critical to successful exploration.

## ACKNOWLEDGMENTS

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Oil analyses were provided by Humble Geochemical Services and Amoco Oil Company, Salt Lake Business Unit (now operated by Tesoro Corporation). Cheryl Gustin and Kevin McClure (UGS) assisted with data compilation. James Parker and Cheryl Gustin of the

UGS prepared the figures; Michael Laine and Thomas Dempster of the UGS Core Research Center photographed core. Condensate photo by Christine Wilkerson, UGS. This report was reviewed by David Tabet and Michael Hylland of the UGS. Cheryl Gustin, UGS, formatted the manuscript.

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