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DELIVERABLE 1-3A CATALOG OF LEADVILLE POROSITY TYPES AND DIAGENESIS: LISBON FIELD, SAN JUAN COUNTY, UTAH

THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

**Submitted by:
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by

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INTRODUCTION

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m³) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km²) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves. These goals are designed to assist the independent producers and explorers who have limited financial and personnel resources.

Exploring for 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, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save funds and work effort, which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

GEOLOGIC SETTING

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 1). 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). The Mississippian Leadville Limestone is

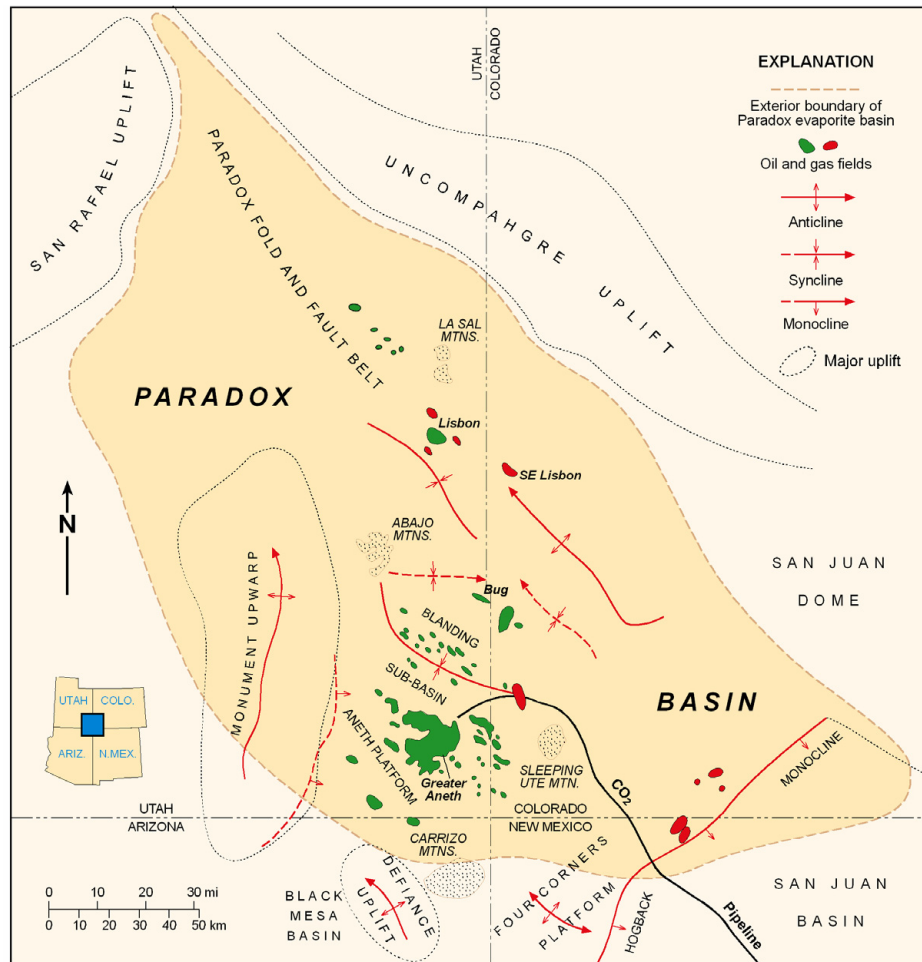


Figure 1. Oil and gas fields in the Paradox Basin of Utah, Arizona, and Colorado.

one of two major oil and gas reservoirs 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 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

PENN	Hermosa Group	Paradox Fm	2000-5000'		potash & salt
		Pinkerton Trail Fm	0-150'		
	Molas Formation		0-100'		
M	Leadville Limestone		300-600'		
DEV	Ouray Limestone		0-150'		
	Elbert Formation		100-200'		
DEV	McCracken Ss M		25-100'		
	"Lynch" Dolomite		800-1000'		

Oil and gas production; Condensate and oil production

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).

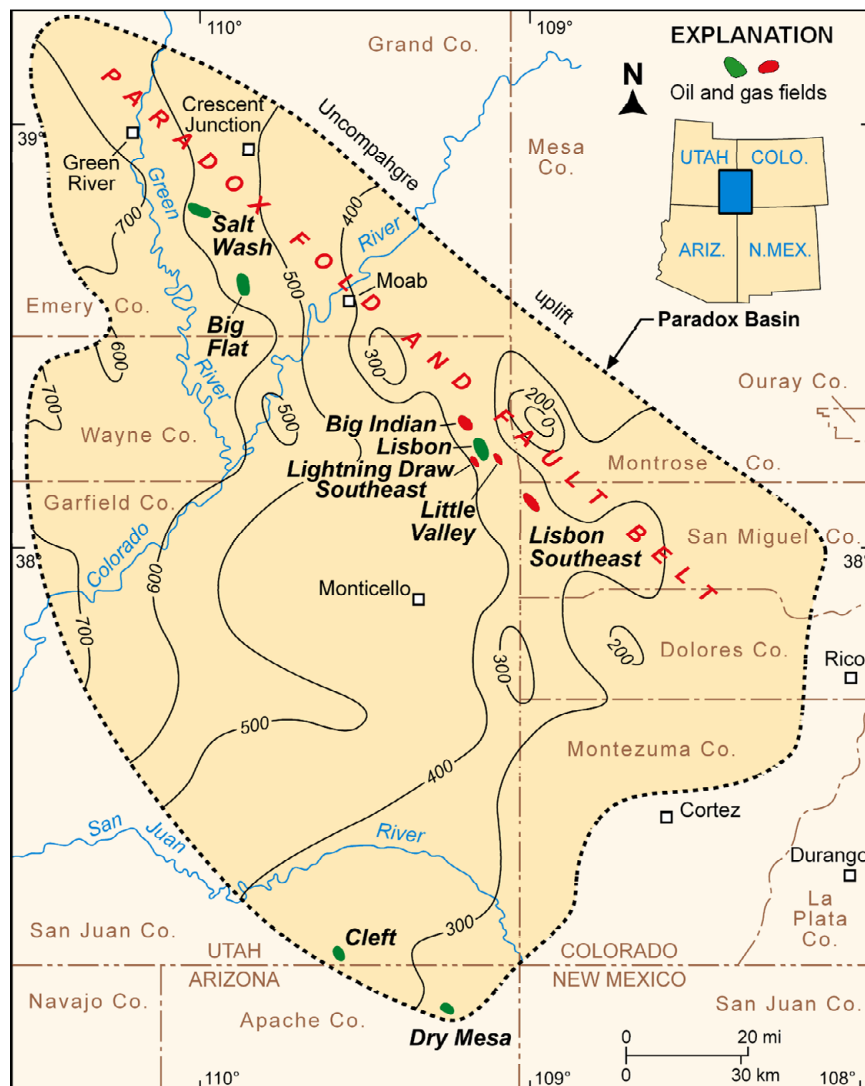


Figure 3. Location of fields that produce from the Mississippian Leadville Limestone, Utah, Arizona, and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

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).

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 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

Regional Leadville Facies

The Mississippian (late Kinderhookian through Osagean to early Meramecian time) Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit (figure 5). 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). 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 6). Solution breccia and karstified surfaces are common, including possible local development of cavernous zones (Fouret, 1982, 1996).

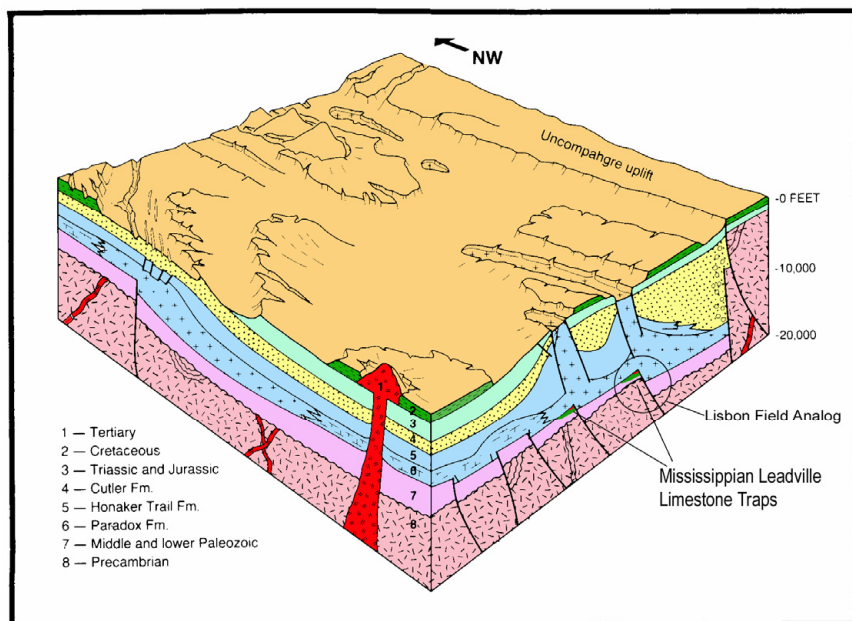


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

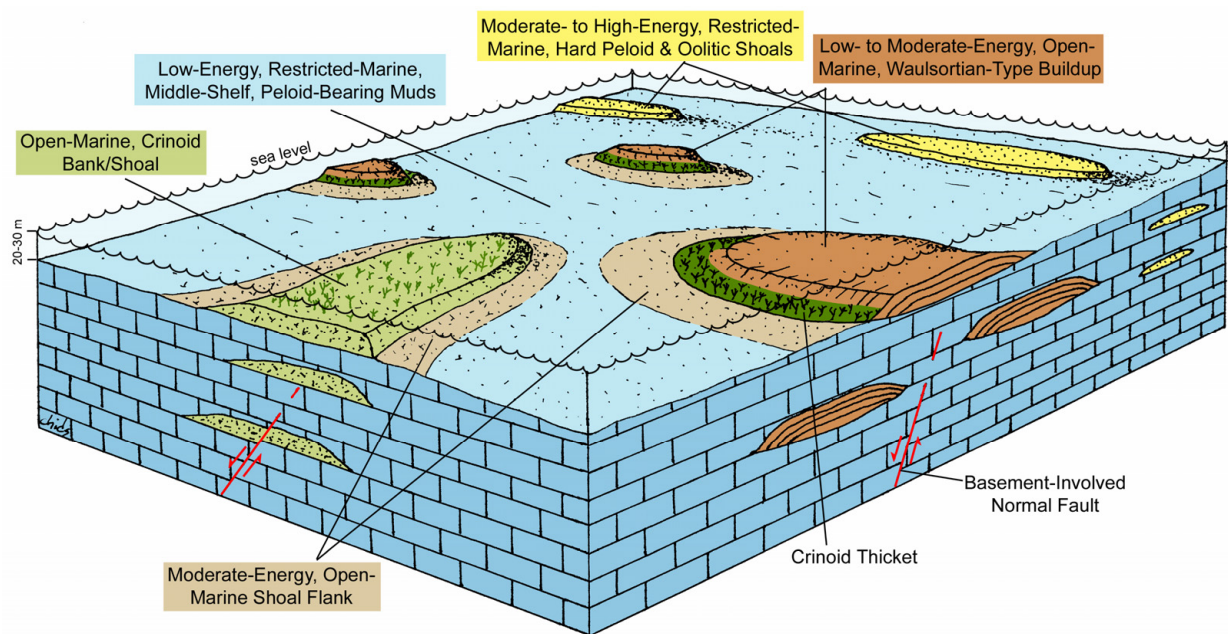


Figure 5. Block diagram displaying major depositional facies, as determined from core, for the Leadville Limestone, Lisbon field, San Juan County, Utah.

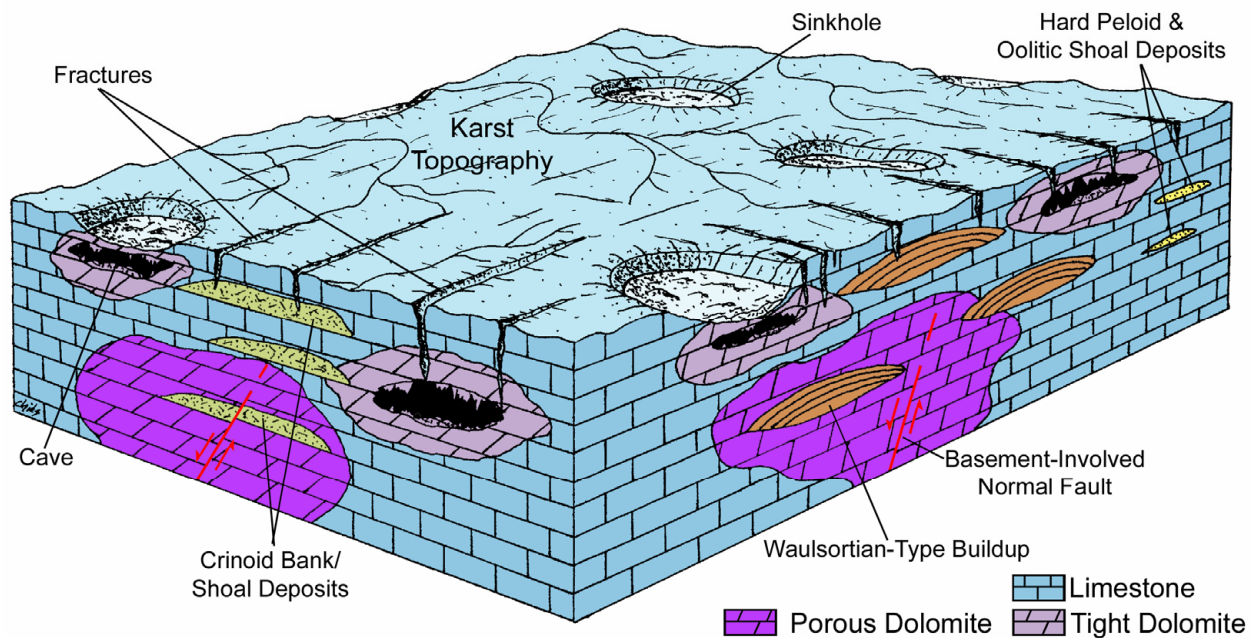


Figure 6. Block diagram displaying post-Leadville karst and fracture overprint.

The Leadville Limestone thins from more than 700 feet (230 m) in the northwest corner of the Paradox Basin to less than 200 feet (60 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 overlain by the Pennsylvanian Molas Formation and underlain by the Devonian Ouray Limestone (figure 2).

Periodic movement along northwest-trending faults affected deposition of the Leadville Limestone. Crinoid banks or mounds, the primary reservoir facies (figure 5), 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).

The Leadville Limestone is divided into two members separated by an intraformational disconformity. The dolomitic lower member is composed of mudstone, wackestone, packstone, and grainstone deposited in shallow-marine, subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids, fenestrate bryozoans, and brachiopods. Locally, mud-supported boundstone creates buildups or mud mounds (Waulsortian facies), involving growth of “algae” (Wilson, 1975; Ahr, 1989; Fouret, 1982, 1996). The upper member is composed of mudstone, packstone, grainstones (limestone and dolomite), and terrigenous clastics also deposited in subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids and rugose coral. Reservoir rocks are crinoid-bearing packstone (Baars, 1966).

LISBON CASE-STUDY FIELD, SAN JUAN COUNTY, UTAH

Introduction and Field Synopsis

Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project. This evaluation included data collection and thin section analysis which catalogued Leadville porosity types and diagenesis as summarized in this report.

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 7). Several minor, northeast-trending normal faults divide the Lisbon Leadville reservoir into segments.

Producing units in Lisbon field contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, 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 expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 133 to 189°F (56-87°C).

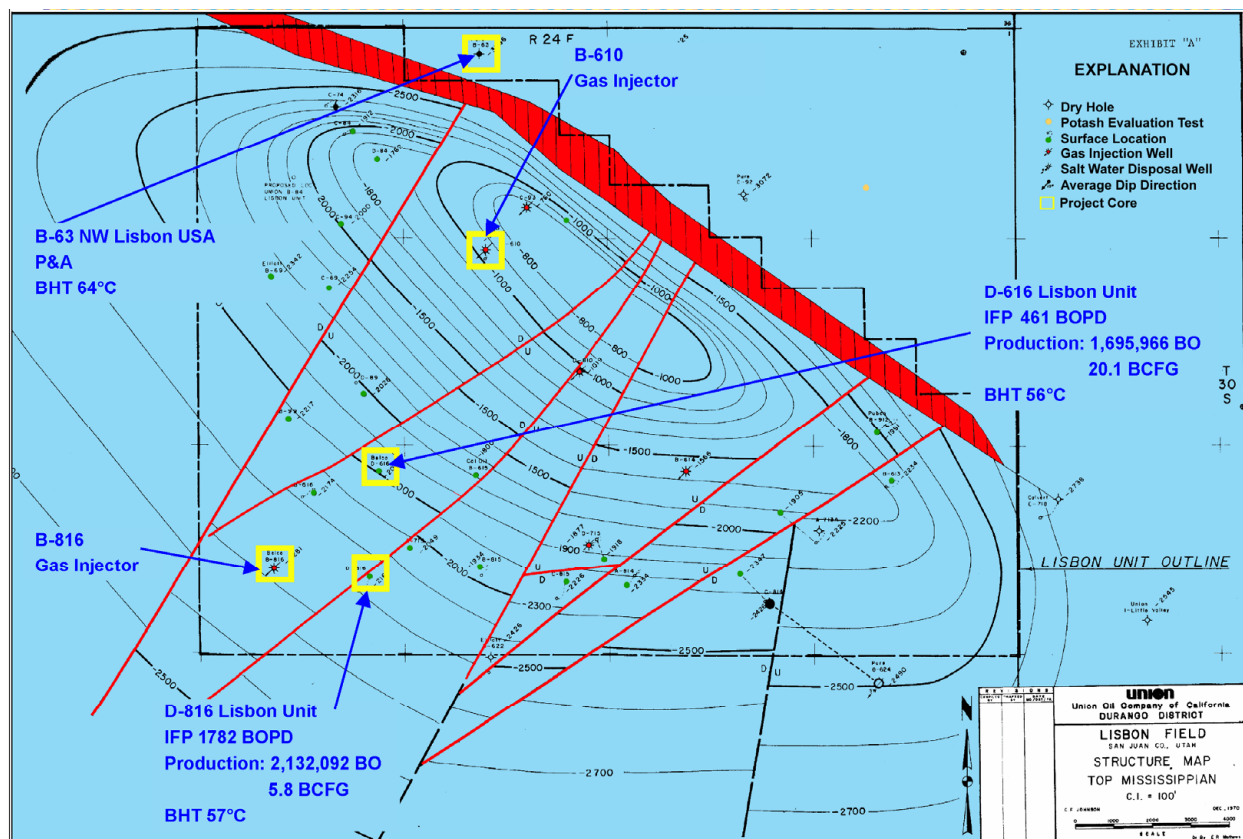


Figure 7. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). Also displayed are wells from which cores were described in this study.

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., SLBL&M (figure 7), with an initial flowing potential of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (psi [$20,560 \text{ kPa}$]) (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 March 31, 2006, was 51,145,231 bbls of oil ($8,132,092 \text{ m}^3$), 785.4 billion cubic feet of gas (BCFG) (22.2 BCMG) (cycled gas), and 50,073,622 bbls of water ($7,961,706 \text{ m}^3$) (Utah Division of Oil, Gas and Mining, 2006). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Data Collection and Compilation

Geophysical well logs, cores and cuttings, reservoir data, various reservoir maps, and other information from Lisbon field development wells were collected by the UGS. Well locations, formation tops, production data, completion tests, basic core analysis, porosity and permeability data, and other data were compiled and entered in a database developed by the UGS. This database, INTEGRAL, is a geologic-information database that links a diverse set of geologic data to records using MS AccessTM. The database is designed so that geological information, such as lithology, petrophysical analyses, or depositional environment, can be exported to software programs to produce cross sections, strip logs, lithofacies maps, various graphs, and other types of presentations. The database containing information on the geological reservoir characterization case study as well as later regional correlations will be available at the UGS's Leadville Limestone project Web site at the conclusion of the project.

DIAGENETIC ANALYSIS

Techniques

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Lisbon field can be indicators of reservoir flow capacity, storage capacity, and untested potential. In order to determine the diagenetic histories of the various Leadville rock fabrics, including both reservoir and non-reservoir, 82 thin sections of representative samples were selected from the conventional cores for petrographic description and possible geochemical analysis (table 1 and Appendix). Carbonate fabrics were again determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. Pores and pore systems were described using Choquette and Pray's (1970) classification (figure 8). Each thin section was photographed with additional close-up photos of (1) typical preserved primary and secondary pore types, (2) cements, (3) sedimentary structures, (4) fractures, and (5) where present, pore-plugging anhydrite and halite.

Typical geochemical and petrographic techniques that may be later employed include (1) epifluorescence and cathodoluminescence petrography for the sequence of diagenesis, (2) stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites, (3) strontium isotopes for tracing the origin of fluids responsible for different diagenetic events, (4) scanning electron microscope analysis of

Table 1. List of well conventional slabbed core examined and described from the Leadville Limestone, Lisbon field, San Juan County, Utah.*

Well	Location	API No.	Core Interval (feet)	Thin Sections
Lisbon D-816	NE SE 16, T. 30 S., R. 24 E.	43-037-16253	8417-8450	15
Lisbon D-616	C NE NE 16, T. 30 S., R. 24 E.	43-037-15049	8300-9110	13
NW Lisbon B-63	NE NW 3, T. 30 S., R. 24 E.	43-037-11339	9934-10,005	14
Lisbon B-816	NE SW 16, T. 30 S., R. 24 E.	43-037-16244	8463-8697	22
Lisbon B-610	NE NW 10, T. 30 S., R. 24 E.	43-037-16469	7590-8001.5	18

*Repository: Utah Core Research Center.

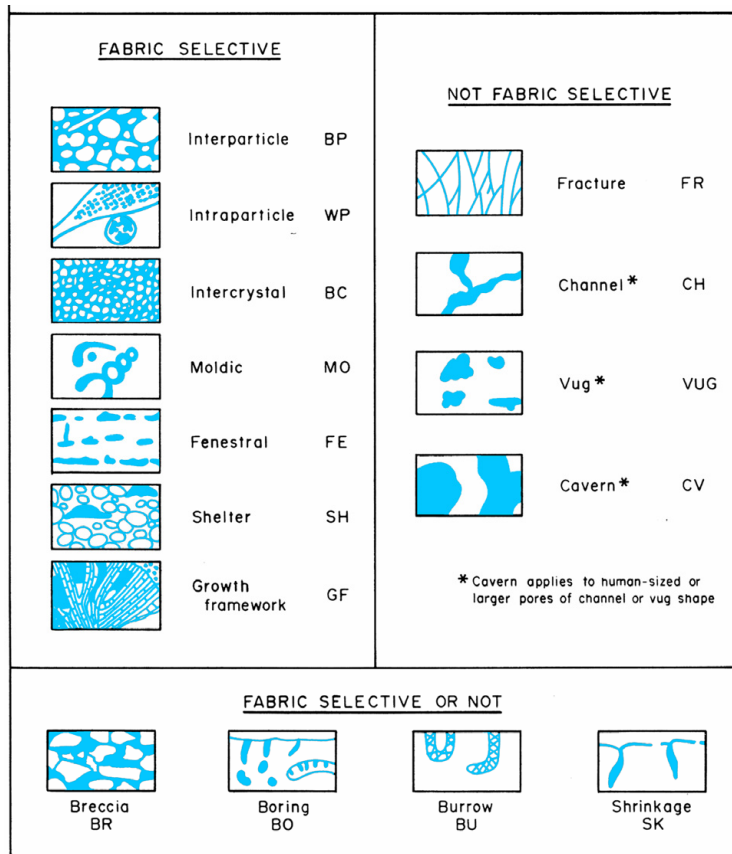


Figure 8. Classification of pores and pore systems in carbonate rocks (Choquette and Pray, 1970).

various dolomites to determine reservoir quality of the dolomites as a function of diagenetic history, (5) fluid inclusion evaluation to determine the temperatures of secondary dolomite formation and the salinity of the original brines, and (6) analysis of the bitumen plugging pore throats.

Reservoir diagenetic fabrics and porosity types of these carbonate buildups were analyzed to (1) determine the sequence of diagenetic events, (2) predict facies patterns, and (3) provide data input for reservoir modeling studies. Diagenetic characterization focused on reservoir heterogeneity, quality, and compartmentalization within the field. All depositional, diagenetic, and porosity information will be combined with the production history in order to analyze the potential for the Leadville Limestone regionally.

Results

An ideal diagenetic sequence based on our analysis of Leadville thin sections from Lisbon field is presented in figure 9. The early diagenetic history of the Leadville sediments, including some early dolomitization and leaching of skeletal grains, resulted in low-porosity and/or low-permeability rocks. Most of the porosity and permeability associated with hydrocarbon production was developed during deeper subsurface dolomitization and dissolution. Some of these important subsurface processes are shown with the purple bars in figure 9 and are discussed below generally in the order in which they occur.

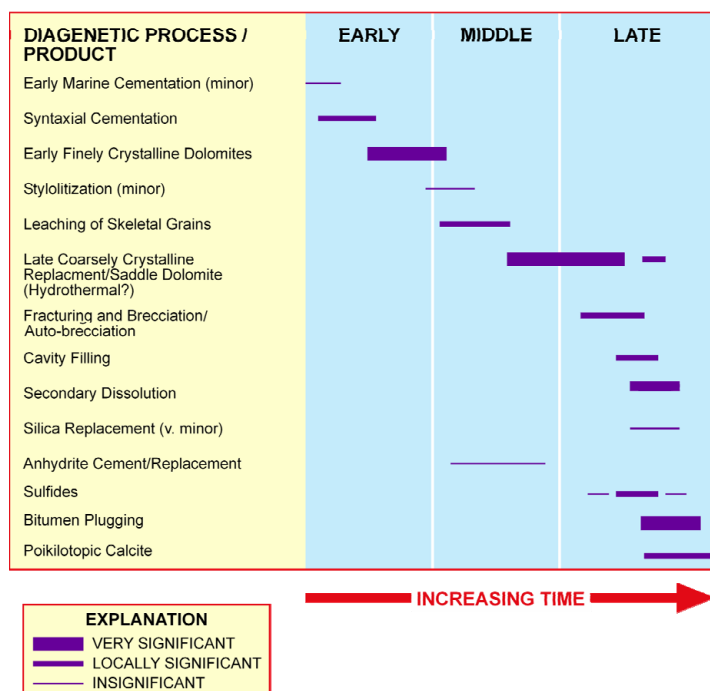


Figure 9. Ideal diagenetic sequence through time based on thin section analysis, Leadville Limestone, Lisbon field.

Syntaxial Cement

Syntaxial cementation is an early diagenetic event (figure 9). This type of cementation is found exclusively as overgrowths on echinoderms (figure 10), in this case dominantly crinoids deposited in banks or shoals of the open-marine facies. Crinoid ossicles often appear to be “floating” in cement with little evidence of compaction. If extensive syntaxial cementation has occurred, the result will be a significant reduction of porosity. However, from the thin sections evaluated, it appears that this diagenetic process has been relatively minor.

Dolomitization and Porosity Development

Two basic types of dolomite have been seen within the cores (figure 11A). The first type consists of “stratigraphic” dolomites that preserve original depositional grains and textures. Very fine ($<5\ \mu$), interlocking dolomite crystals with no intercrystalline pore spaces are the norm (figure 11B). Commonly, this type of dolomite can be correlated across the field in several relatively thin intervals. The second type of dolomite is a much coarser ($>100\ \mu$), later replacement of all types of limestone and earlier “stratigraphic” dolomites (figure 11C). Crosscutting relationships with carbonate bedding and variable dolomite thickness across the field are common. Petrographically, the coarse, second dolomite type consists of crystals with thick, cloudy, inclusion-rich cores and thin, clear overgrowths with planar crystal terminations. Commonly, these coarser dolomites show saddle dolomite characteristics of curved crystal shape (figure 12) and sweeping extinction under cross-polarized lighting. Predating or concomitant with saddle dolomite formation, are pervasive leaching and dissolution episodes that crosscut the carbonate host rocks, and result in late vugs, as well as extensive microporosity. Pyrobitumen appears to coat most intercrystalline dolomite, as well as dissolution pores associated with the second type of dolomite. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.

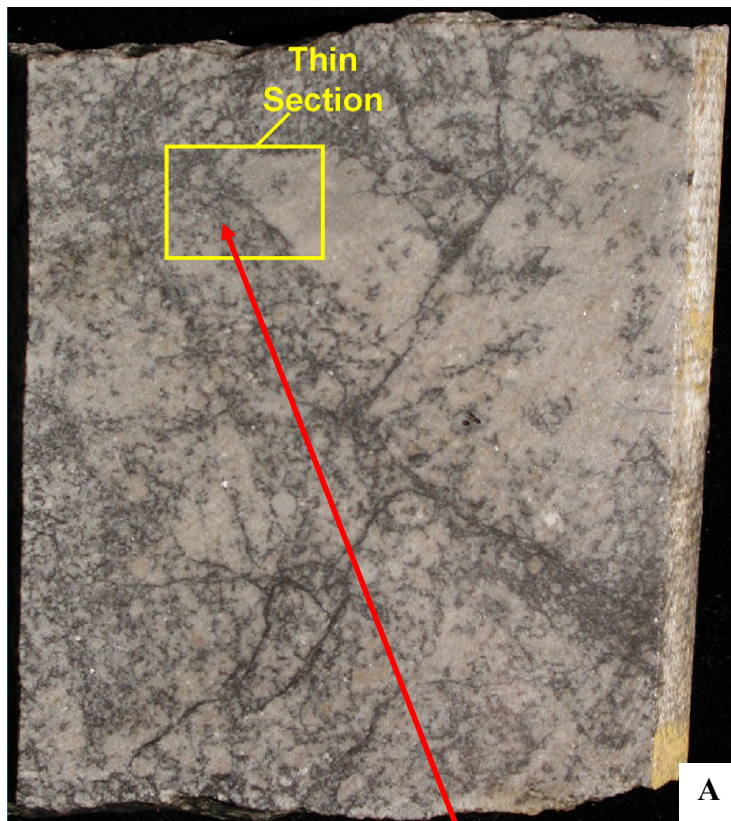
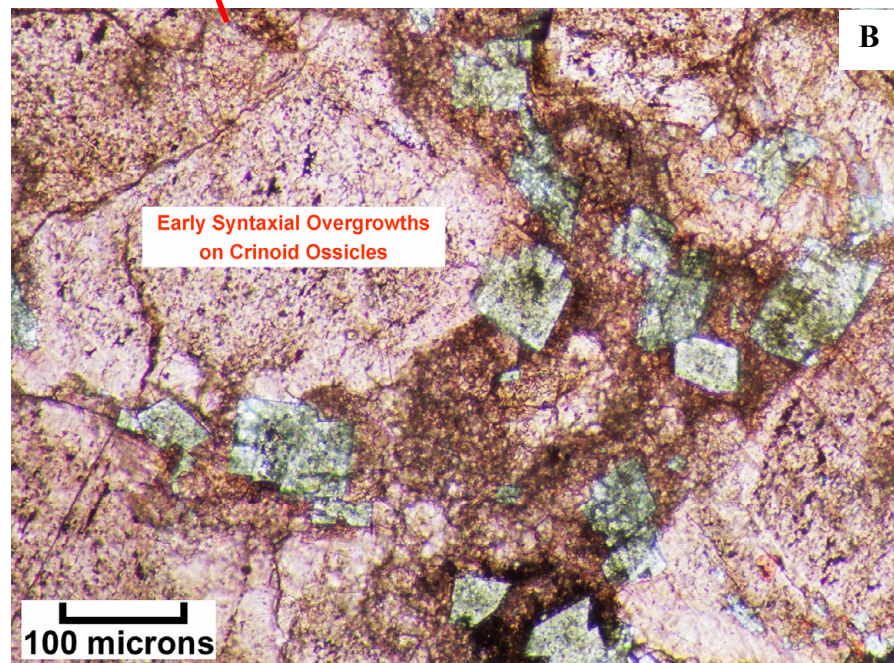


Figure 10. (A) Conventional core slab showing partially dolomitized crinoidal/grainstone packstone. (B) Representative photomicrograph (plane light) from the core in A, showing early syntaxial overgrowths on crinoid ossicles. Crinoids appear cloudy due to inclusions of organic matter. Lisbon No. D-816 well (figure 7), 8435 feet, porosity = 7.5 percent, permeability = 0.03 mD.



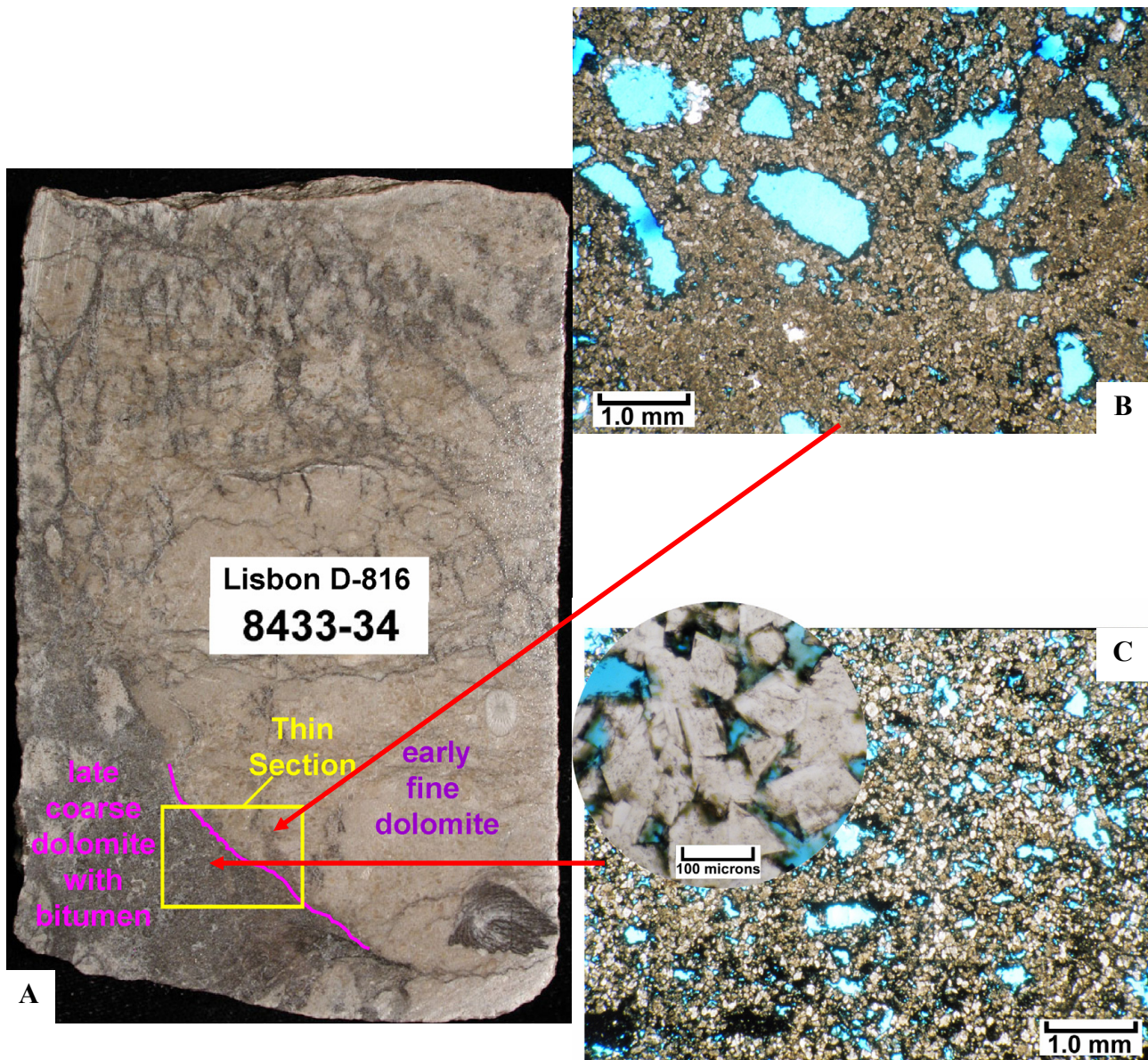


Figure 11. (A) Conventional core slab showing tight, fabric selective, very fine early dolomite as well as porous, coarser late dolomite. Most of the late dolomite crystal faces are coated with films of pyrobitumen. Hence, most of the areas of crosscutting coarser dolomites are black in this view. Note the position of the thin section which captures the contact between low-permeability early dolomite (upper right part of the thin section box) and high-permeability late, “black dolomite” (lower left). (B) 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. (C) Representative photomicrograph (plane light) of the coarser, replacement dolomite (both euhedral rhombs and a few “saddle” overgrowths [close-up view in inset]). The black (opaque) areas are the result of pyrobitumen films and minor sulfide precipitation. Lisbon No. D-816 well (figure 7), 8433 feet, porosity = 2 percent, permeability <0.1 mD.

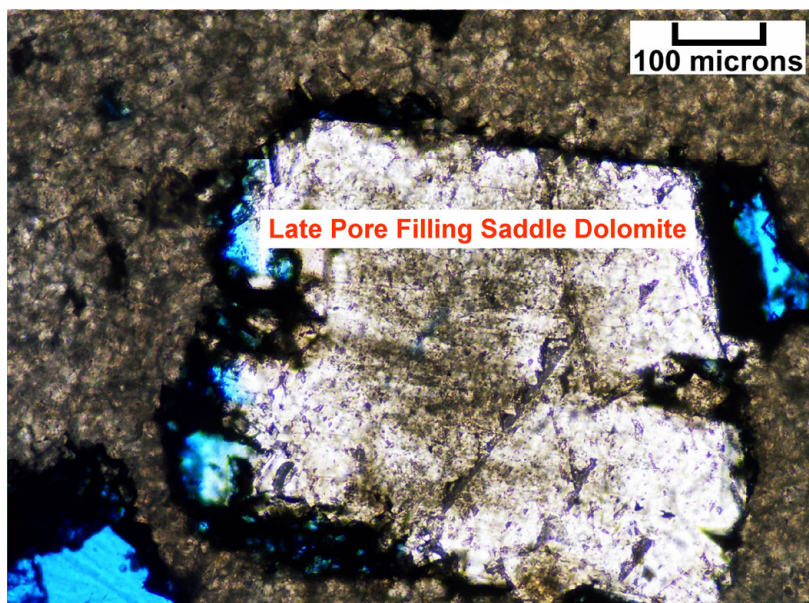


Figure 12. Thin section photomicrograph (plane light) showing a saddle dolomite cement that is filling a large pore (either a grain mold or small vug). The dolomite cement has been surrounded by a coating of pyrobitumen (in black). It appears that this late dolomite cement has been partially dissolved or corroded around its margins after the bitumen coating. Lisbon No. D-816 well (figure 7), 8421 feet, porosity = 8.3 percent, permeability = 34 mD.

Later dolomitization, saddle dolomite, and dolomite cement precipitation may have occurred at progressively higher temperatures, that is, hydrothermal dolomite. Hydrothermal events can improve reservoir quality by increasing porosity through dolomitization, leaching, development of microporosity, and natural fracturing (forming breccia) kept open with various minerals (Smith, 2004). Hydrothermal dolomite precipitates under temperature and pressure conditions greater than the ambient temperature and pressure of the host limestone (Davies, 2004). The result can be the formation of large, diagenetic-type hydrocarbon traps. Further geochemical analysis is planned to confirm the presence of hydrothermal dolomite in the Leadville Limestone at Lisbon field and the reservoir potential it would imply for the Paradox Basin.

Post-Burial Brecciation

Fracturing and brecciation are quite common within Lisbon field (figure 13 through 15). However, brecciation is most commonly caused by hydrofracturing, creating an explosive-looking, pulverized rock. The result yields an “autobreccia” as opposed to a collapse breccia. Clasts within an autobreccia have basically remained in place and moved very little. Dolomite clasts are commonly surrounded by solution-enlarged fractures partially filled with coarse rhombic and saddle dolomites that are coated with pyrobitumen. Areas between clasts can exhibit very good intercrystalline porosity or microporosity, or they may be filled by low-porosity saddle dolomite cement. Intense bitumen plugging is concurrent or takes place shortly after brecciation. “Reike,” or stair-step fractures, are occasionally present, reflecting shear and the explosive fluid expulsion from the buildup of pore pressure.

Karst-Related Processes

Sediment-filled cavities are relatively common throughout the upper third of the Leadville in Lisbon field (figure 16). These cavities or cracks were related to karstification of the exposed Leadville (figure 6). Infilling of the cavities by detrital carbonate and siliciclastic

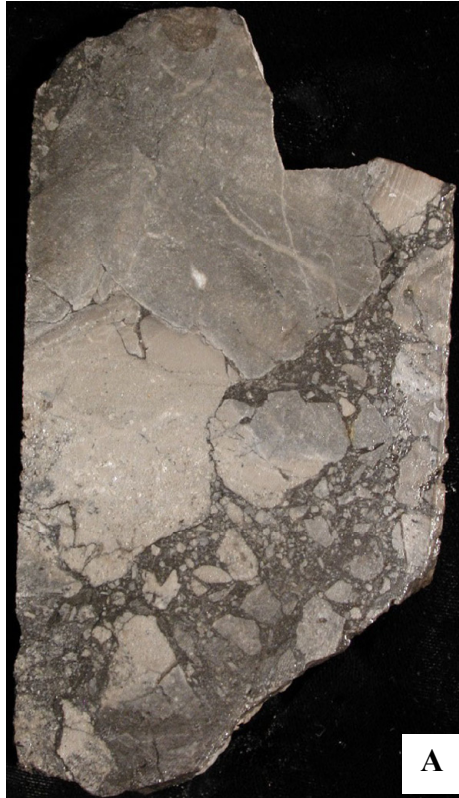
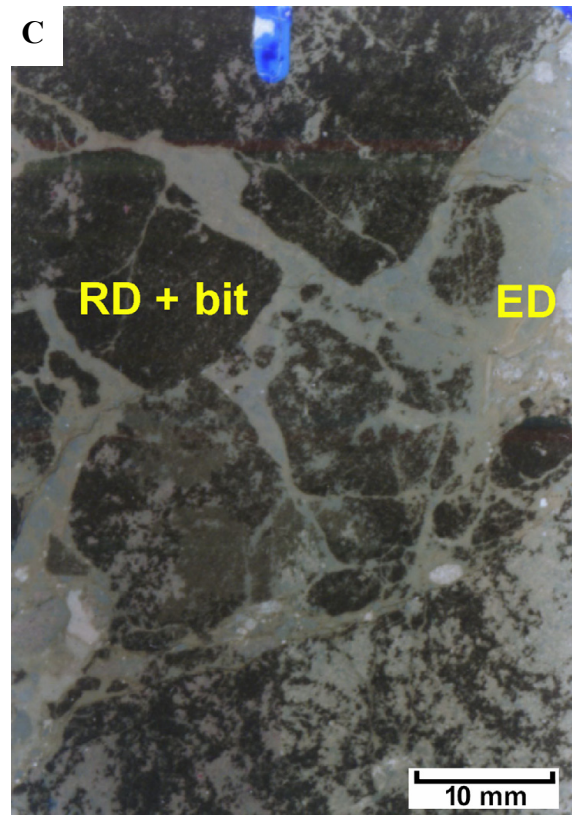
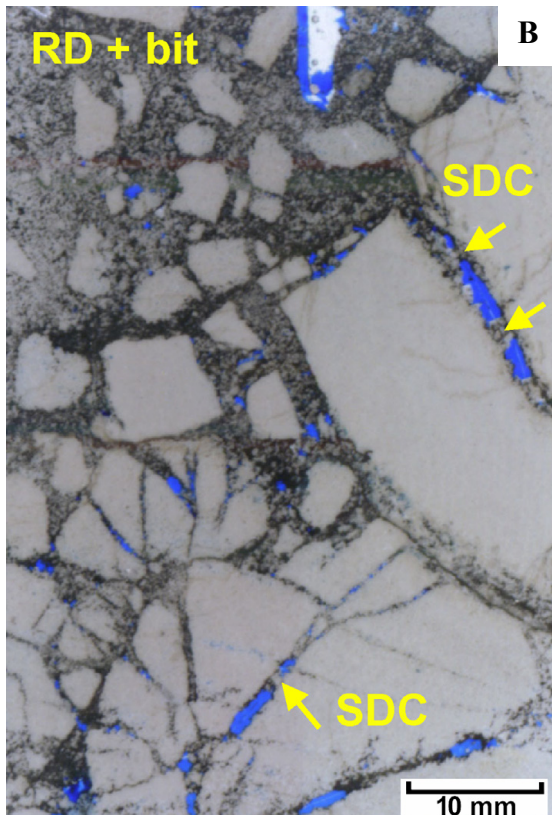
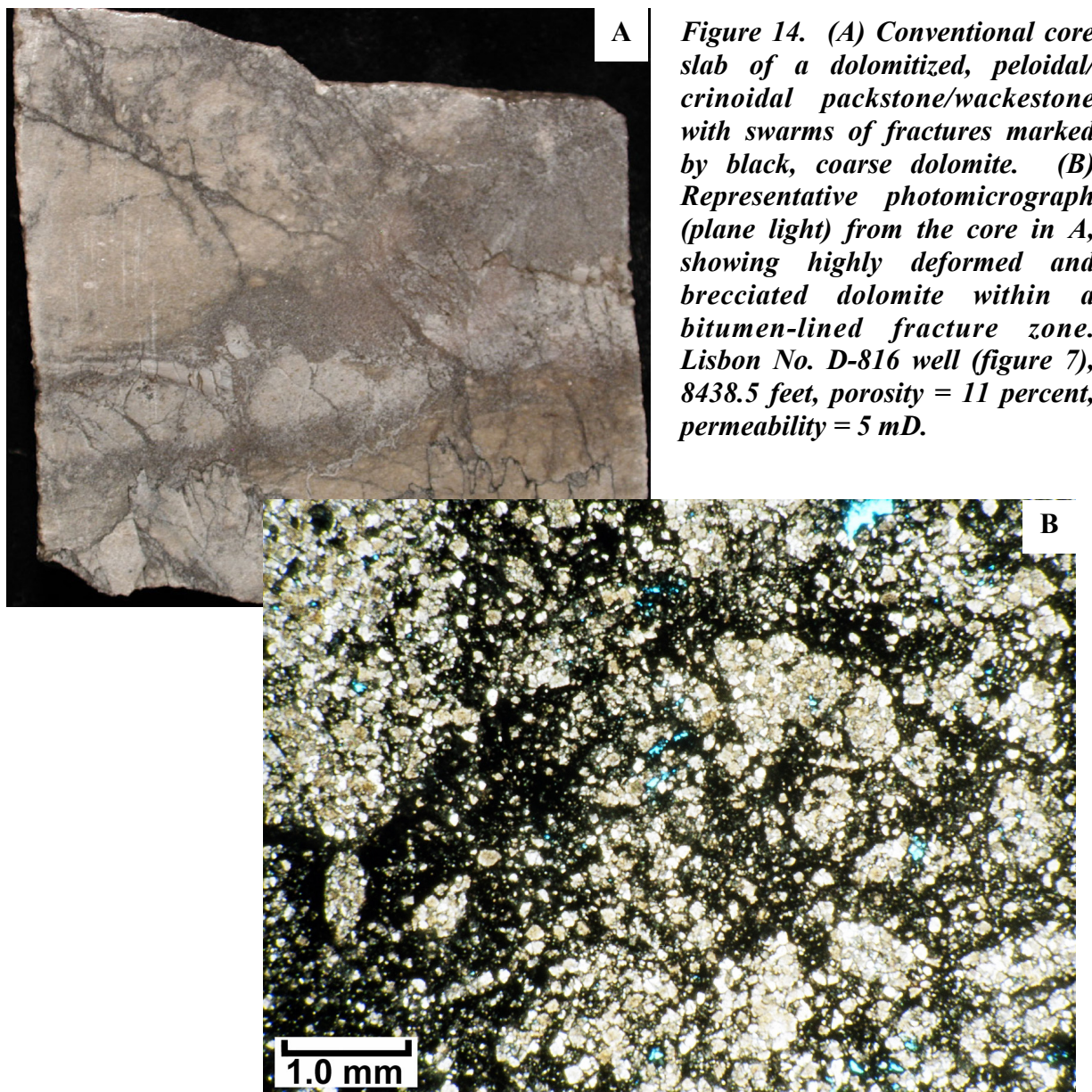


Figure 13. (A) Conventional core slab showing a dolomite “autobreccia” in which the clasts have moved very little. The black material surrounding the in-place clasts is composed of porous late dolomite coated with pyrobitumen. (B) Entire thin section overview from the core in A, showing low-porosity, white dolomite clasts surrounded by solution-enlarged fractures partially filled with coarse rhombic (RD) and saddle dolomites that are coated with pyrobitumen (bit). These black areas between the clasts exhibit very good intercystalline porosity. The open fracture segments (in blue) between clasts are bridged by coarse, saddle dolomite cements (SDC). (C) Entire thin section overview from the core in A, of black, porous, dolomite clasts surrounded in this case by coarse, low-porosity saddle dolomites. These white dolomites were probably early dolomite (ED) filling space between possible “hydrofractured” replacement dolomites. The black porous dolomites are mostly rhombic (planar) dolomites (RD) coated with thin films of pyrobitumen (bit). Lisbon NW USA No. B-63 well (figure 7), 9938.3 feet, porosity = 6.4 percent, permeability = 54 mD.





sediments occurred before the deposition of the Pennsylvanian Molas Formation. The contact between the transported material and the country rock can be sharp, irregular, and corroded with small associated mud-filled fractures. The transported material consists of poorly sorted detrital quartz grains (silt size), chert fragments, carbonate clasts, clay, and a few clasts of mud balls (desiccated and cracked). The carbonate muds infilling the karst cavities are largely dolomitized (a later diagenetic process), very finely crystalline, and non-porous. The infilling some times displays a crude layering in places.

Other karst features observed in Leadville thin sections include the presence of “root hair” – thin, sinuous cracks filled with dolomitized mud. Clasts also may have a coating of clay. Both of these features are evidence of a possible, nearby soil zone.

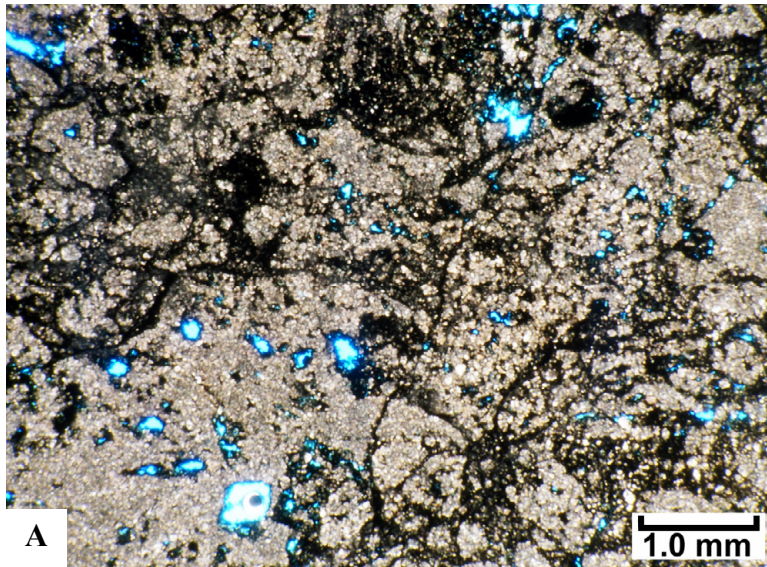
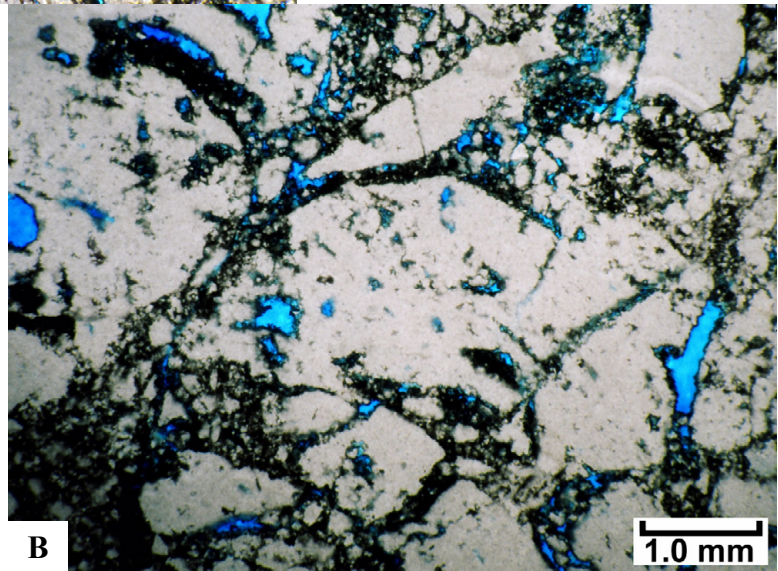


Figure 15. (A) Representative photomicrograph (plane light), showing another example of intensely brecciated dolomite within a bitumen-lined fracture zone. (B) Representative photomicrograph (plane light), showing large autoclasts and bitumen in an intensely brecciated dolomite. Lisbon No. D-816 well (figure 7), 8423 feet, porosity = 10.5 percent, permeability = 47 mD.



Anhydrite and Sulfides

Dissolution pores (molds) and pore throats are in places plugged or bridged by lathes of late anhydrite cement (figure 17). In the photomicrographs studied, complete plugging of porosity was rare and the overall presence of anhydrite cement and replacement was relatively insignificant for the Leadville Limestone in the Lisbon reservoir rocks.

Possible sulfide minerals are observed in several Leadville thin sections (figure 18). They appear as small, angular, brassy crystals. They tend to line moldic pores or form on, and between, rhombic dolomite crystals. These minerals may be associated with hydrothermal fluids responsible for the coarse saddle dolomites. They may also be related to copper mineralization found a few miles to the east at the Lisbon Valley copper mine. The copper deposit includes fracture filling and disseminated copper sulfides (chalcocite, bornite, and covellite) replacing dead oil and pyrite (J.P. Thorson, Summo Minerals, verbal communication, September 20, 1996). The exact nature and composition of the sulfide minerals at Lisbon field is unknown and will be examined in closer detail with the scanning electron microscope later in the reservoir characterization.

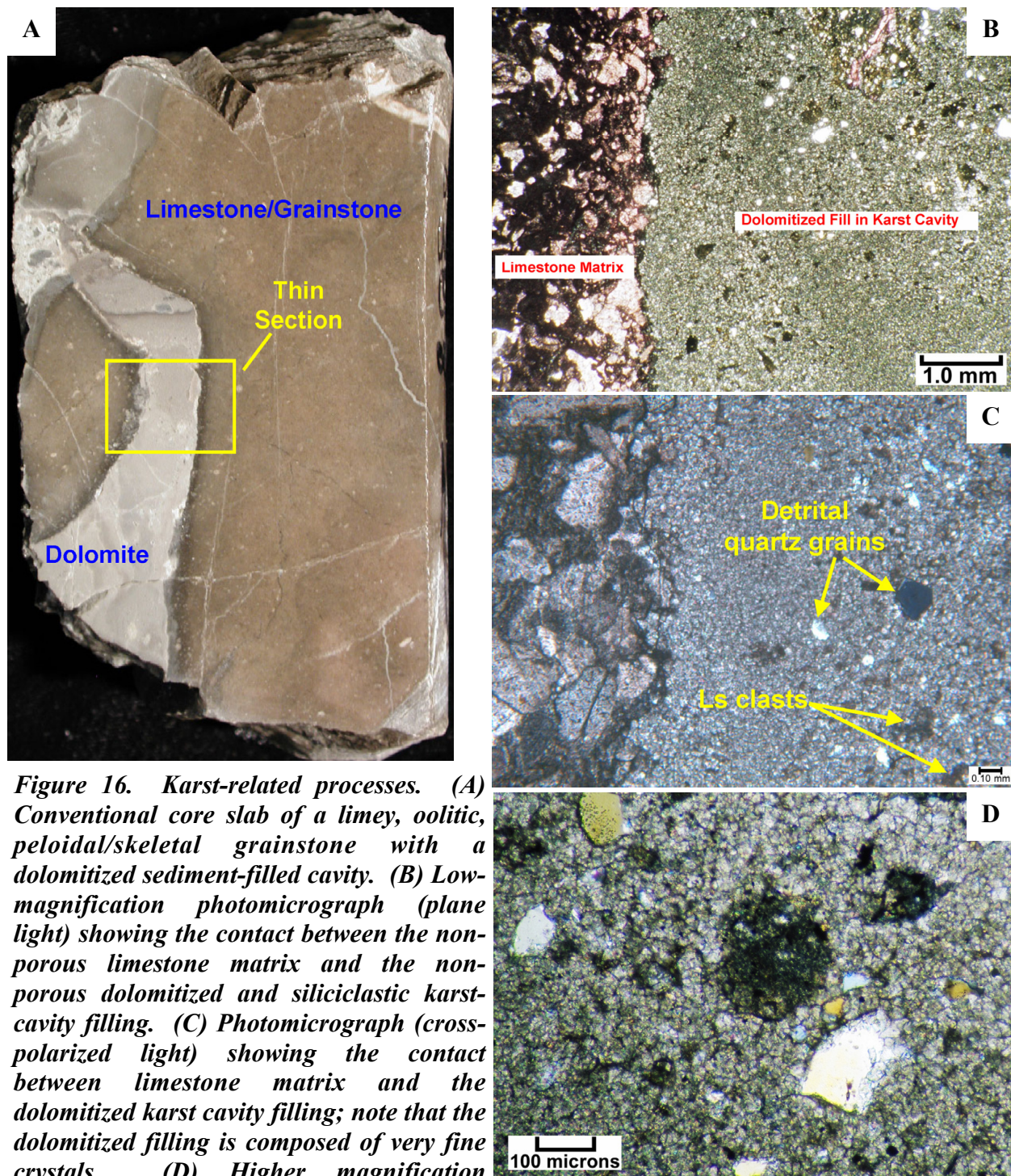


Figure 16. Karst-related processes. (A) Conventional core slab of a limey, oolitic, peloidal/skeletal grainstone with a dolomitized sediment-filled cavity. (B) Low-magnification photomicrograph (plane light) showing the contact between the non-porous limestone matrix and the non-porous dolomitized and siliciclastic karst-cavity filling. (C) Photomicrograph (cross-polarized light) showing the contact between limestone matrix and the dolomitized karst cavity filling; note that the dolomitized filling is composed of very fine crystals. (D) Higher magnification photomicrograph (plane light) of detrital quartz grains (white) and small carbonate clasts (dark gray) within the tight, dolomitized mud filling the karst cavity. Lisbon No. D-616 well (figure 7), 8308-8309 feet, porosity = 1.2 percent, permeability = 11.1 mD.

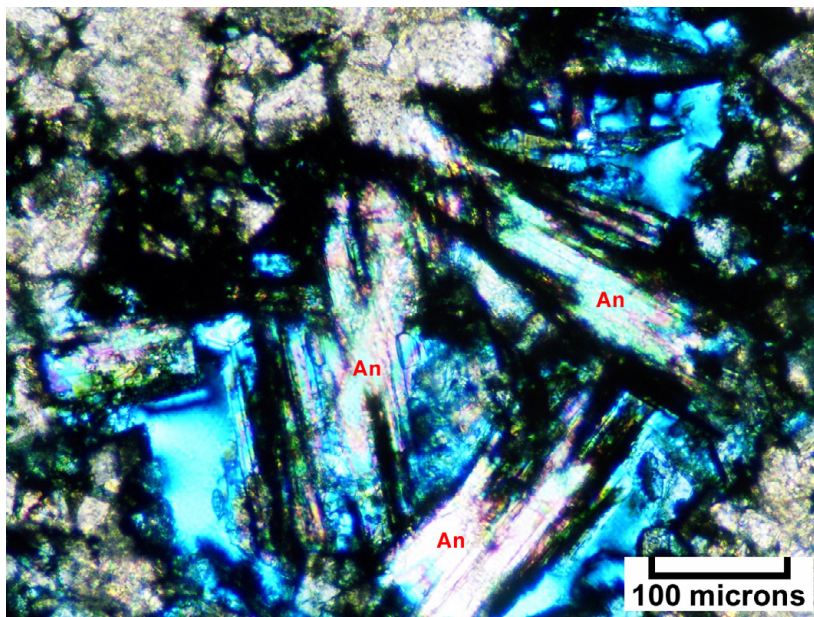


Figure 17. Representative photomicrograph (cross-polarized light) showing lathes of late anhydrite cement (An, in the pastel colors) filling a dissolution pore. The unfilled portions of the pore are seen in the blue areas. Lisbon No. D-816 well (figure 7), 8426-8431 feet, porosity = 11.1 percent, permeability = 15 mD.

Late Macrocalcite

Macrocalcite, also referred to as poikilotopic calcite, is viewed as late, large, slow-growing crystals (figure 19), and although not extensive in the Leadville at Lisbon field, its presence provides some significant insight into the diagenetic history of these rocks. The example shown in figure 19 shows an autobreccia that retains small amounts of early, finely crystalline (tight) dolomite replaced by “mini-saddles” and medium crystalline (euhedral) dolomite. Early during this sample’s history, it had intercrystalline porosity that was enhanced by dissolution to form additional pores. Subsequently, the pores were partially filled with coarsely crystalline saddle dolomite and bitumen. Finally, the remaining solution-enlarged pores were occluded by poikilotopic calcite. Poikilotopic calcite may have formed as oil-field water rose, following the gas/condensate cap.

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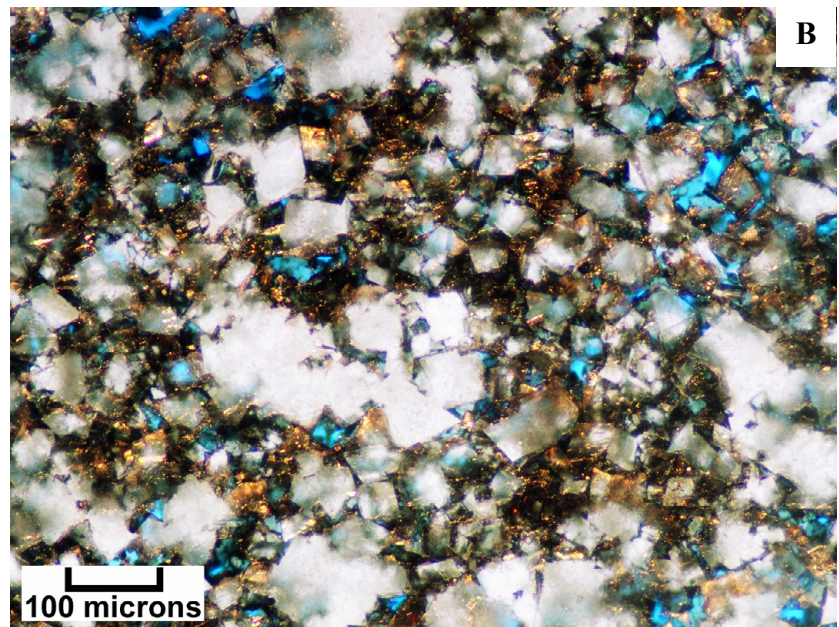
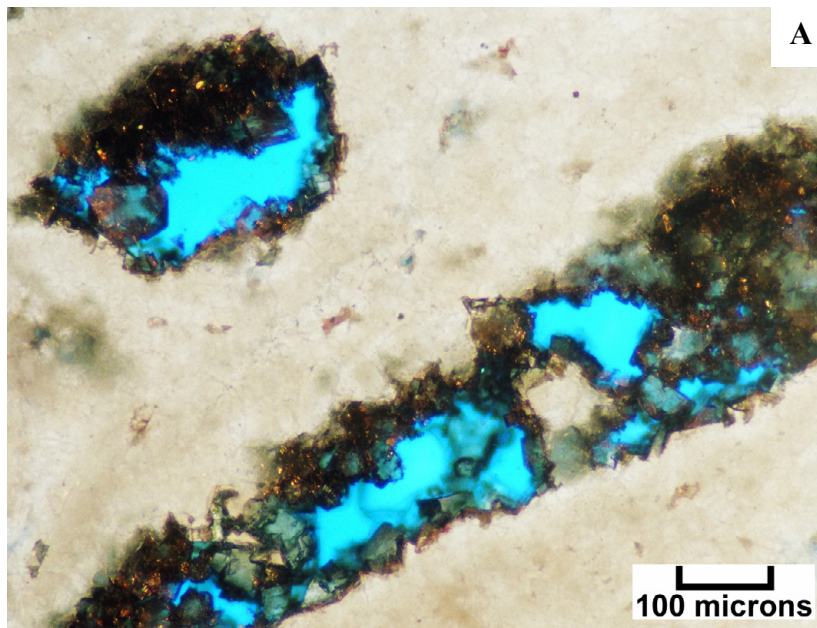
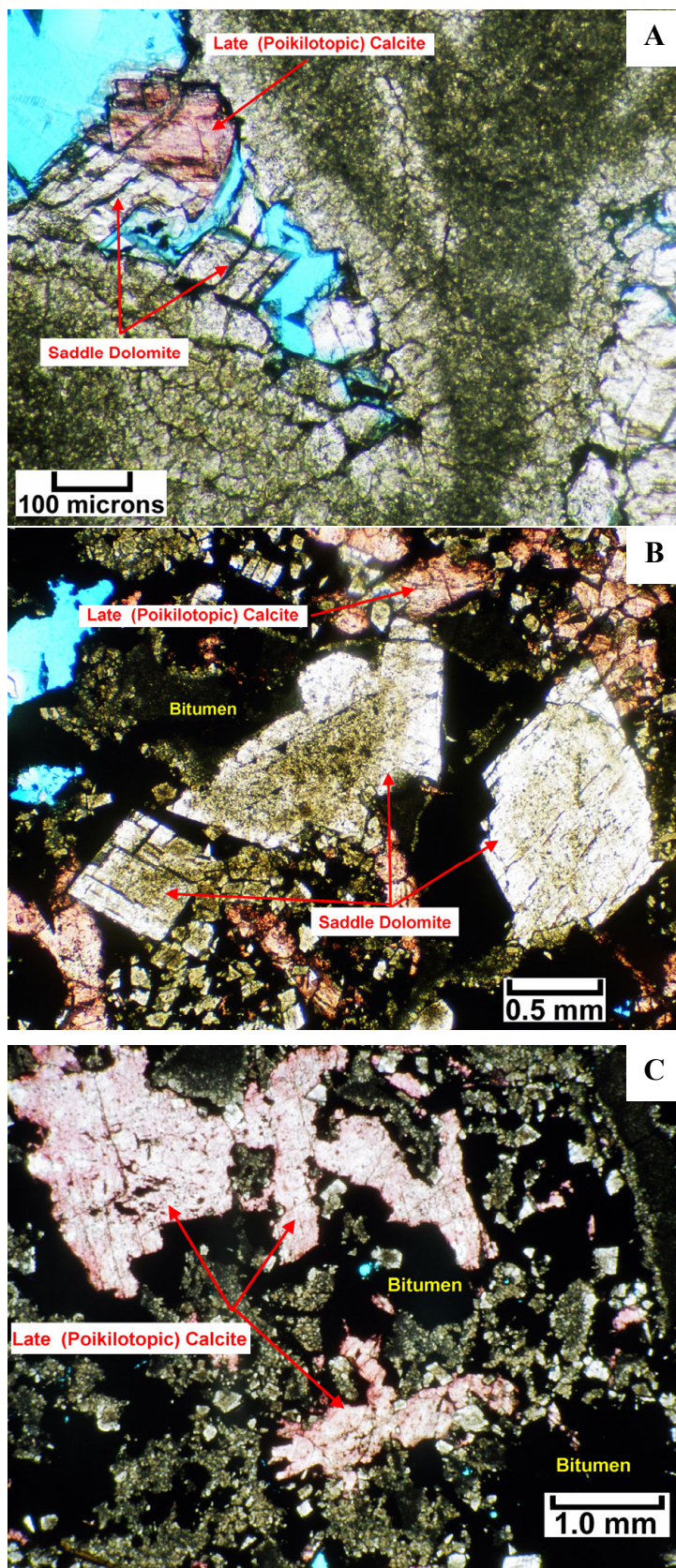


Figure 18. Possible sulfide mineralization within the Leadville Limestone at Lisbon field. (A) Photomicrograph (“white card” and reflected light) showing moldic pore lined with black pyrobitumen and possible sulfide minerals (small brassy crystals). Lisbon No. D-816 well (figure 5), 8444-8445 feet, porosity = 6.6 percent, permeability = 7 mD. (B) Photomicrograph (“white card” and reflected light) showing black pyrobitumen and sulfide minerals on and between rhombic dolomite crystals (in white and light gray). Lisbon No. D-816 well (figure 7), 8446-8447 feet, porosity = 13 percent, permeability = 59 mD.

Figure 19. (A) Photomicrograph (plane light) showing saddle dolomite crystals and a single late macrocalcite crystal (stained red) filling a portion of a large dissolution pore (blue) in a finely crystalline dolomite matrix. Northwest Lisbon No. B-63 well (figure 5), 9991.8 feet, porosity = 6.2 percent, permeability = 0.3 mD. (B) Photomicrograph (plane light) showing coarse rhombic and saddle replacement dolomite that displays cloudy cores and clear rims. Dissolution pores are filled with pyrobitumen (black) and late macrocalcite (stained red). An additional episode of dissolution can be seen as the open (blue) pores that appear to post-date most of the pyrobitumen emplacement. (C) Dissolution pores filled completely with bitumen (black) and late macrocalcite (stained red) that resemble saddle dolomite molds. B and C from Northwest Lisbon No. B-63 well (figure 7), 10,004-10,005 feet, porosity = 14.4 percent, permeability = 1.9 mD.



REFERENCES

- Ahr, W.M., 1989, Mississippian reef facies in the Southwest—a spectrum of variations in depositional style and reservoir characteristics: Ft. Worth Geological Society and Texas Christian University, Symposium on the Petroleum Geology of Mississippian Carbonates in North Central Texas, p. 1-19.
- Baars, D.L., 1966, Pre-Pennsylvanian paleotectonics—key to basin evolution and petroleum occurrences in the Paradox Basin, Utah and Colorado: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2082-2111.
- Choquette, P.W., and Pray, L.C., 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: American Association of Petroleum Geologists Bulletin, v. 54, no. 2, p. 207-250.
- Clark, C.R., 1978, Lisbon, San Juan County, Utah, *in* Fassett, J.E., editor, Oil and gas fields of the Four Corners area: Four Corners Geological Society, v. II, p. 662-665.
- Davies, G.R., 2004, Hydrothermal (thermobaric) dolomite and leached limestone reservoirs – general principles, genetic connections, and economic significance in Canada [abs]: American Association of Petroleum Geologists Annual Convention, Official Program with Abstracts, v. 13, p. A32.
- Doelling, H.H., 2000, Geology of Arches National Park, Grand County, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association Publication 28, p. 11-36.
- Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W.E., editor, Classification of carbonate rocks: American Association of Petroleum Geologists Memoir 1, p. 108-121.
- Embry, A.R., and Klován, J.E., 1971, A Late Devonian reef tract on northeastern Banks Island, Northwest Territories: Canadian Petroleum Geologists Bulletin, v. 19, p. 730-781.
- Fouret, K.L., 1982, Depositional and diagenetic environment of the Mississippian Leadville Formation at Lisbon field, Utah: College Station, Texas A&M University, M.S. thesis, 119 p.
- 1996, Depositional and diagenetic environment of the Mississippian Leadville Limestone at Lisbon field, Utah, *in* Huffman, A.C., Jr., Lund, W.R., and Godwin, L.H., editors, Geology and resources of the Paradox Basin: Utah Geological Association Publication 25, p. 129-138.
- Harry, D.L., and Mickus, K.L., 1998, Gravity constraints on lithospheric flexure and the structure of the late Paleozoic Ouachita orogen in Arkansas and Oklahoma, south-central North America: Tectonics, v. 17, no. 2, p. 187-202.

- Hintze, L.F., 1993, Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.
- Johnson, C.F., 1970, Top of structure of the Leadville Limestone, Lisbon field: unpublished map, Union Oil Company of California files.
- Kluth, C.F., 1986, Plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J.A., editor, Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 353-369.
- Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: *Geology*, v. 9, p. 10-15.
- Morgan, C.D., 1993, Mississippian Leadville Limestone, *in* Hjellming, C.A., editor, Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, p. 94.
- Parker, J.W., and Roberts, J.W., 1963, Devonian and Mississippian stratigraphy of the central part of the Colorado Plateau: Four Corners Geological Society, 4th Field Conference Guidebook, p. 31-60.
- Petroleum Information, 1984, Paradox Basin—unravelling the mystery: *Petroleum Frontiers*, v. 1, no. 4, p. 22.
- Smith, K.T., and Prather, O.E., 1981, Lisbon field – lessons in exploration, *in* Wiegand, D.L., editor, *Geology of the Paradox Basin: Rocky Mountain Association of Geologists Guidebook*, p. 55-59.
- Smith, L.B., 2004, Hydrothermal alteration of carbonate reservoirs – how common is it? [abs.]: American Association of Petroleum Geologists Annual Convention, Official Program with Abstracts, v. 13, p. A130.
- Smouse, DeForrest, 1993, Lisbon, *in* Hill, B.G., and Bereskin, S.R., editors, *Oil and gas fields of Utah: Utah Geological Association Publication 22*, non-paginated.
- Stevenson, G.M., and Baars, D.L., 1987, The Paradox—a pull-apart basin of Pennsylvanian age, *in* Campbell, J.A., editor, *Geology of Cataract Canyon and vicinity: Four Corners Geological Society, 10th Field Conference*, p. 31-55.
- Utah Division of Oil, Gas and Mining, 2006, Oil and gas production report, March: Online, <http://www.ogm.utah.gov/oilgas/PUBLICATIONS/Reports/PROD_book_list.htm>, accessed July 25, 2006.
- Welsh, J.E., and Bissell, H.J., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Utah: U.S. Geological Survey Professional Paper 1110-Y, 35 p.
- Wilson, J.L., 1975, *Carbonate facies in geologic history*: New York, Springer-Verlag, 471 p.

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