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DELIVERABLE 1-3B SCANNING ELECTRON MICROSCOPY, EPIFLUORESCENCE, CATHODOLUMINESCENCE, FLUID INCLUSIONS, AND ISOTOPIC STUDIES: LISBON FIELD, SAN JUAN COUNTY, UTAH

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

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FLUID INCLUSIONS, AND ISOTOPIC
STUDIES: LISBON FIELD,
SAN JUAN COUNTY, UTAH**



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

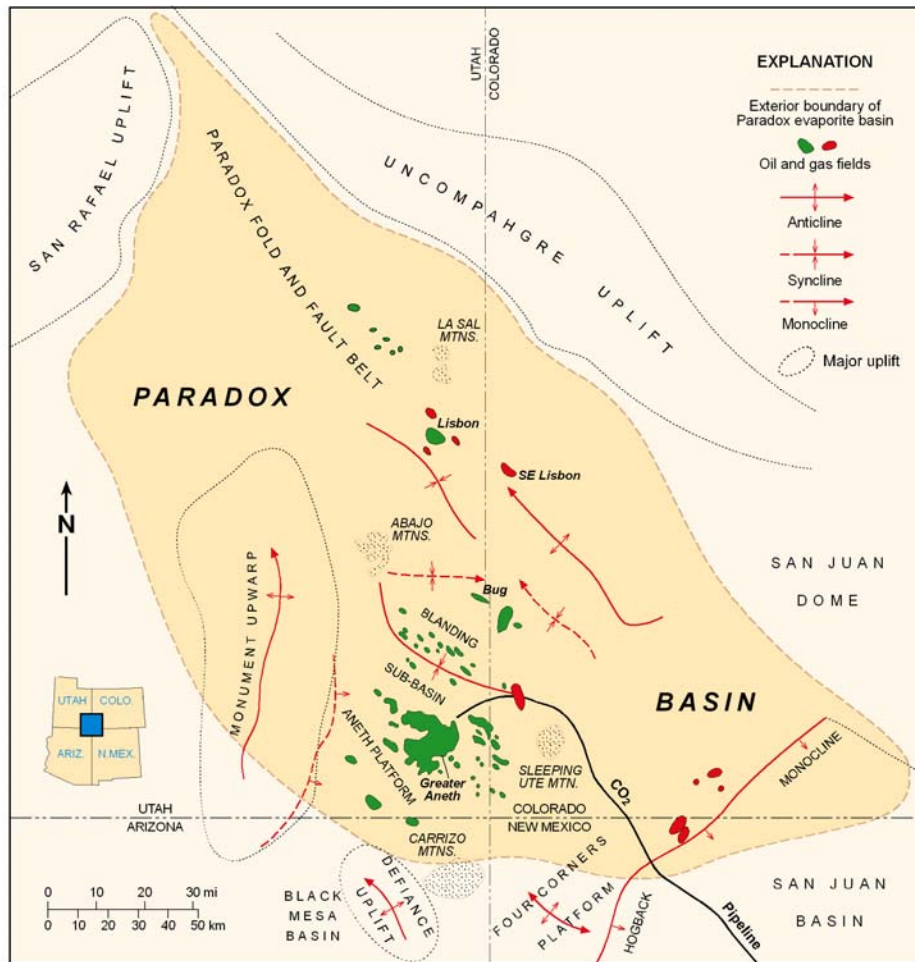


Figure 1. Oil and gas fields in the Paradox Basin of Utah, Arizona, and Colorado.

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'		potash & salt
DEV	Ouray Limestone		0-150'		
	Elbert Formation		100-200'		
DEV	McCracken Ss Mbr		25-100'		potash & salt
	"Lynch" Dolomite		800-1000'		

Oil and gas 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).

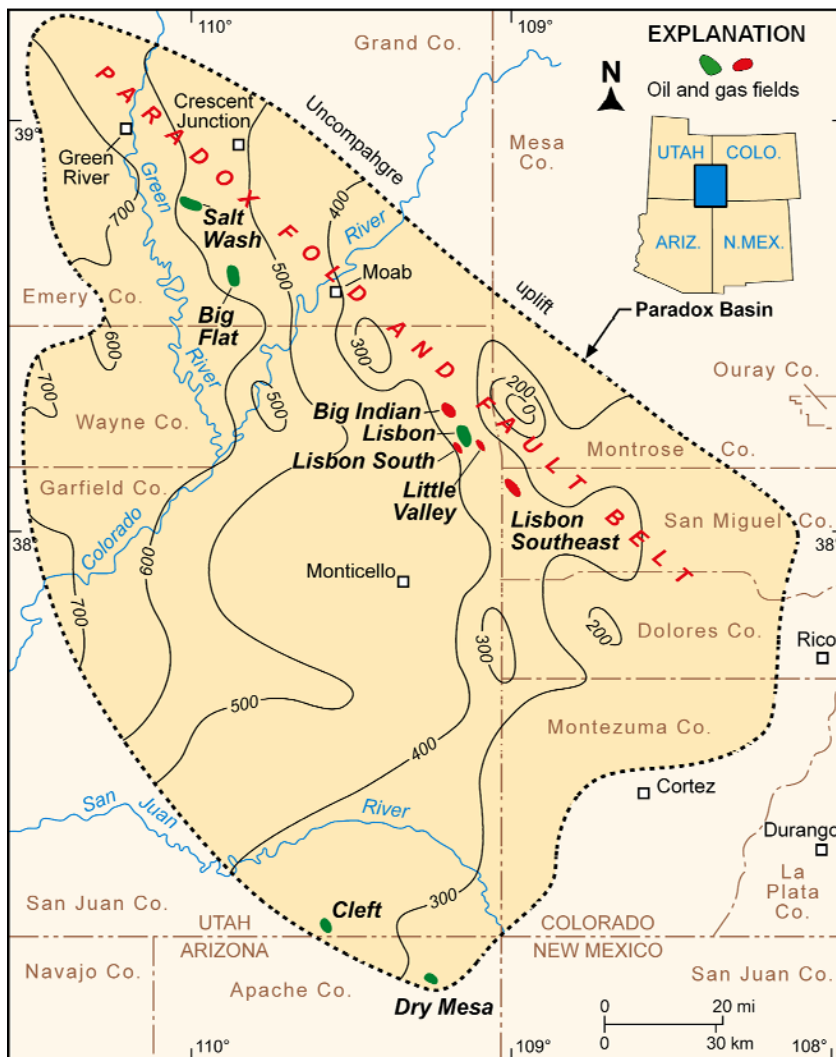


Figure 3. Location of fields that produce from the Mississippian Leadville Limestone, Utah, Arizona, and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

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.

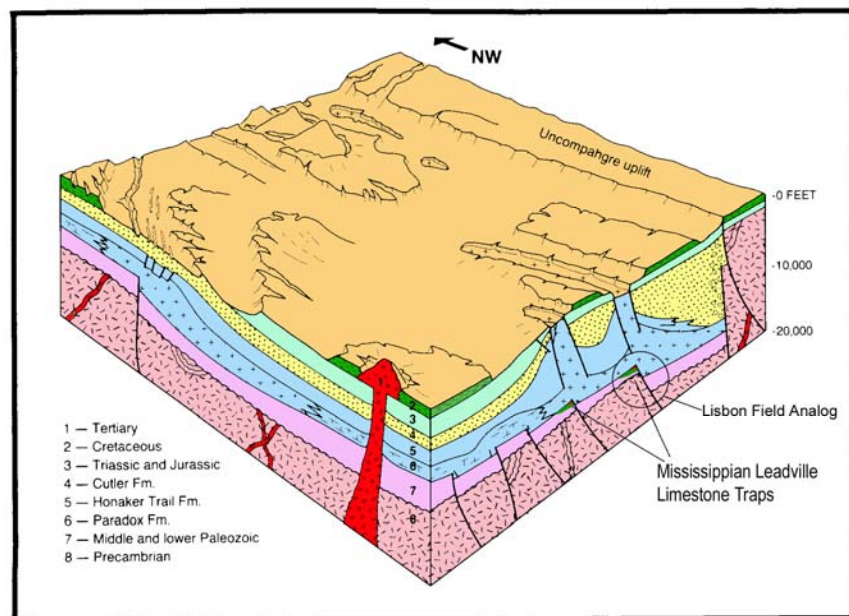


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

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).

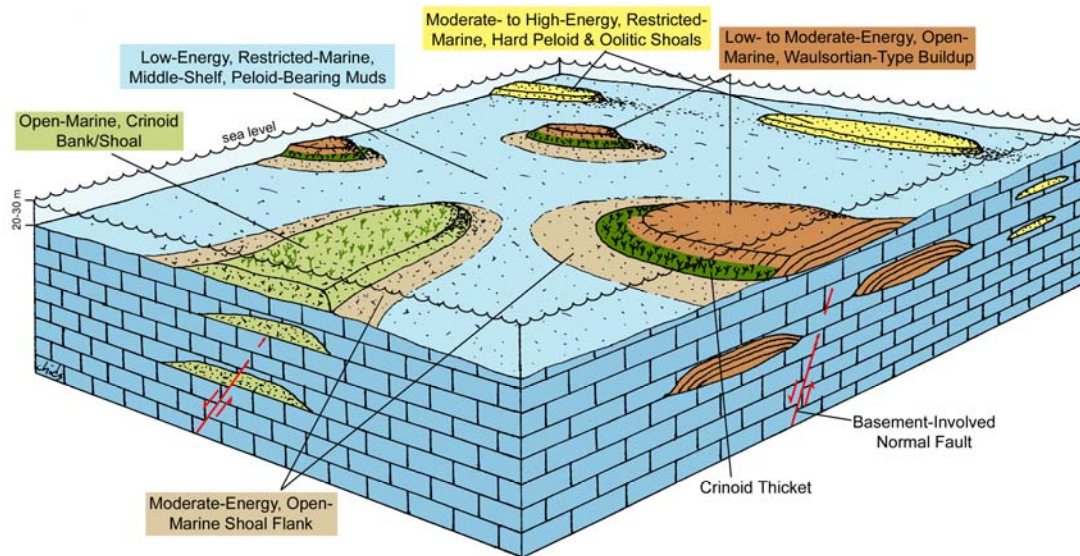


Figure 5. Block diagram displaying major depositional facies, as determined from core, for the Leadville Limestone, Lisbon field, San Juan County, Utah.

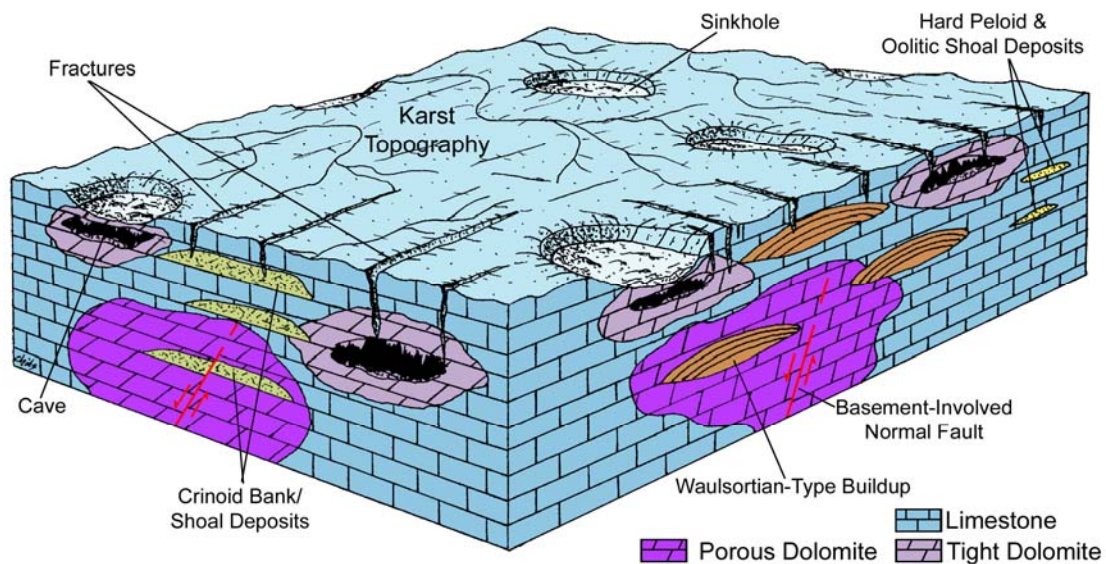


Figure 6. Block diagram displaying post-Leadville karst and fracture overprint.

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 scanning electron microscopy, epifluorescence, cathodoluminescence, fluid inclusions, and isotopic studies 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).

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 m³) 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 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 m³), 785.4 billion cubic feet of gas (BCFG) (22.2 BCMG) (cycled gas), and 50,073,622 bbls of water (7,961,706 m³) (Utah Division of Oil, Gas

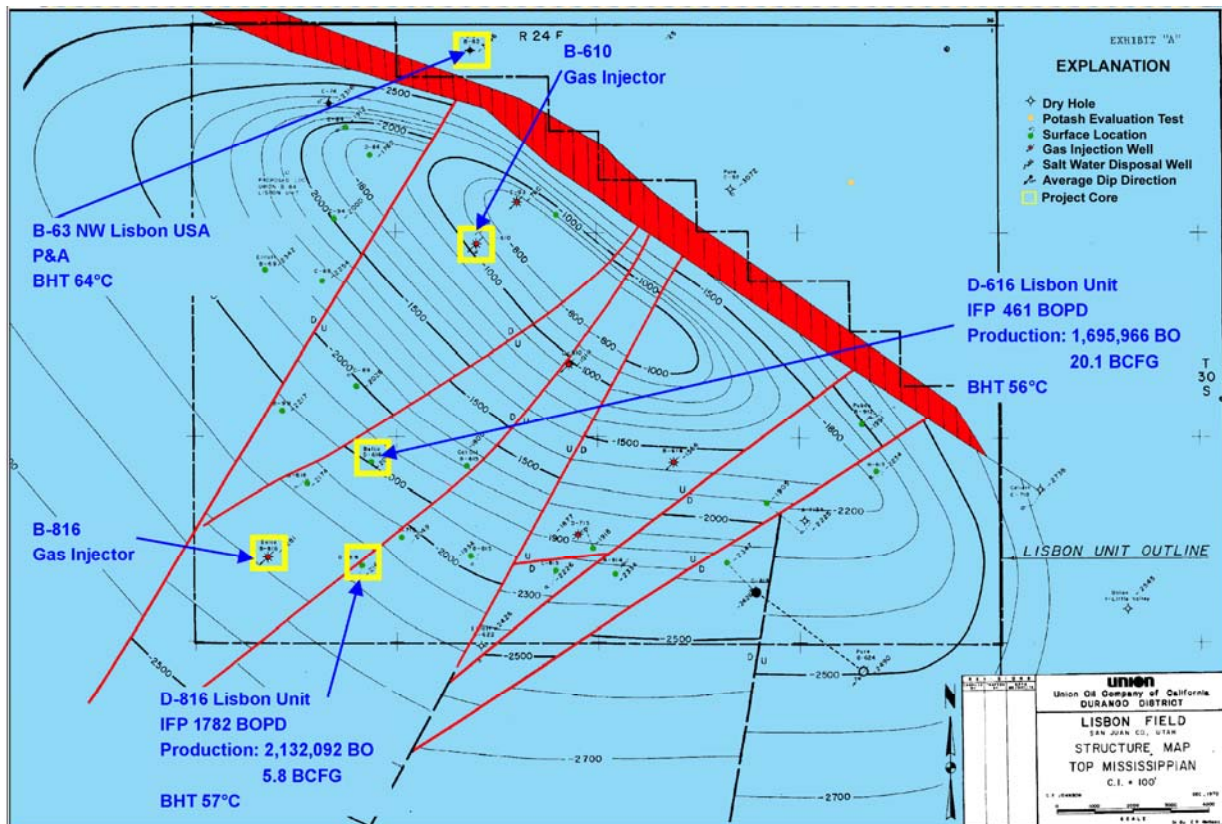


Figure 7. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). Also displayed are wells from which cores were described in this study.

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

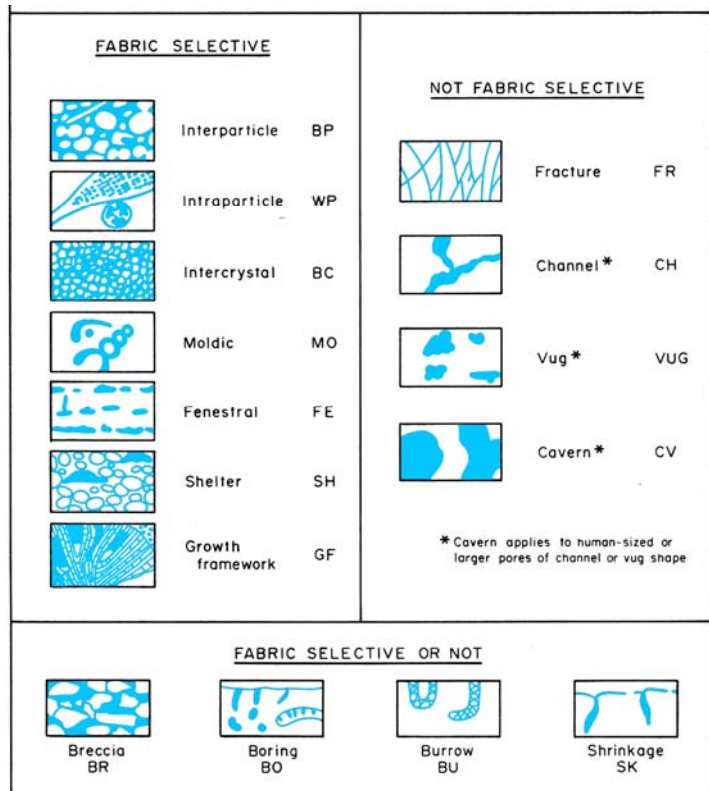
Geophysical well logs, cores and cuttings, reservoir data, various reservoir maps, and other information from Lisbon field development wells were collected by the UGS. Well locations, formation tops, production data, completion tests, basic core analysis, porosity and permeability data, and other data 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 Access™. 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 - Overview

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. 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 regionally. In order to determine the diagenetic histories of the various Leadville rock fabrics, including both reservoir and non-reservoir, representative samples were selected from the conventional cores for petrographic description and geochemical analysis. Carbonate fabrics were 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).

An ideal diagenetic sequence based on our analysis of Leadville thin sections from Lisbon field is presented in figure 9. Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of limestone. There are two basic types of dolomite: very fine, early dolomite and coarse, late dolomite. The early dolomitization and leaching of skeletal grains resulted in low-porosity and/or low-permeability rocks. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events. Other diagenetic products include pyrobitumen, syntaxial cement, sulfide minerals, anhydrite cement and replacement, and late macrocalcite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are present in the upper third of the formation. Late dolomitization, sulfides, and brecciation may have developed from hydrothermal events that can greatly improve reservoir quality.

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



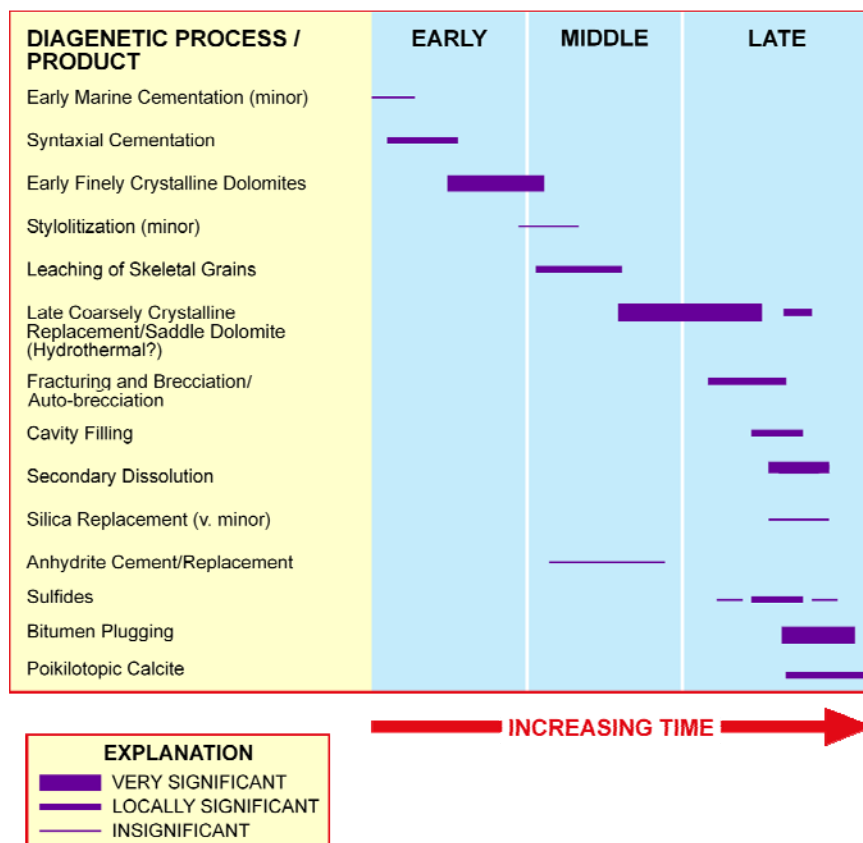


Figure 9. Ideal diagenetic sequence through time based on thin section analysis, Leadville Limestone, Lisbon field.

The geochemical and petrographic techniques that were employed consisted of (1) scanning electron microscope (SEM) analysis of various dolomites to determine reservoir quality of the dolomites as a function of diagenetic history, (2) epifluorescence (EF), (3) cathodoluminescence (CL) petrography for the sequence of diagenesis, and (4) fluid inclusion (FI) evaluation to determine the temperatures of secondary dolomite formation and the salinity of the original brines. Additional geochemical analysis includes (1) stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites, and (2) strontium isotope analysis for tracing the origin of fluids responsible for different diagenetic events.

SCANNING ELECTRON MICROSCOPY

Introduction

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks in the Leadville Limestone of Lisbon field can be indicators of reservoir flow capacity and storage capacity. In order to determine the diagenetic histories of the Leadville reservoir, representative samples were selected from the conventional cores which were used for thin sections (Appendix A). Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. A scanning electron microscope (SEM) was used to photograph: (1) typical preserved primary and secondary pore types and pore

throats, (2) cements, (3) sedimentary structures, (4) fractures, and (5) pore-plugging anhydrite, halite, and bitumen. Diagenetic characterization focussed on reservoir heterogeneity, quality, and compartmentalization within the field. Of special interest is the identification of possible hydrothermal dolomite and the determination of the most effective pore systems for oil drainage versus storage. Scanning electron microscope analyses were conducted on 12 thin section blanks from the core samples that displayed particular characteristics of interest (table 1). Porosity types and associated abbreviations included in this report are from Choquette and Pray (1970) (figure 8).

Table 1. Summary of characteristics observed with scanning electron microscopy in samples from the Lisbon No. D-816, Lisbon No. D-616, and Lisbon No. B-610 wells, Lisbon field, San Juan County, Utah.

Well	Lisbon D-816					Lisbon D-616					Lisbon B-610	
DEPTH (ft)	8423'	8426'	8433'	8442'	8486'	8308'	8356'	8559'	8619'	8682'	7886'	7897'
POROSITY												
Intergranular (Micro) (BC)	X	X	X	X	X	X	X	X	X	X	X	X
Dissolution (MO)	X	X	X	X	X		X		X		X	X
Dissolution (VUG)		X	X	X	X				X		X	X
Dissolution (CH)											X	
Fractures	X			X		X	X		X	X	X	
CEMENTS												
Anhydrite		X	X							X		
Calcite					X	X	X				X	
Quartz					X	X	X		X			
Dolomite	X	X	X	X	X	X	X	X	X	X	X	X
Illitic Clay	X					?				X		X
Pyrobitumen	X	X	X	X	X				X			
Sulfides	X		X	X	X				X		X	X
DIAGENESIS												
Dolomitization	X	X	X	X	X	X	X		X	X	X	X
Dissolution	X	X	X	X	X	X	X		X	X	X	X
Calcite Cementation					X	X	X					
Quartz Cementation					X	X	X		X			
Illitic clay Deposition	X					X			X	X	X	X
Anhydrite Cementation		X	X							X		
Pyrobitumen Emplacement	X	X	X	X	X				X			
Fracturing	X			X		X	X		X	X	X	

Data from SEM, EDS, and optical microscopy by Standard Geological Services, Inc. and petrography by Eby Petrography & Consulting.

Porosity Types

All samples exhibit microporosity in the form of intercrystalline (BC) porosity (figure 10). Dissolution has contributed to porosity in most samples as well. Dissolution has created moldic (MO), vuggy (VUG), and channel (CH) porosity. Dissolution pores are most often in the mesopore size range (62.5 microns to 4.0 mm.).

Permeability is related to the size and number of pore throats, and, particularly, to the continuity of pore throats. In general, permeability is good in the samples studied, but is limited slightly by mineral cements and pyrobitumen (figure 11).

Fractures enhance the permeability in several intervals (figure 12). Scanning electron microscopic examination identified fractures in the 8423- and 8442-foot (2567- and 2573-m) intervals of the Lisbon No. D-816 well, and the 8356- and 8682-foot (2547- and 2646-m) intervals of the Lisbon No. D-616 well. In addition to the fractures reported here, petrographic analysis revealed fractures in the 8308- and 8619-foot (2532- and 2627-m) intervals of the Lisbon No. D-816 well, and the 7886-foot (2404-m) interval of the Lisbon No. B-610 well.

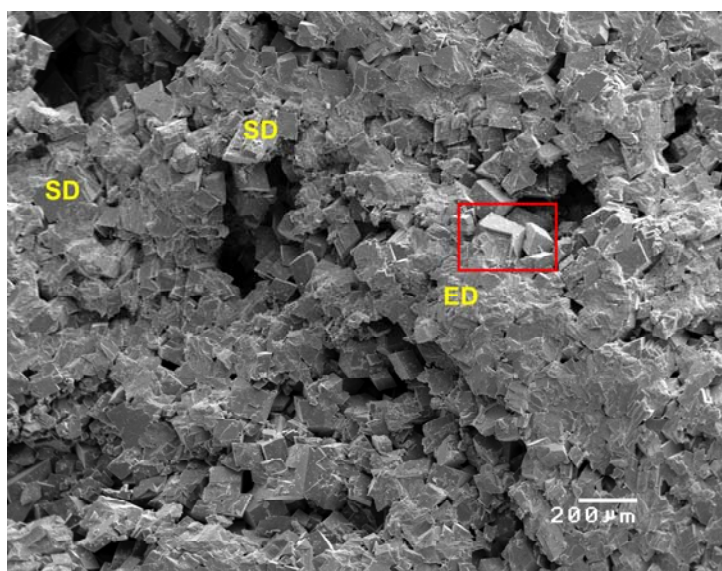
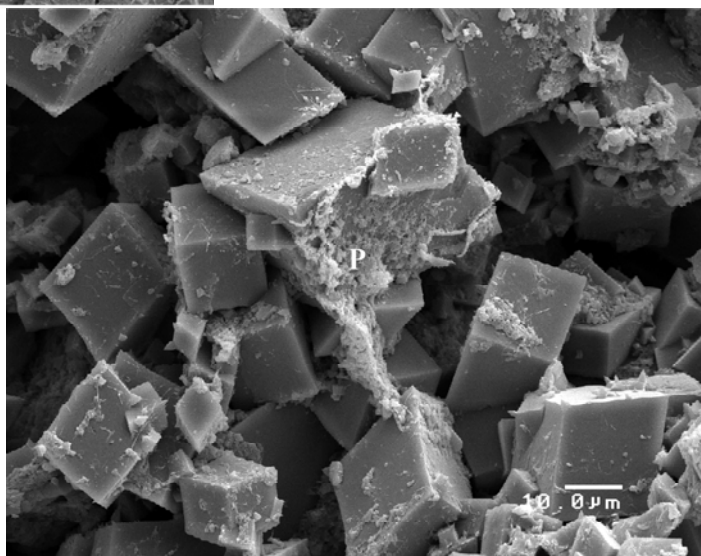


Figure 10. Scanning electron microscope photomicrograph of a core plug from 8433 feet, Lisbon No. D-816 well, showing typical Leadville dolomites at Lisbon field. Note the very fine, tight early dolomites (ED) that have been replaced with late, rhombic and saddle (SD) dolomites. There is a significant porosity increase associated with the late dolomite replacement. Scale bar represents 200 microns (0.2 mm). Porosity = 2 percent; permeability < 0.1 mD based on core-plug analysis.

Figure 11. Scanning electron microscope photomicrograph of a core plug from 7886 feet, Lisbon No. B-610 well, showing probable pyrobitumen (P) coating the rhombic dolomite crystal in the center. Pyrobitumen coats many other dolomite crystals as well. Scale bar represents 10 microns (0.01 mm). Porosity = 13.8 percent; permeability = 114 mD based on core-plug analysis.



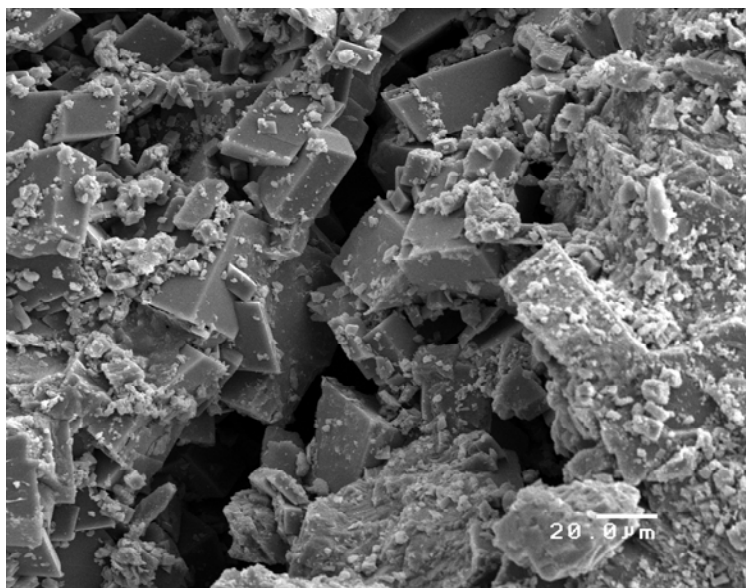


Figure 12. *Scanning electron microscope photomicrograph of a core plug from 8423 feet, Lisbon No. D-816 well, showing enlargement of a fracture partially filled with secondary dolomite. Scale bar represents 20 microns (0.02 mm). Porosity = 10.5 percent; permeability = 47 mD based on core-plug analysis.*

Undoubtedly, fractures enhance the permeability in the 8423- and 7886-foot (2567- and 2404-m) samples given their respective measured values of 46 mD and 114 mD. The 83 mD measured permeability of the 7897-foot (2407-m) interval and the 15 mD of the 8426-foot (2568-m) interval suggest that fractures are present in these intervals as well. They were not observed during analysis, however.

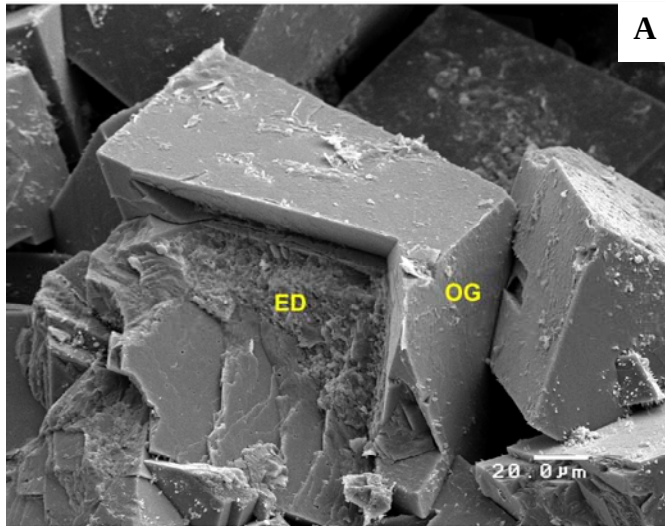
Lithology, Diagenesis, and Cements

All samples are dolomite except for the limestone matrix present in the 8308-foot (2532-m) sample of the Lisbon No. D-616 well. That sample, however, contains dolomite as fill material. Secondary materials present include dolomite, calcite, clays, and pyrobitumen. Their presence is discussed below and also included in table 1.

Dolomite is the dominant cement (figure 10) in all samples except the 8426-foot (2568-m) sample from the Lisbon No. D-816 well, where anhydrite is the abundant cement. The two basic types of dolomite are well displayed by SEM (figure 10): the low-porosity and/or low-permeability, very fine, early dolomite and higher porosity and/or high permeability, coarse, late dolomite (figure 13).

Pores in the 8426-foot (2568-m) sample from the Lisbon No. D-816 well are partially filled with anhydrite (figure 14). Anhydrite is also reported from petrographic analysis of the 8433-foot (2570-m) interval of this well and the 8682-foot (2646-m) sample of the Lisbon No. D-616 well. Scanning electron microscopic analysis indicates that anhydrite is abundant in the 8426-foot (2568-m) sample; it is most likely much less abundant in the other intervals.

Minor euhedral quartz is present in several samples (figure 15). Rare illitic clays, possibly illite/smectite mixed-layer clays, are also present. Sulfide mineral(s) containing an unknown cation are present in moderate abundance (figure 16). Calcite cement, although rare, was observed in a few samples. The minor constituents of quartz, clays, calcite, and sulfides contribute little to the overall lithology and are relatively insignificant with respect to reservoir quality. The quartz, clay, and calcite cements are rare, and the more abundant sulfide mineral (s) consist of extremely small crystals, about 2 microns or smaller.



A Figure 13. Scanning electron microscope photomicrograph of a core plug from 8433 feet shown in figure 10 (see red box), Lisbon No. D-816 well. A – Closeup shows the composition of typical replacement rhombic dolomites. The core of each rhombic crystal is composed of a dense remnant of fine, early dolomite (ED), which is surrounded by a euhedral dolomite overgrowth (OG). The rhombic dolomite faces are often covered with a thin film of pyrobitumen. Scale bar represents 20 microns (0.02 mm). B – High magnification across a section of poorly crystalline, early dolomite core (ED) and dense overgrowth (OG) that forms the dolomite into coarser rhombs. The very small, angular decorations on the crystal surfaces may very well be small sulfide precipitates (S). Scale bar represents 5 microns (0.005 mm). Porosity = 2 percent; permeability < 0.1 mD based on core-plug analysis.

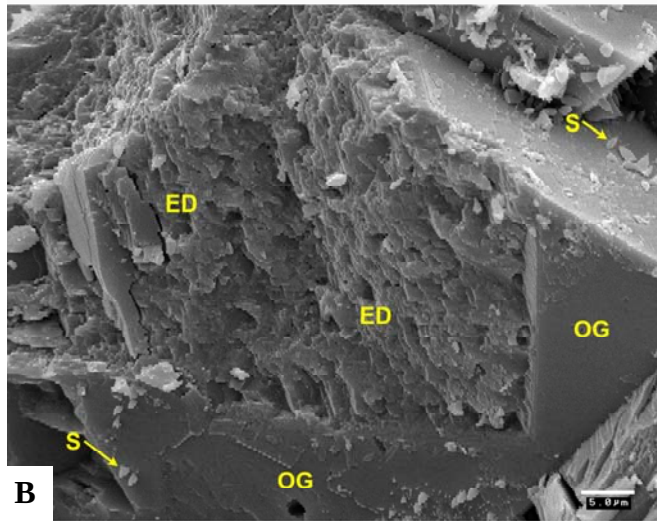
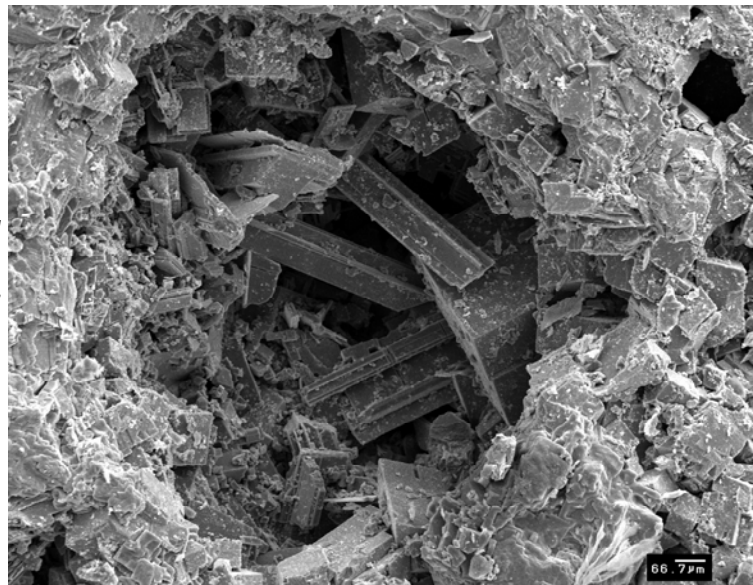


Figure 14. Scanning electron microscope photomicrograph of a core plug from 8426 feet, Lisbon No. D-816 well, showing anhydrite cement lathes partially filling a small dissolution vug. Scale bar represents 66.7 microns (0.067 mm). Porosity = 11.1 percent; permeability = 15 mD based on core-plug analysis.



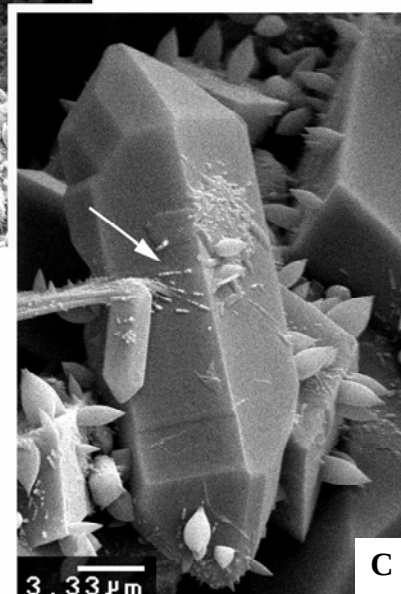
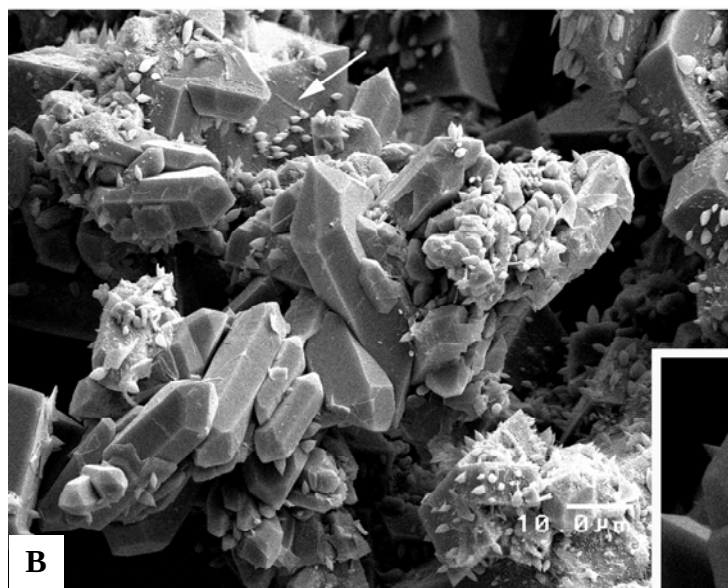
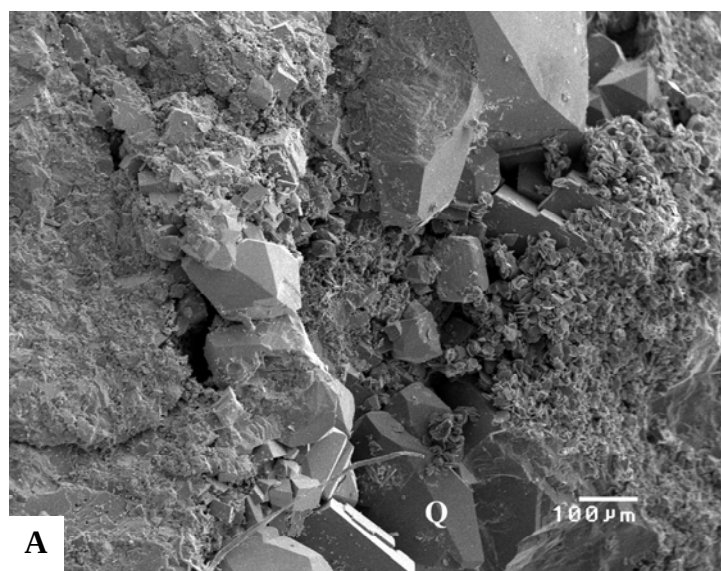


Figure 15. Scanning electron microscope photomicrograph showing euhedral quartz void fillings (Q) within late dissolution pores. A – Typical euhedral quartz surrounded by rhombic dolomite; core plug from 8356 feet, Lisbon No. D-616 well. Scale bar represents 100 microns (0.1 mm). No core-plug analysis available. B – Core plug from 8486 feet, Lisbon No. B-816 well, showing showing clusters of euhedral, doubly terminated quartz crystals (“miniherkimers”). The small spiky materials precipitated on many of the surfaces are either pyrobitumen or sulfide minerals. Scale bar represents 10 microns (0.01 mm). Porosity = 5.9 percent; permeability = 0.2 mD based on core-plug analysis. C - Closeup of a typical doubly terminated quartz crystal from same core sample in B. The linear features (arrow) and the spiky materials on many of the crystal surfaces are composed of either pyrobitumen or sulfide minerals.

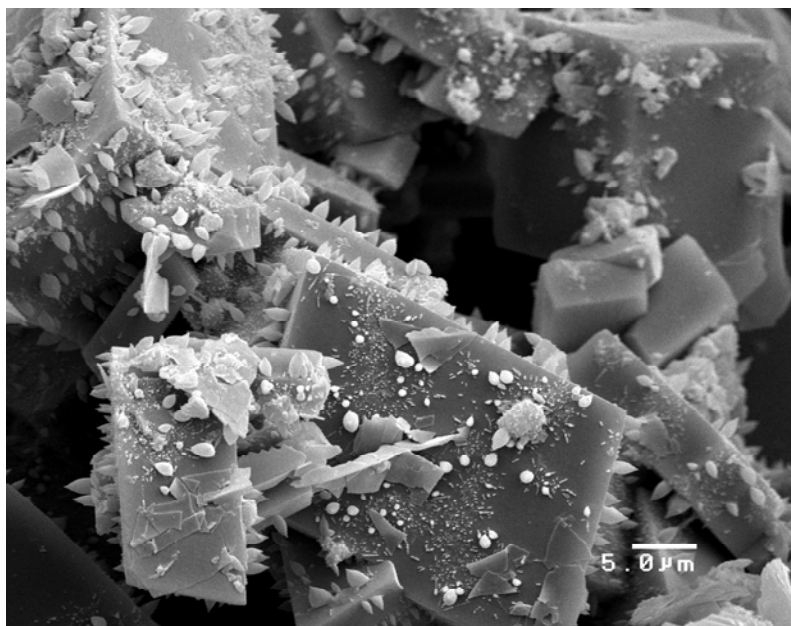


Figure 16. Scanning electron microscope photomicrograph of a core plug from 8442 feet, Lisbon No. D-816 well, showing possible sulfide minerals on large dolomite rhombs. Scale bar represents 5 microns (0.005 mm). Porosity = 8.6 percent; permeability = 1.0 mD based on core-plug analysis.

An approximate diagenetic sequence based on SEM is listed below (not all diagenetic events were identified in every sample). The various diagenetic events are included in table 1.

1. Dolomitization
2. Dissolution
3. Dolomite cementation
4. Fracturing
5. Quartz cementation
6. Calcite cementation
7. Clay precipitation
8. Anhydrite cementation
9. Pyrobitumen emplacement
10. Sulfide precipitation

EPIFLUORESCENCE

Introduction

Epifluorescence (EF) microscopy is a technique that has been used successfully in recent years to provide additional information on diagenesis, pores, and organic matter (including “live” hydrocarbons) within sedimentary rocks. It is a rapid, non-destructive procedure that can be done using a high-quality petrographic (polarizing) microscope equipped with reflected light capabilities. The basic principles and equipment for EF were largely developed in the 1960s and 1970s for applications in coal petrology and palynology (see reviews by van Gijzel, 1967; Teichmuller and Wolf, 1977). All applications depend upon the emission of light (by a material capable of producing fluorescence) that continues only during absorption of the excitation-generating light beam (Rost, 1992; Scholle and Ulmer-Scholle, 2003).

Epifluorescence techniques have been used within industry and research for three objectives. Firstly, EF microscopy has been used extensively for enhancing petrographic observations, including the recognition of depositional and diagenetic fabrics within recrystallized limestone and massive dolomite (see, for instance, Dravis and Yurewicz, 1985; Cercone and Pedone, 1987; Dravis, 1991; LaFlamme, 1992). Secondly, the study of pore structures, microfractures, and microporosity within both carbonates and sandstones has been greatly facilitated by impregnating these voids with epoxy spiked with fluorescing dyes (Yanguas and Dravis, 1985; Gies, 1987; Cather and others, 1989a, 1989b; Soeder, 1990; and Dravis, 1991). Thirdly, the evaluation of “oil shows” (Eby and Hager, 1986; Kirby and Tinker, 1992) and determination of the gravity or type cements and minerals has been facilitated by EF microscopy (Burruss, 1981, 1991; Burruss and others, 1986; Guihaumou and others, 1990; LaVoie and others, 2001). Only the first two objectives were pursued in this study.

Previous Work

There is no known published use of EF microscopy on the Leadville Limestone of the Paradox Basin. However, the published work cited above, applications to carbonate reservoirs listed in Eby and Hager (1986) for a study done within a Permian Basin carbonate field, and case studies documented by Dravis (1988, 1992) provided incentives to apply EF petrography to Leadville reservoir rocks within the Lisbon case-study field.

Methodology

Epifluorescence petrography for this project used incident (reflected) blue-light fluorescence microscopy employing the general procedures outlined by Dravis and Yurewicz (1985), including the use of the modified “white card” technique outlined by Folk (1987) and Dravis (1991). Ultraviolet (UV) fluorescence did not effectively add any textural or pore structure information that could not otherwise be seen under blue-light excitation, even though some workers utilize UV fluorescence for evaluating fluid inclusions and compositional zoning within dolomite crystals (see Scholle and Ulmer-Scholle, 2003). Fluorescence data and observations collected for this study utilized a Jena (now part of Carl Zeiss) research-grade combination polarizing-reflected light microscope equipped with a high-pressure mercury vapor lamp for EF excitation, a Zeiss IIIRS epifluorescence nosepiece, and a 35-mm camera system. Magnification ranges for examination and photo-documentation were between ~130 and 320x. The EF optical configuration used is similar to that shown in figure 17.

The light pathways and mechanics of the EF used in this study have been generally described by Soeder (1990). As described by Burruss (1991), “these excitation wavelengths are reflected to the microscope objective and sample by a dichroic beamsplitter which has a dielectric coating that reflects a specific short wavelength range. Fluorescence emission and reflected short wavelength excitation light is collected by the objective. The dichroic beamsplitter transmits the long wavelength fluorescence emission, but reflects the short wavelengths back toward the light source. The fluorescence emission passes through a barrier filter which removes any remaining short wavelength excitation light.” Blue light (~420-490 nm exciter filter/520 nm barrier filter) was used to excite the cuttings and core-chip samples. We have found broad-band, blue-light EF to be the most helpful in observational work on dolomite, although some workers report applications using UV light (330-380 nm exciter

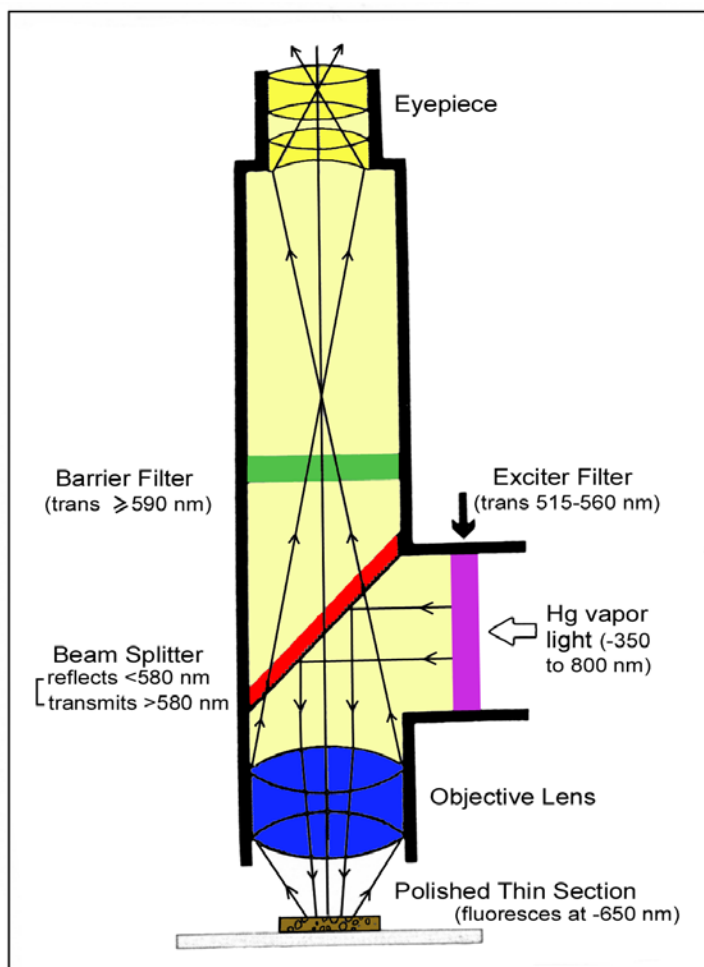


Figure 17. Generalized microscope optical configuration for observing fluorescence under incident light (modified from Soeder, 1990).

filter/420 nm barrier filter) or narrow-band, blue-violet light (400-440 nm exciter filter/480 nm barrier filter). Finally, the greater depth of investigation into a sample by the reflected fluorescence technique than by transmitted polarized light or other forms of reflected light makes it possible to resolve grain boundary and compositional features that are normally not appreciated in cutting or thin-section petrography.

Sample preparation is inexpensive and rapid, involving standard thin section preparation techniques. Thin sections were prepared from representative Leadville fabrics. These thin sections were vacuum- and pressure-impregnated with blue-dyed epoxy (see Gardner, 1980) that was spiked with a fluorescing compound. Microscopy used only uncovered polished surfaces. Examination for each thin section area of interest included photo-documentation under EF and plane-polarized light at the same magnification. Photomicrography of the compositional, textural, and pore structure attributes was done using high-speed film (ISO 800 and 1600) with some bracketing of exposures as camera metering systems do not always reliably read these high-contrast images in the yellow and green light spectrum. Since the image brightness is directly proportional to magnification, the best images are obtained at relatively high magnifications (such as greater than 100x). Low-power fluorescence is often too dim to effectively record on film. These techniques are applicable to thin sections from both core and cuttings samples.

Epifluorescence Petrography of Leadville Limestone Thin Sections

Blue-light, EF microscopy was completed on 15 core samples for a variety of rock textures and diagenetic phases of Leadville limestone and dolomite within Lisbon field (Appendix B). These samples were selected to be representative of compositional, diagenetic, and pore types encountered within the five cored wells (see figure 7 for core locations). A detailed description and interpretation of the fluorescence petrography of each sample follows along with photomicrographs (as figures 18 through 22) to show representative views under both blue-light EF and plane-polarized light. Short descriptive captions for these photomicrographs are included with each photo pair.

Lisbon No. D-816 well: Blue-light, EF microscopy nicely shows pore spaces and structures that are not readily seen under transmitted, plane-polarized lighting, and it shows the range of crystal sizes or shapes within bitumen-rich areas (figure 18). Samples from this well are fairly massive dolomite which is generally non-fluorescence but has a slight hint of fluorescence showing vague relict grains. Some samples display complex zoning, alternating from dull to bright fluorescence within rhombs. Blue light, EF also shows the clear difference between dull replacement dolomite and much lighter replacement dolomite cement. Rare saddle dolomite cements in molds appear to show crystal zonation.

Microfractures cutting through tight dolomite matrix are visible only with blue-light EF. Some pores (isolated molds) are lined with bright, yellow oil film fluorescence possibly from oil staining while others show no oil staining.

Lisbon No. D-616 well: Blue-light, EF microscopy shows replacement dolomite that is fine to medium crystalline with planar to curved crystal faces, weakly yellow fluorescent with possible fluid inclusions (figure 19); limestone does not fluoresce. Saddle dolomite cements growing into some of the moldic pores display moderately dull blue fluorescence. Blue-light, EF displays replacement rhombic dolomite outlines with high intercrystalline porosity despite the appearance of significant bitumen plugging.

Blue-light, EF microscopy also shows syngenetic dolomite, laminated cryptoalgal (?) mudstone with soft pellets, and abundant wispy seam, low-amplitude stylolites. Moderate yellow fluorescence is observed throughout the samples. Ghosts of original skeltetal/pelletal grains show moderate yellow fluorescence transitioning into coarse replacement dolomite displaying modest intercrystalline porosity. The replacement rhombs have generally dead cores and moderate yellow fluorescence overgrowths.

Lisbon No. B-610 well: Ultraviolet-light, EF microscopy shows two regions within the sample. Region 1 consists of white, syngenetic dolomite with no visible porosity and blue-purple moderate fluorescence. The UV fluorescence nicely shows a variety of corrosion and dissolution fabrics, which sometimes mimic original grain boundaries. Region 2 consists of black, non-fluorescent, finely crystalline dolomite, as well as “floating” large dolomite rhombs that appear to have precipitated out of the finely crystalline groundmass (figure 20).

Blue-light EF also displays syngenetic dolomite, both unaltered and corroded, with moderate yellow fluorescence. Within the black dolomite region, the larger floating dolomite rhombs have a dull green fluorescence.

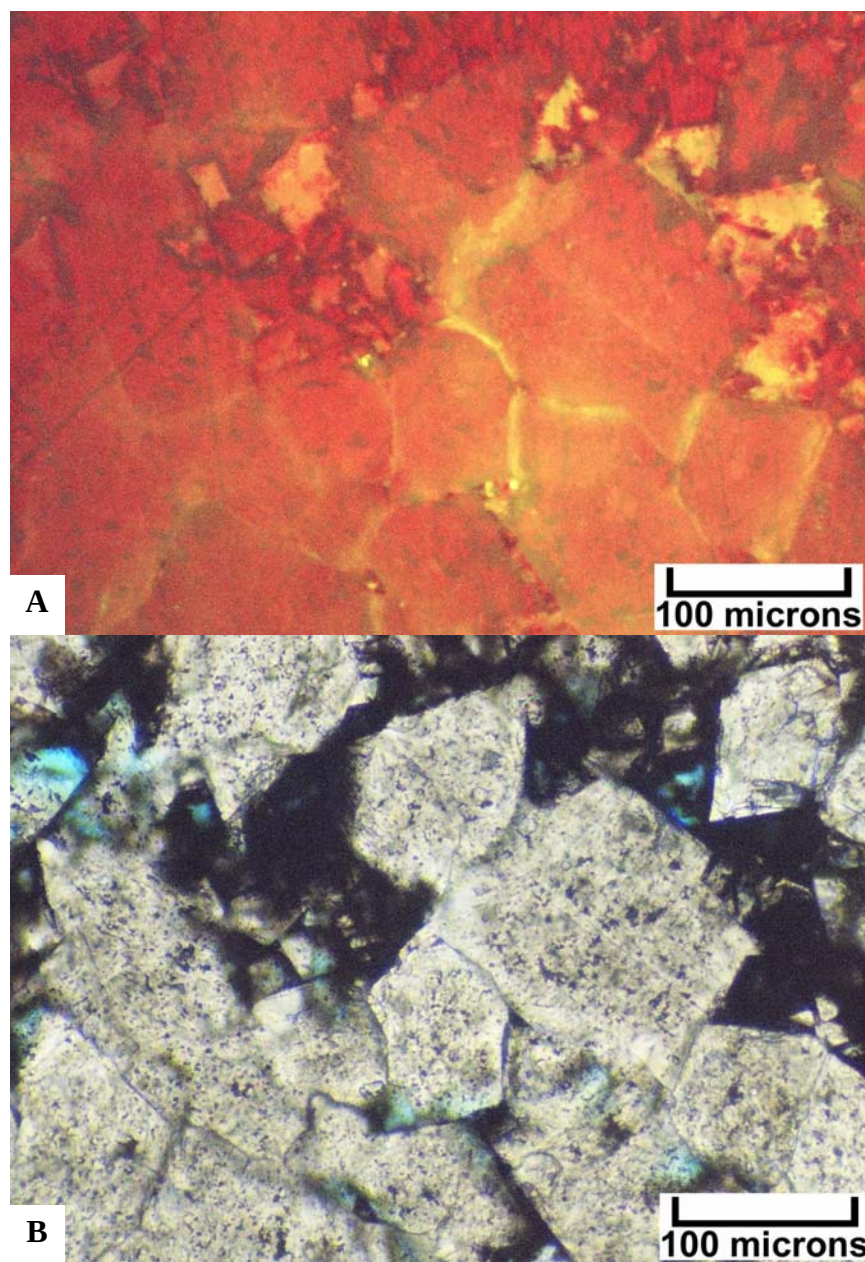


Figure 18. Photomicrographs from Lisbon No. D-816 well at 8435.8 feet. A – Epifluorescence under moderate magnification, showing a representative area showing fluorescence zonation within coarse dolomite crystals. The reddish areas are pores with abundant bitumen linings and plugging (see figure 16B). Fluorescence petrography makes it possible to clearly see the dolomite crystals versus the pore space. In places, very small rhombic outlines of dolomite crystals can be resolved. Many of these pores appear to be completely surrounded by an interlocking network of dolomite crystals. B - The same field of view as above is shown under plane light at the same magnification. Note that the black (and opaque) areas composed of bitumen mask the crystal boundaries of the dolomite as well as individual pore outlines. The white and gray areas are remnants of the dolomite matrix that are not masked by the bitumen. Only a small amount of pore space (blue-dyed areas) can be seen in this view compared to the fluorescence photomicrograph above.

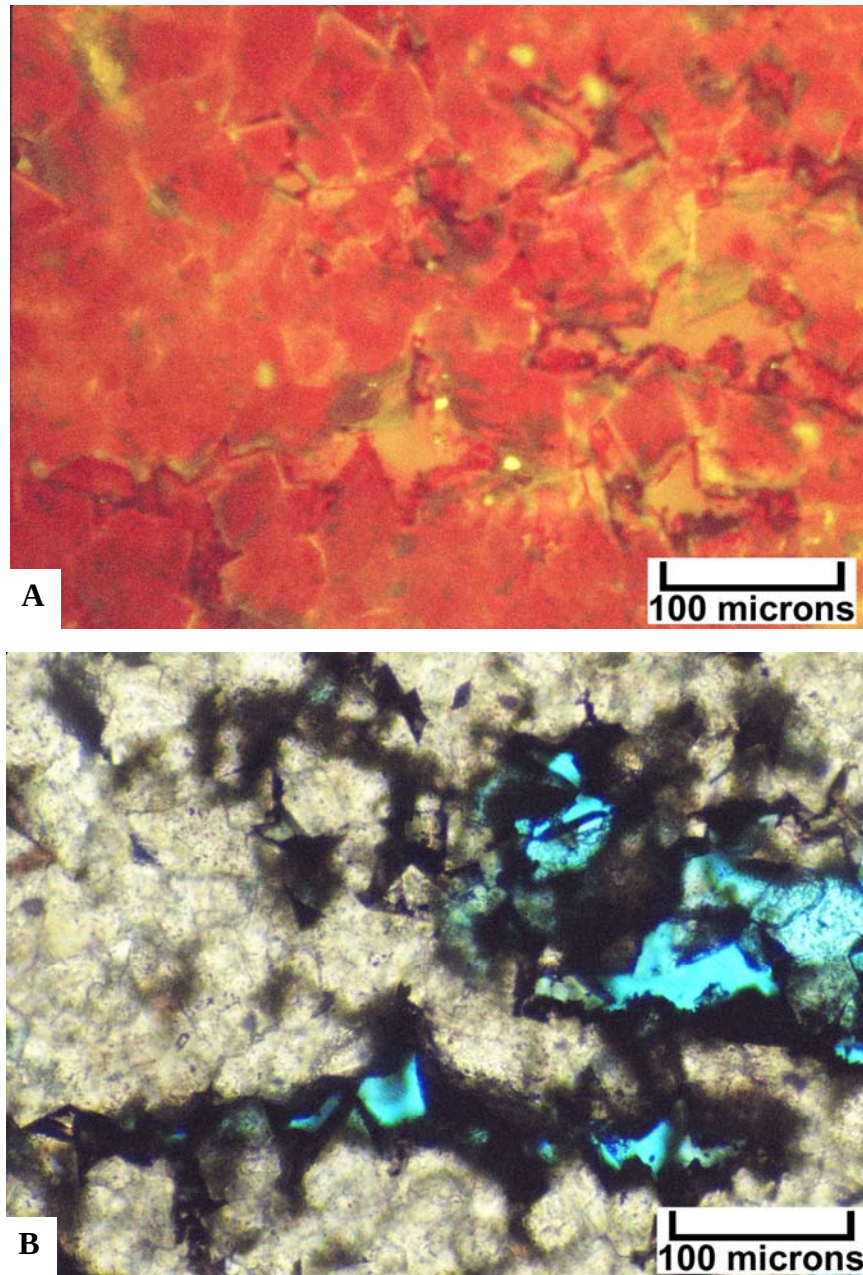


Figure 19. *Photomicrographs from Lisbon No. D-616 well at 8584 feet. A – Epifluorescence under moderate magnification, showing fine- to medium-sized crystals of replacement dolomite. The rhombs display dead cores and fluorescent rims. B - The same field of view as above is shown under plane light at the same magnification. Again, note that the black (and opaque) areas composed of bitumen mask the crystal boundaries of the dolomite as well as individual pore outlines.*

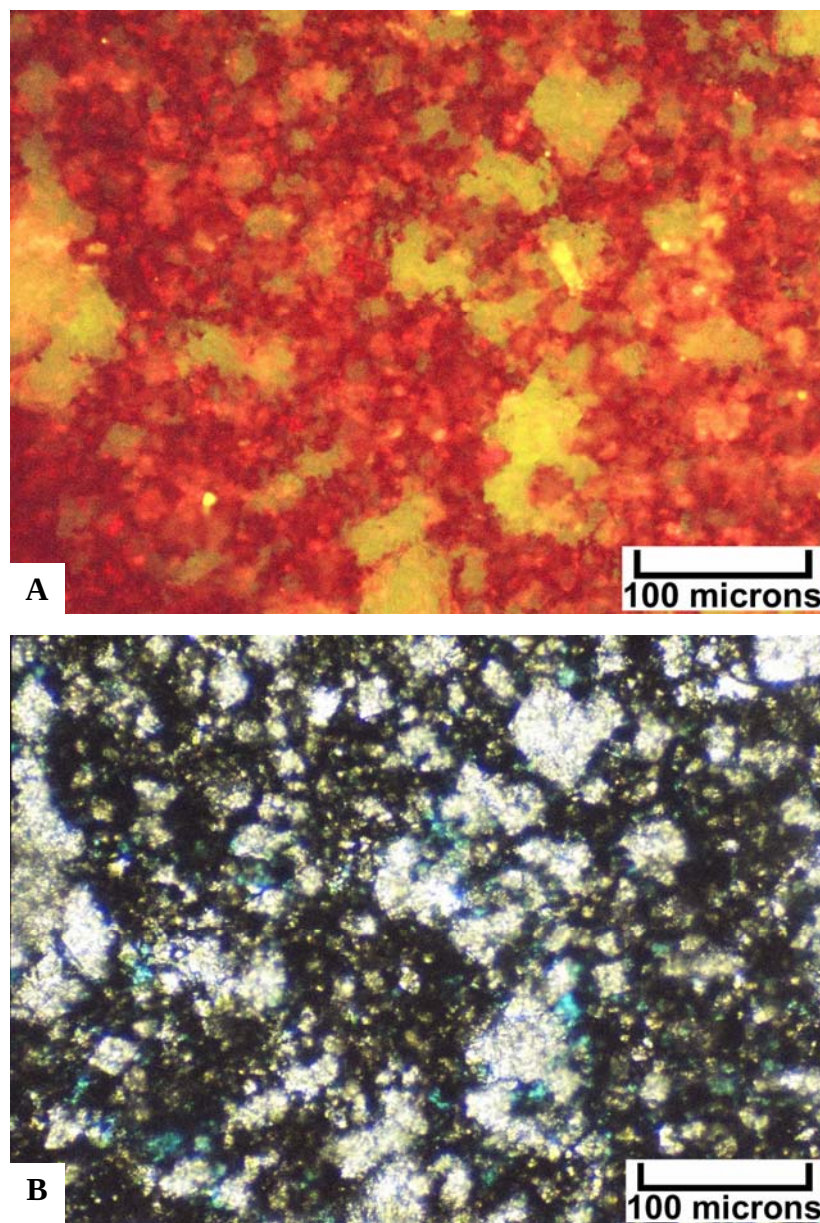


Figure 20. Photomicrographs from Lisbon No. B-610 well at 7897 feet. A – Epifluorescence under moderate magnification, showing individual, yellow-fluorescing dolomite rhombs “floating” in a of non-fluorescing dolomite matrix. B - The same field of view as above is shown under plane light at the same magnification.

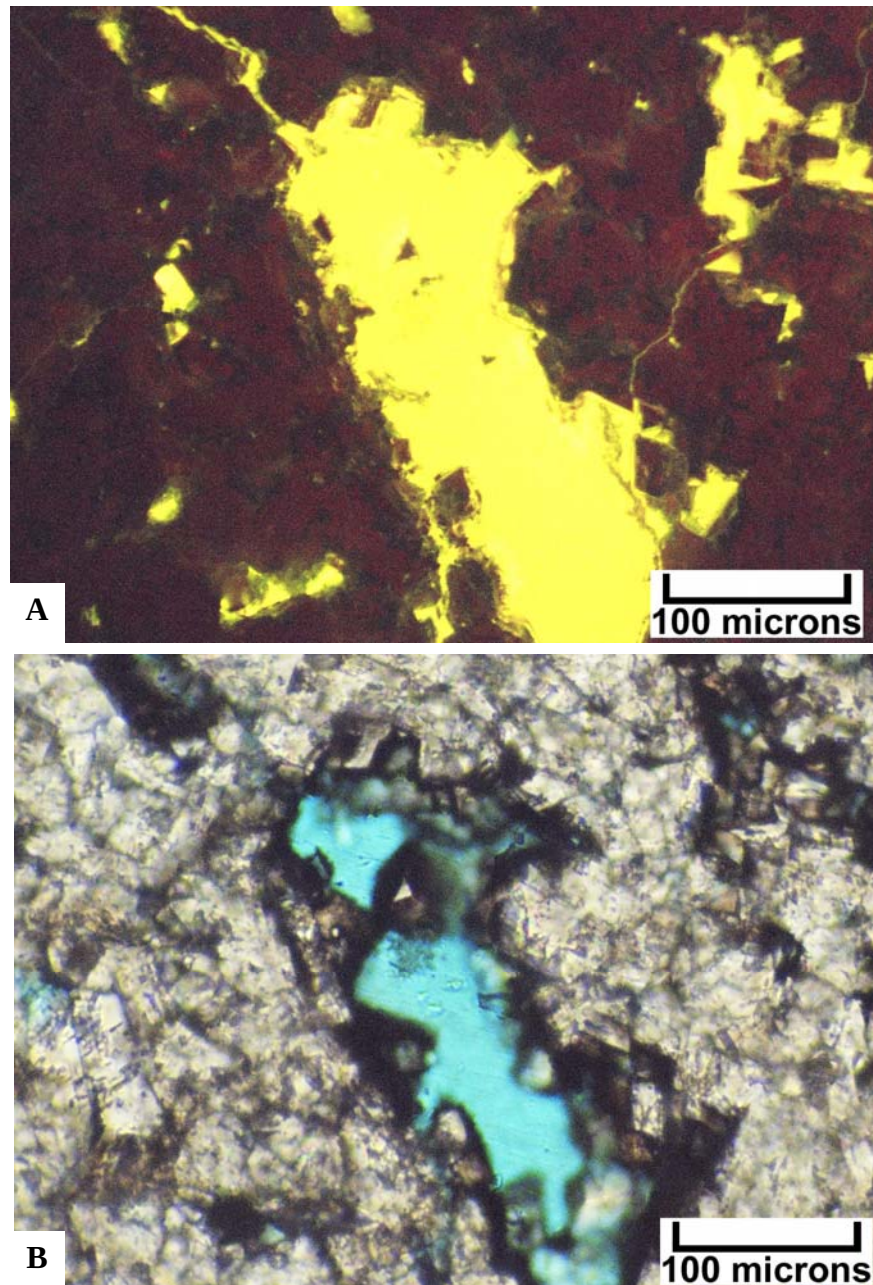


Figure 21. Photomicrographs from Lisbon No. B-816 well at 8486 feet. A – Epifluorescence under moderate magnification, showing zoned, rhombic replacement dolomite with dead cores and highly fluorescent rims. B - The same field of view as above is shown under plane light at the same magnification. Note the large solution pore (blue area).

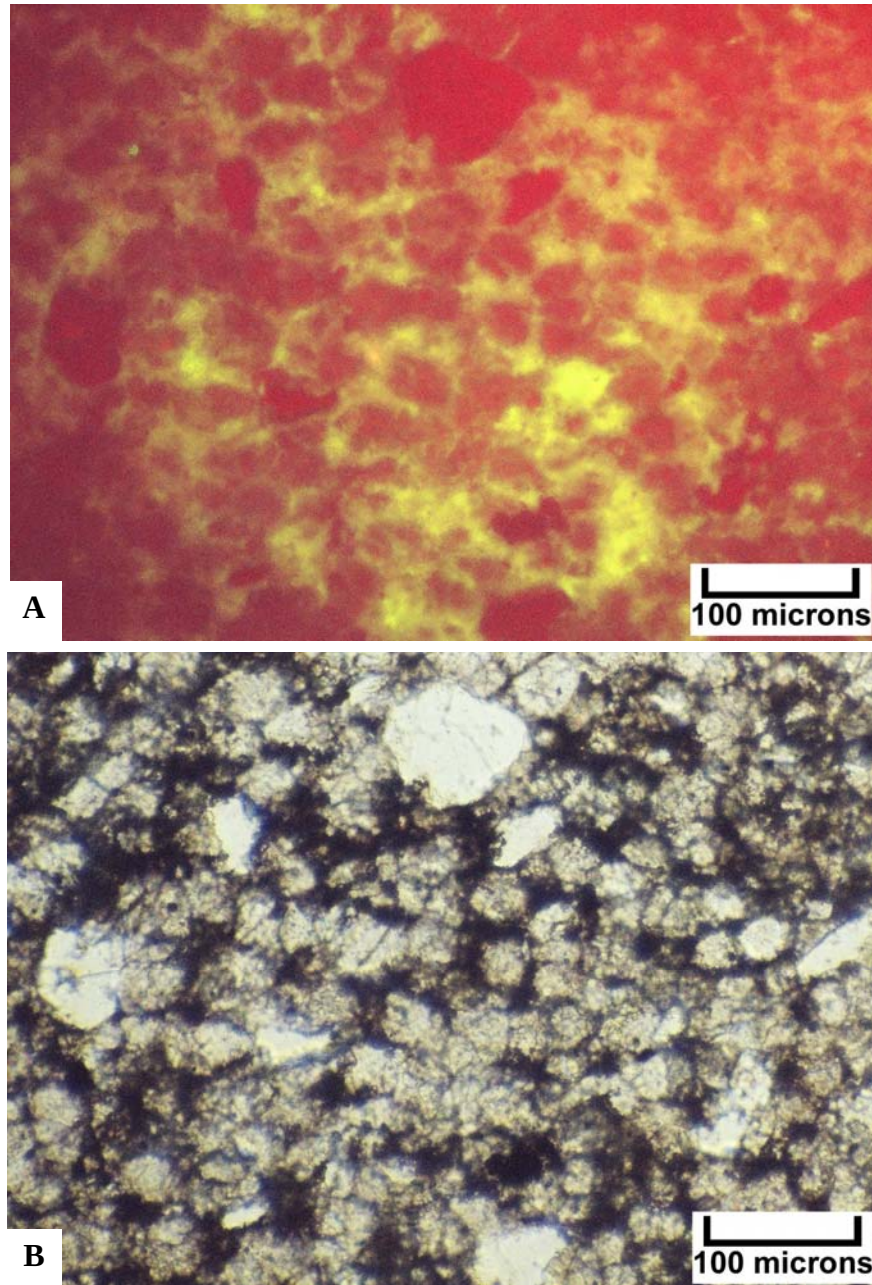


Figure 22. *Photomicrographs from Northwest Lisbon No. B-63 well at 9935.6 feet. A – Epifluorescence under moderate magnification, showing dolomitized detrital fill within a karst cavity. B - The same field of view as above is shown under plane light at the same magnification. Note the large quartz grains, and angular limestone and dolomite clasts. These clasts do not fluoresce.*

Lisbon No. B-816 well: Blue-light, EF microscopy shows replacement dolomite with highly yellow fluorescent rims (figure 21). Saddle dolomite cement has moderate yellow-green fluorescence. Late calcite cements are generally non-fluorescent.

Lisbon NW USA No. B-63 well: Blue-light, EF microscopy shows massive, very finely crystalline, non-porous syngenetic dolomite displaying a mottled dull to medium yellow fluorescence with occasional ghosts of original grain types (can see grain outlines with fluorescence). Dolomitized grains include detrital carbonate (pellets) and siliciclastic (quartz silts and clays) components of the karst cavity infilling (figure 22); clay minerals between grains display a pale reddish fluorescence. Outside of the cavity, the host rock is almost pure limestone composed of fossils and coated grains – all calcitic with little visible fluorescence.

Late calcite (poikilotopic) also displays no fluorescence. This late calcite occurs as cements within former isolated molds, fracture fillings, and some replacement of syngenetic dolomitic matrix.

CATHODOLUMINESCENCE

Introduction

Cathodoluminescence (CL) is the emission of light resulting from the bombardment of materials using a cathode ray (Allan and Wiggins, 1993). This petrographic technique can be an invaluable tool in petrographic studies of carbonate rocks. This technique can provide important information about the complex modification of rock fabrics and porosity within the Leadville Limestone of the Paradox Basin. Diagenesis played a major role in the development of reservoir heterogeneity in Lisbon field as well as throughout all of the Leadville fields. Diagenetic processes started during deposition and continued throughout burial history (figure 9). A complete discussion on the diagenetic history based upon visual core examination and thin-section petrography was documented previously by Chidsey and others (2005).

Cathodoluminescence has been used in recent years to provide insights into the chemical differences between preserved remnants of depositional components resulting from various diagenetic events in carbonate rocks as recognized from core examination and thin-section petrography. In particular, CL provides visual information on the spatial distribution of certain trace elements, especially manganese (Mn^{2+}) and iron (Fe^{2+}) in calcites and dolomites (Machel and Burton, 1991; Scholle and Ulmer-Scholle, 2003). The visible CL responses are red to orange in color, and their intensity is usually described as non-luminescent, dull luminescent, and brightly luminescent. As a general rule, incorporation of Mn^{2+} into the calcite lattice stimulates luminescence and the incorporation of Fe^{2+} quenches or reduces luminescence (Fairchild, 1983; Allan and Wiggins, 1993; Scholle and Ulmer-Scholle, 2003). Qualitative interpretation of CL usually assigns non-luminescent responses to oxidizing settings in which the reduced forms of both Mn and Fe are unavailable for incorporation into the lattices of carbonate mineral precipitates. Oxidized forms of Mn and Fe are not incorporated into calcite or dolomite crystals. Therefore, there is nothing in these crystals to excite luminescence. Bright luminescence is related to carbonate precipitates with high Mn/Fe trace element ratios, typically as a result of reducing environments during early (near-surface) to intermediate stages of burial diagenesis. Dull luminescence seems to happen where the Mn/Fe trace element ratios

are present in carbonate precipitates. Thus, dull luminescence is usually thought to be the result of intermediate to late stages of burial diagenesis. It appears that elements other than Mn and Fe do not have any appreciable effect in enhancing or reducing luminescence (Budd and others, 2000).

Particularly useful references on the uses and limitations of CL interpretations in ancient carbonate studies include Sipple and Glover (1965), Frank and others (1982, 1996), Marshall (1988), Hemming and others (1989), Barker and Kopp (1991), Gregg and Karakus (1991), Machel (2000), Lavoie and others (2001), Coniglio and others (2003), and Lavoie and Morin (2004).

Methodology

The analysis done in this study was completed using uncovered, polished thin sections, although rock chips and unpolished thin sections could be used. The equipment needed for CL can be installed on almost any polarizing microscope (see Marshall, 1988; Miller, 1988). A Cambridge Image Technology Ltd. luminoscope (model CLmk3A/4) mounted on an Olympus petrographic microscope (figure 23; see also Marshall, 1988) belonging to the Colorado School of Mines Department of Geological Engineering was used for this analysis (figure 24). Operating conditions were generally at 10-16kV accelerating potential, 0.5-0.7 mA of beam current, and a beam focused at ~2 cm. All the work involved visual observations and some photographic documentation. Photomicrographs were recorded on a digital camera. No attempt was made to measure intensities or spectral information on the CL responses (for example Marshall, 1991; Filippelli and Delaney, 1992) to the Leadville carbonate samples. Image analysis and regional mapping of cement zones (that is “cement stratigraphy”) have been done by some workers on carbonate cements (for example Meyers, 1974, 1978, 1991; Dorobek and others, 1987; Cander and others, 1988; Dansereau and Bourque, 2001), but these applications are beyond the scope of diagenesis documentation attempted in this project.

Cathodoluminescence Petrography of Leadville Limestone Thin Sections

Cathodoluminescence examination was completed on four thin-section samples from the Leadville limestone and dolomite within Lisbon field (Appendix C). These thin-section samples were selected to be representative of mineralogy (for example dolomite, calcite, anhydrite, and quartz), composition, diagenesis, and pore types encountered within typical cores from the field (see figure 7 for core locations). The following remarks summarize our findings.

Lisbon No. D-816 well, 8442-8443 feet: Cathodoluminescence shows a wide range of crystal size and growth habits within the dull-red-luminescing, matrix-replacing dolomite (figure 25). The vast majority of the dolomite within areas of fabric selective dolomitization is a deep or intense red color. Between many of the grains, there is a lighter red luminescence where early cements have been dolomitization. Some of the coarser dolomite crystals appear to have an overgrowth of brighter red luminescent material. The range in dolomite rhomb sizes may reflect rapid precipitation. The amount of open porosity under CL is considerably greater than that visible under plane light microscopy. Cathodoluminescence also displays original depositional textures and the outlines of original carbonate grains. Between other grains, there are interparticle pores that are still open. In a few areas, these early pores have been solution-enlarged and lined with a later generation of coarse, rhombic dolomite.

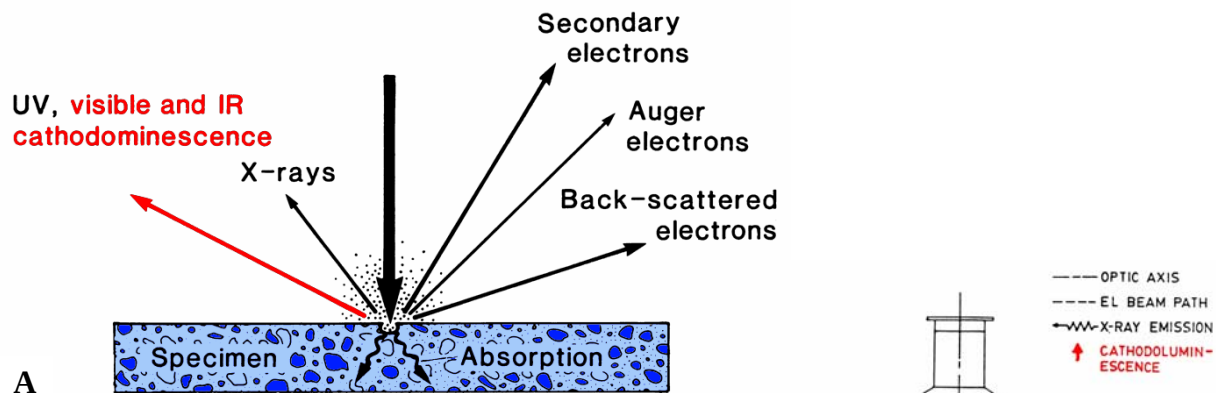
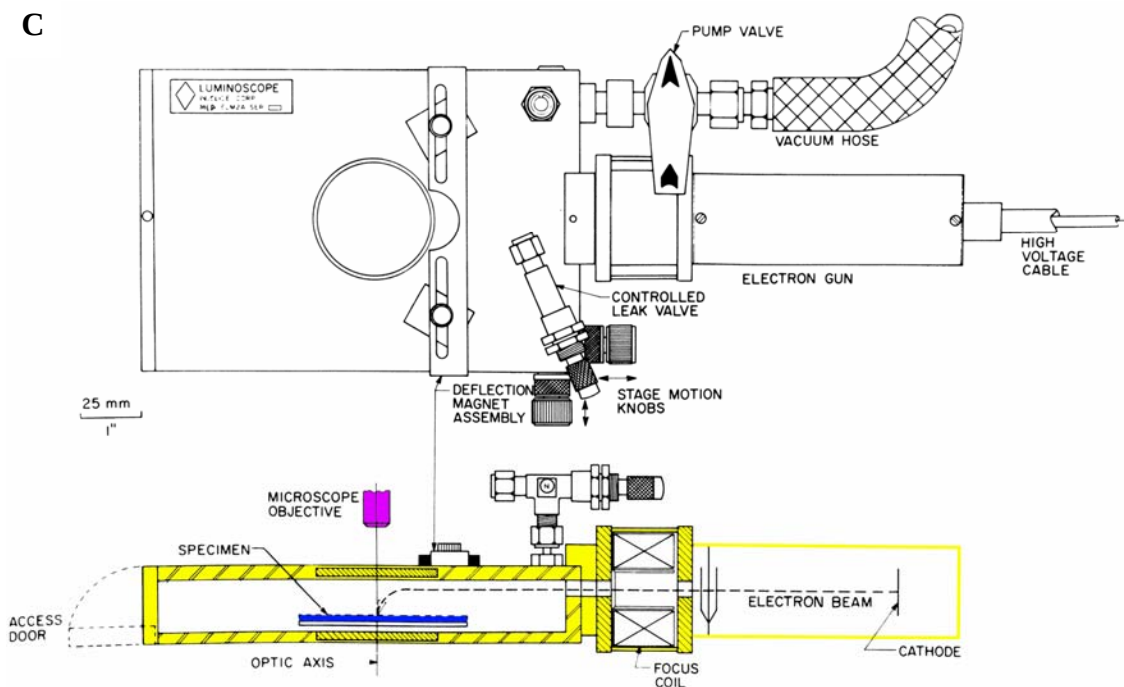
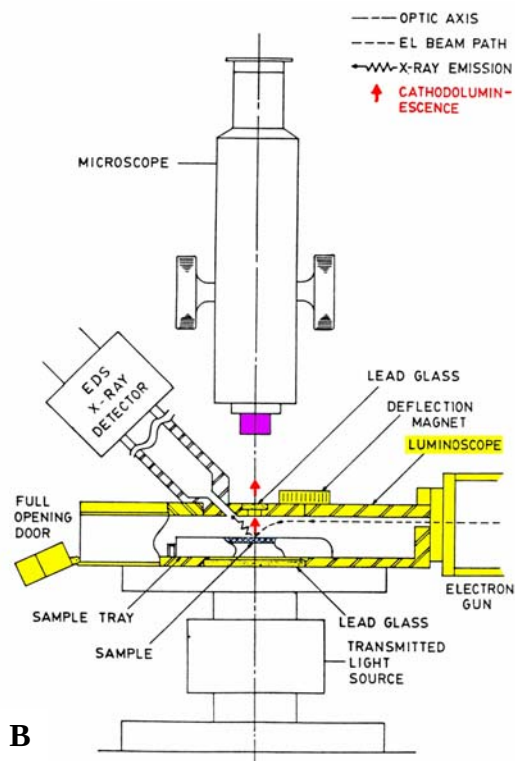


Figure 23. Generalized microscope optical configuration for observing cathodoluminescence (A modified from Walker and Burley, 1991; B modified from Marshall, 1991; and C modified from Marshall, 1988).



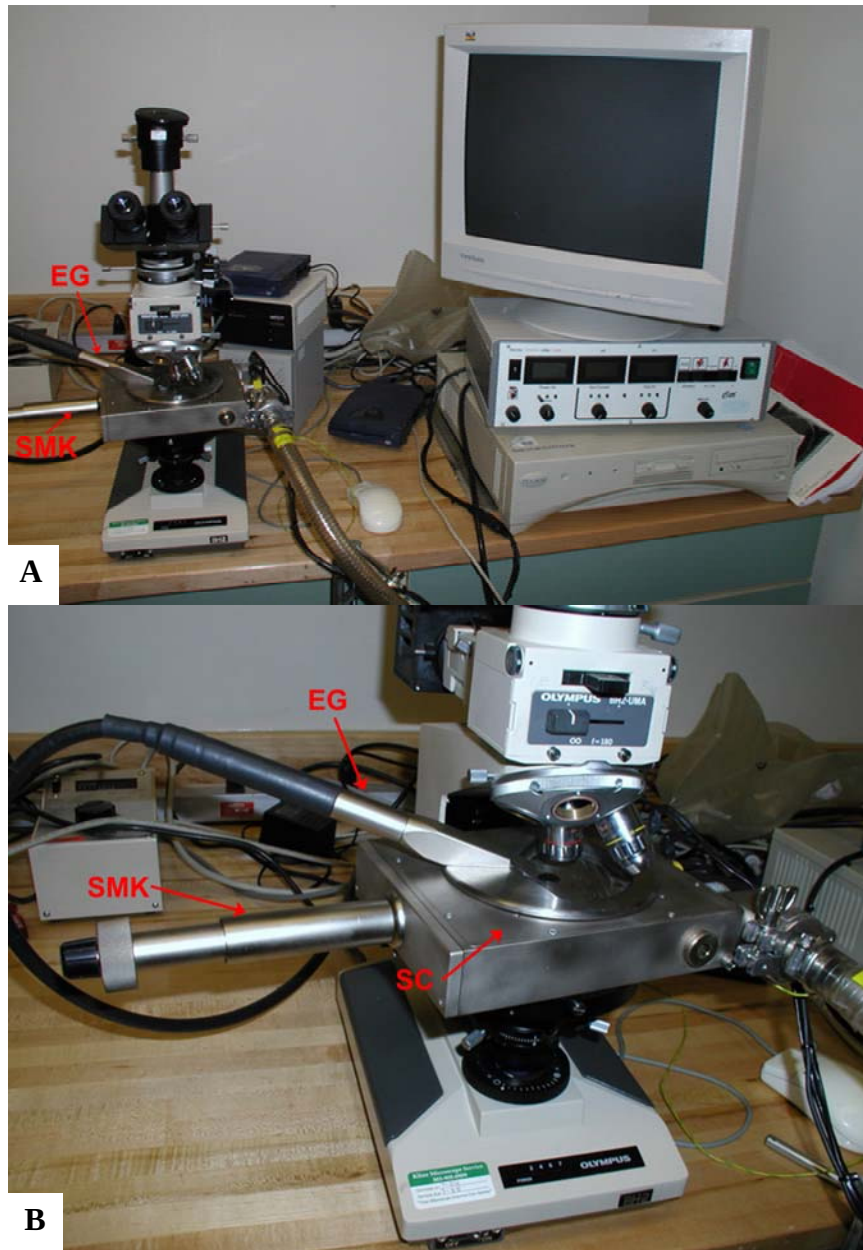


Figure 24. Colorado School of Mines cathodoluminescence setup used for the Leadville samples from Lisbon field. A - Cambridge Image Technology Ltd. CLmk3A/4 cathodoluminescence instrument is mounted on an Olympus BH2 petrographic microscope. The electron gun (EG) can be seen in the inclined position to the left of the sample chamber. The stage motion knob (SMK) is the silver cylinder to the left of the sample chamber. The hose to the vacuum pump can be seen to the right of the chamber. The front panel controls (beneath the video monitor) include (from left to right) the diagnostic selector, vacuum and diagnostic metering, gun current metering, gun kV metering, and main power switch. The video monitor and CPU were used for handling and displaying the CL images captured by a digital camera. B - Closeup of the cathodoluminescence instrument sample chamber (SC), electron gun (EG), and stage motion knob (SMK) mounted on an Olympus BH2 petrographic microscope.

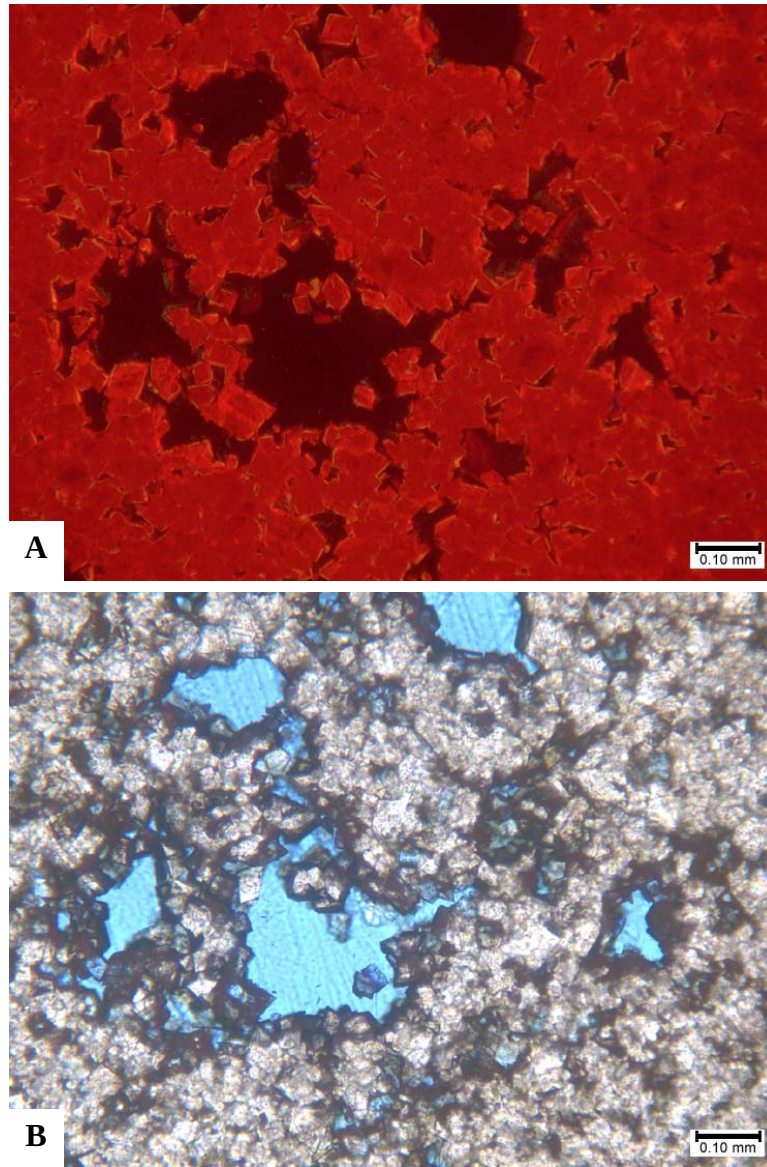


Figure 25. Photomicrographs from Lisbon No. D-816 well at 8442-8443 feet. **A** - Cathodoluminescence shows sharp outlines between the dolomite crystals and adjoining pore spaces. Note that the porosity (seen in black) in this sample seems to be a combination of intercrystalline space and solution-enlarged molds. The vast majority of the dolomite seen here consists of bright-red-luminescing dolomite with only minor thin rinds of dull-luminescing overgrowth. There are also rare non-luminescing dolomite cement crystals within some of the smaller pore spaces (see, for instance, the cement occluding a small pore in the lower center of this image). Finally, note that “ghosts” of former grains such as “hard” peloids can be seen in the luminescing pattern of the dolomites in the upper right corner of this view. **B** - The same field of view under plane light. The outlines of the dolomite crystals are not nearly as distinct and crisp here as in the previous CL view. In fact, it is difficult to pick out the crystal outlines or faces in this type of lighting. Black pyrobitumen makes it difficult to see the smaller, but important, intercrystalline pores. The larger solution-enlarged molds in blue are easy to see, but their interconnection through the smaller intercrystalline space is better seen under CL imaging.

Lisbon No. D-816 well, 8433 feet: Cathodoluminescence imaging was very useful in identifying various generations of dolomite. Two types of CL response are visible within these moderately coarse dolomite crystals. Bright red luminescence can be seen within the interiors of most of the replacement dolomite (figure 26). However, many of the crystals exhibit non-luminescent overgrowths of variable thickness. In addition, some crystals exhibit mostly non-luminescent material. These particular crystals may be largely dolomite cements. Finally, some dolomite crystals exhibit a thin rind of red-luminescing dolomite overlying the non-luminescent overgrowth stage. It is possible that the red-luminescing dolomite is the product of the replacement of a previous limestone or earlier dolomite matrix while the non-luminescing crystal additions may be overgrowth cements growing into open pores. Dissolution and corrosion of some crystals is evident between the second (non-luminescent) and the final luminescent rim.

Lisbon No. B-816 well, 8486 feet: Cathodoluminescence imaging was very useful in identifying the presence of saddle dolomites (Radke and Mathis, 1980) within microporous dolomites (figure 27). Large dolomite crystals (1.0 to 2.0 mm in diameter) with distinctly curved crystal faces occur as both replacements of finer, earlier dolomites, and as pore-filling cements. These saddle dolomites display dull, red luminescence in their core areas and slightly bright, orange-red luminescence toward their rim areas. In addition, CL makes it possible to see the growth bands in these coarse dolomite crystals due to slight luminescence differences between each growth zone.

In general, the presence of saddle dolomites within a carbonate sample is indicative of the growth of strained, slightly iron-rich, dolomite replacements and cements under elevated temperatures during burial conditions (Radke and Mathis, 1980). Thus, saddle dolomite, as well as the other coarse dolomite crystals with reddish luminescence, are probably late, burial or hydrothermal dolomites. Additional published descriptive work on saddle dolomites using CL may be found in LaVoie and Morin (2004).

Lisbon No. D-616 well, 8308 feet: Sediment-filled cavities are relatively common throughout the upper third of the Leadville Limestone in Lisbon field. These cavities or cracks were formed by karstification of the exposed Leadville. Infilling of the cavities by detrital carbonate and siliciclastic sediments occurred before the deposition of the Pennsylvanian Molas Formation. Cathodoluminescence imaging shows that the contact between the transported material and the limestone country rock can be sharp, irregular, and corroded with small associated mud-filled fractures (figure 28). 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.

FLUID-INCLUSION SYSTEMATICS OF LISBON FIELD SAMPLES

Introduction

During crystal growth, imperfections may trap fluids present in the environment at that time. Later mineral precipitation and deformation, such as the development of fractures, can

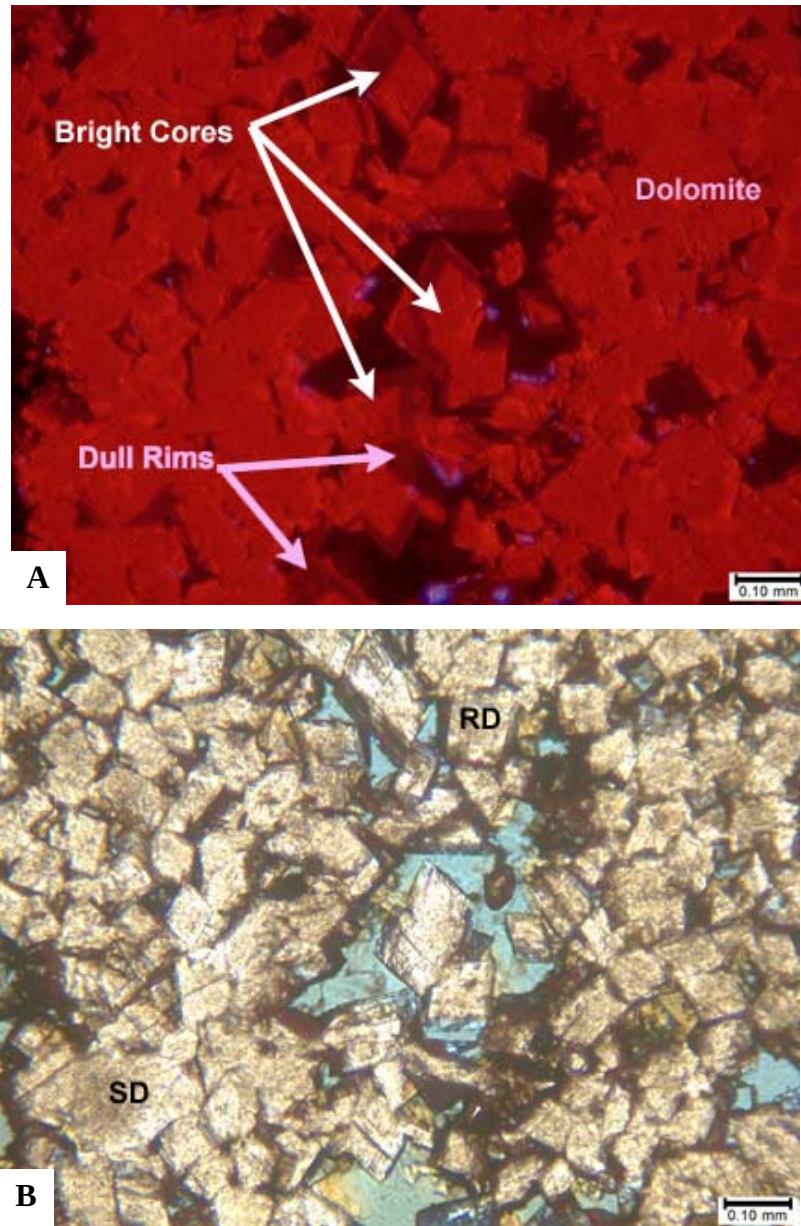


Figure 26. Photomicrographs from Lisbon No. D-816 well at 8433 feet. A - This CL image shows beautiful luminescence zonation of many of the dolomite crystals, especially in a band from the top center to the bottom center of the image. Note the bright-red-luminescing dolomite cores surrounded by rim zones of non-fluorescent overgrowth. The black areas on this image are currently open pore spaces. B - The same field of view under plane light showing replacement dolomite (RD) and saddle dolomite (SD). The dolomite crystals shown here are well formed with planar crystal faces and generally rhombic outlines. Note that some crystal terminations may display curved (or saddle) outlines. Plane light does not make it possible to distinguish the crystal composition zonation imaged in the CL photomicrograph. The black areas within this field of view are due to pyrobitumen coatings on many of the dolomite crystal surfaces. The blue areas between many of the replacement dolomite crystals are open pores.

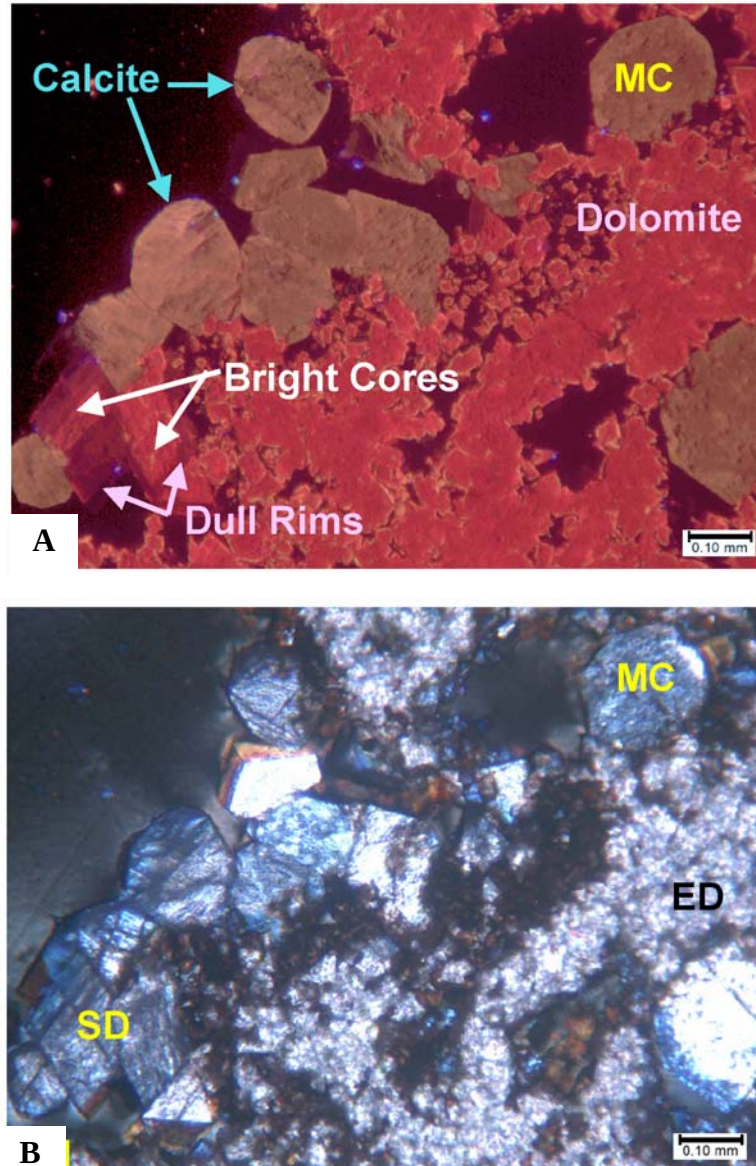


Figure 27. Photomicrographs from Lisbon No. B-816 well at 8486 feet. **A** - This area of high matrix porosity (in black) shows early replacement dolomite (ED) that displays intense red luminescence. Some of these replacement crystals display very thin orange overgrowths. However, some of the largest dolomite rhombs (saddle dolomite [SD]) in this field of view display a coarser crystal zonation in which the bright-red-luminescent core is overgrown with thick, dull-luminescent rims (see the lower left corner of this photomicrograph). Finally, note the large, late calcite spar crystals (macrocalcite [MC]) with orange luminescence within the large pores from lower left to upper right as well as in the lower right portion of this view. **B** - The same field of view under crossed nicols. Note that some of the large dolomite crystals in the lower left portion of this image display sweeping extinction and possibly curved crystal faces that are consistent with probable saddle dolomites. The replacement dolomites throughout most of this field of view are too small or too inclusion-rich to distinguish extinction patterns. The late calcite spar cements generally display straight extinction.

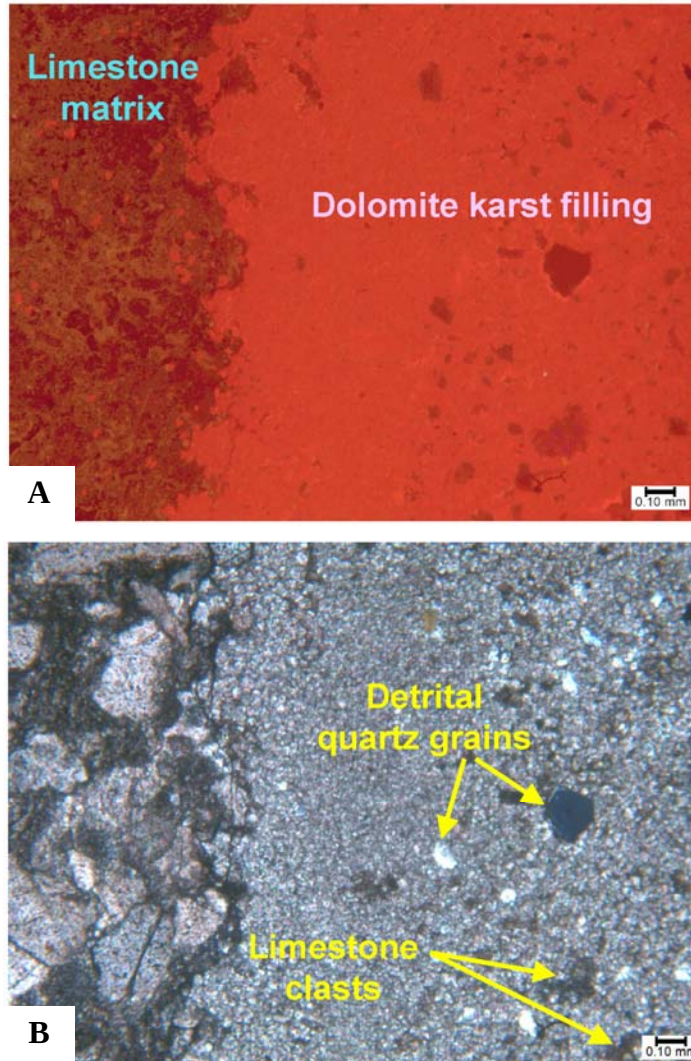


Figure 28. Photomicrographs from Lisbon No. D-616 well at 8308 feet. **A** - This low-magnification image nicely shows a sharp contact that runs from top to bottom toward the left side of the photomicrograph. The bright red field is composed mostly of dolomite, while the field with the orangish cast (to the left) is almost entirely limestone. The dolomite area is composed of carbonate grains and sediments that have filled a karst-related crack or cavity. The poorly sorted, angular grains that are seen “floating” within the dolomite field are a combination of detrital siliciclastic (mostly quartz) grains and lithified limestone clasts. The limestone field along the left side of the photomicrograph is composed of non-luminescent skeletal (crinoid-rich) sediments with orangish cements. Neither the dolomite with siliclastic sediments nor the limestone display any visible matrix porosity. The contact between the dolomite and limestone fields is irregular but sharp. Finally, there are few scattered replacement dolomite rhombs (also with red luminescence) within the well-cemented limestone. **B** - The same field of view under crossed nicols. Note that the siliciclastic grains within the microcrystalline dolomite field display plane extinction positions with colors ranging from white to yellow to dark grain. The polygonal grain in the right center contains overgrowths that form a prismatic quartz form in cross section. In the limestone field to the left, many of the fossils are surrounded by straight extinction syntaxial cements.

create additional crystal imperfections that may also trap fluids (figure 29). These fluid inclusions are defined as fluid-filled vacuoles, typically 5 to 20 microns in size. They provide pressure, volume, and temperature information about the conditions when the crystal precipitated (Paul Carey and John Parnell, University of Aberdeen, written communication, 2005). The fluids in the inclusion may be connate water, oil, or a sample of the mineralizing fluid. The following properties are assumed not to have changed since an inclusion formed: (1) the composition of the trapped fluid, (2) the density of the trapped fluid, and (3) the volume of the inclusion (Paul Carey and John Parnell, University of Aberdeen, written communication, 2005). The study of fluid inclusions can help determine (1) the temperature of mineral precipitation, (2) the composition and origin of mineralizing fluids, (3) later history of temperature, pressure, and fluid composition, (4) petroleum migration history, (5) relative timing of porosity occlusion, and (6) deformation event conditions (Paul Carey and John Parnell, University of Aberdeen, written communication, 2005).

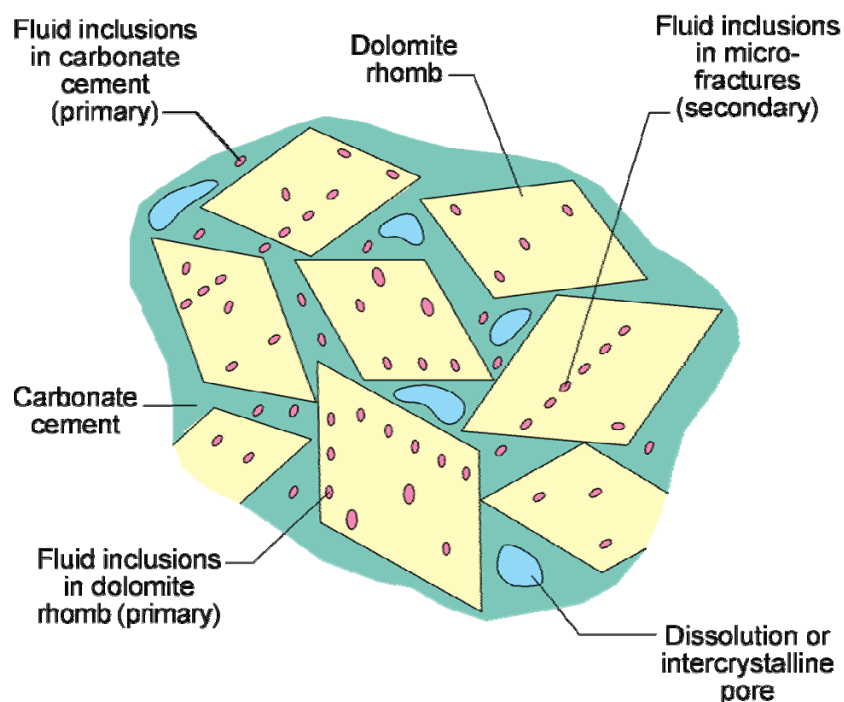


Figure 29. Schematic diagram of basic fluid inclusion types.

Fluid inclusions trapped in calcite, quartz, and dolomite were studied from three wells: Lisbon NW USA No. B-63, Lisbon No. D-616, and Lisbon No. D-816 (figure 7). The inclusions were categorized on the basis of origin, number of phases present, and composition. All inclusions were classified as either primary or secondary. Primary inclusions are trapped at the time of mineral growth; secondary inclusions are trapped along healed fractures. Primary inclusions typically define growth zones, although in quartz, large isolated inclusions are typical. All of the inclusions observed contained either one or two fluid phases at room temperature. Inclusions containing brine and vapor are the most common, but single-phase aqueous inclusions, gas-rich inclusions, and inclusions consisting of oil and vapor are present. Single-phase aqueous inclusions are indicative of trapping at temperatures less than 50°C (~122°F) (Goldstein and Reynolds, 1994).

Fluid-Inclusion Measurements

Heating and freezing measurements were made on doubly polished thick sections and hand picked crystals using a Linkham THSMG 600 freezing and heating stage calibrated with synthetic fluid inclusions. The data are tabulated in Appendix D. The precision of the measurements is estimated to be $\pm 0.1^{\circ}\text{C}$ at 0.0°C and $\pm 3^{\circ}\text{C}$ at 374°C (5°F at 705°F). Homogenization and ice-melting temperatures were measured. Homogenization temperatures are minimum trapping temperatures. Ice-melting temperatures provide a measure of the fluid salinity. The salinities of the two-phase aqueous inclusions with ice-melting temperatures between 0 and -21.2°C (32 and -6.2°F) were converted to weight percent NaCl equivalent using the equation of Bodnar (1993). Salinities of inclusions with lower ice-melting temperatures displayed eutectic (first melting) temperatures of $<-45^{\circ}\text{C}$ (-49°F), indicating the presence of divalent ions (most likely Ca and Mg). These inclusions had ice-melting temperatures as low as about -27°C ($\sim -17^{\circ}\text{F}$). The equation of Bodnar (1993) cannot be used to calculate the salinities of these fluids. As a first approximation, assuming that only Ca, Na, and water are present in the inclusions, the salinities would be in the range of 25 to 30 weight percent NaCl-CaCl₂ equivalent (Yanatieva, 1946). Such high-salinity brines imply interactions with evaporite deposits.

Caveats and Practical Aspects of Fluid-Inclusion Studies

Several factors can affect the utility and validity of fluid-inclusion measurements and these factors can play a significant role in sedimentary environments. Two general tenets of fluid-inclusion research are that: (1) the volume of the cavity has not changed since generation of the vapor bubble, and (2) the bulk composition of the inclusion has remained constant. However, both the volume and compositions of the inclusions can be modified by necking, stretching, refilling, and leakage. As a general rule of thumb, a population of fluid inclusions that formed contemporaneously (termed a fluid inclusion assemblage by Goldstein and Reynolds, 1994) will yield homogenization temperatures within 15 to 20°C (27 - 36°F) of each other.

All fluid inclusions neck or anneal after trapping as the temperatures decrease. This process typically leads to the splitting of a large inclusion into a number of smaller inclusions. Necking occurring after generation of the vapor bubble is recognized by the petrographic association of inclusions with variable liquid to vapor ratios. Many of the inclusions in calcite and dolomite have variable liquid to vapor ratios. Qualitatively, the presence of all inclusions with vapor bubbles, but variable ratios, suggests necking occurred at elevated temperatures greater than at least 50°C (122°F). Although the homogenization temperatures of necked inclusions are not meaningful, because they can be both greater and lower than the true homogenization temperature, the minimum homogenization temperatures can provide a qualitative measure of the minimum temperatures that have affected the rocks. The salinities of necked inclusions, however, are not greatly affected by necking and can be measured and used. Oil inclusions are less prone to necking than aqueous inclusions, although some secondary inclusions in the latest calcite clearly displayed evidence of necking.

Stretching is the inelastic expansion of the fluid inclusion leading to an increase in its volume. This can lead to the generation or growth of a vapor bubble, which in turn yields an anomalously high temperature of homogenization. The degree of stretching is highly variable

even within a single crystal. Its effect is dependent on original fluid inclusion size, shape, location in a crystal, degree of overheating, pressure, and fluid composition. Often a significant percentage of the inclusions will retain their original characteristics. For example, single-phase inclusions, if originally present, will persist after stretching. Stretched inclusions do not yield meaningful homogenization temperatures. The salinities of stretched inclusions, however, can be utilized.

Refilling of fluids may be common but is difficult to recognize. Both the homogenization temperatures and compositions can be utilized. Refilling of fluids can be recognized by comparing the fluid inclusion characteristics of minerals whose relative ages are known.

Leakage of fluids, particularly the liquid phase, from fluid inclusions is also common. Leaked inclusions are typically vapor-rich. Leakage can often be recognized because it will often affect only a small percentage of the total fluid inclusion population.

Fluid Inclusions in Early Calcite

Early calcite represents original fossil material (figure 30). It is characteristically coarsely crystalline and decorated with abundant aqueous liquid-rich inclusions with variable liquid to vapor ratios (figure 31). Less commonly, oil inclusions are present (figures 32 and 33). The vast majority of both the aqueous and oil inclusions are randomly distributed throughout the calcite crystals and appear to be primary in origin. Secondary inclusions defining healed fractures are uncommon.

The characteristically variable liquid to vapor ratios of the aqueous inclusions are interpreted as resulting from necking. Reconnaissance homogenization temperature measurements on spatially associated inclusions have temperatures greater than 20°C (>68°F) and are consistent with this interpretation. These homogenization temperatures are not considered meaningful and are not reported here. However, the occurrence of all two-phase inclusions, in contrast to the presence of numerous single-phase, liquid inclusions in dolomite suggests the inclusions in calcite were trapped at elevated temperatures.

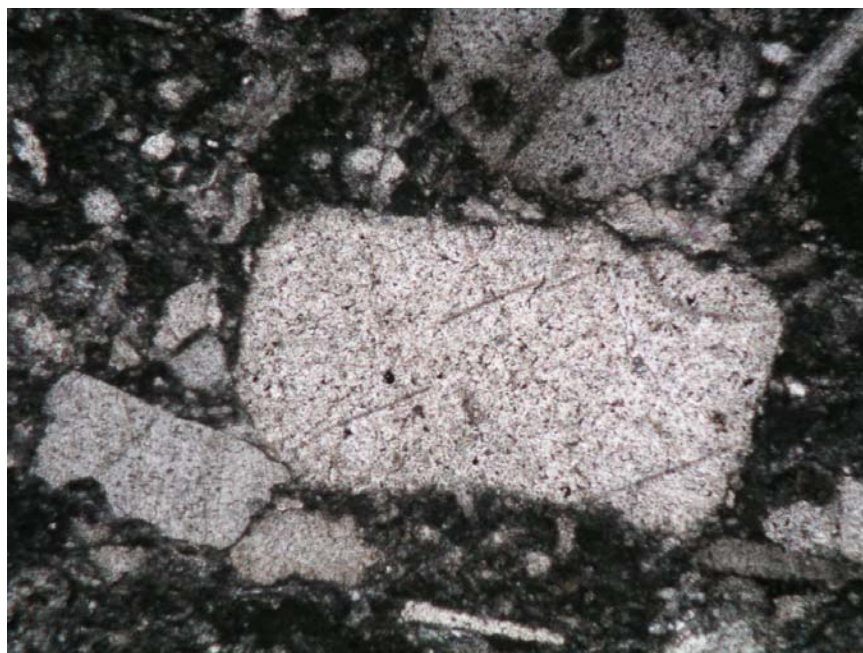


Figure 30. Early calcite from the Lisbon No. D-616 well at 8356 feet. The mottled appearance of the calcite is due to abundant fluid inclusions. Width of image is 3.3 mm.

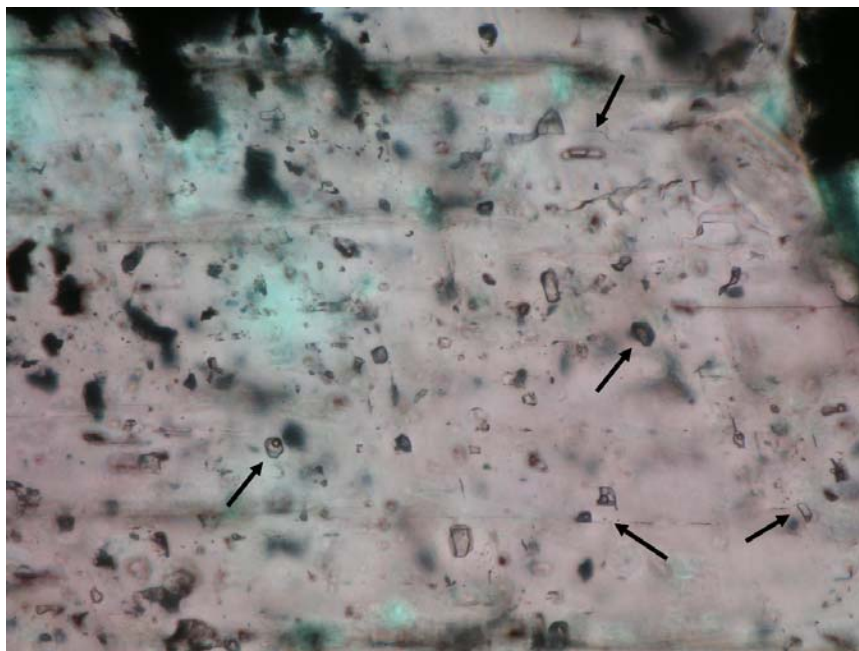


Figure 31. *Fluid inclusions in early calcite from the Lisbon No. D-616 well at 8356 feet. Arrows point to inclusions with different liquid to vapor ratios, resulting from necking after trapping. Width of image is 0.7 mm.*



Figure 32. *Brown primary oil inclusion (arrow) in calcite from the Lisbon No. D-616 well at 8356 feet. Clear inclusions are aqueous. Width of image is 0.3 mm.*

Ice-melting temperatures were measured on the aqueous inclusions in two samples from Lisbon No. D-616 well (figure 34). These temperatures ranged from -19.5 to -25.5°C (-3.1 to -13.9°F) indicating that the fluids were highly saline.

Early calcite containing primary oil inclusions was found in Lisbon No. D-616 well at a depth of 8356 feet (2547 m) (figures 32 and 33). The color of the oil under fluorescent light suggests it has an API gravity of 35 to 45° (Goldstein and Reynolds, 1994). Twelve primary oil inclusions were measured in a single calcite crystal. All but two yielded homogenization temperatures ranging from 48 to 68°C (118-154°F). The oil is interpreted as having formed in place from trapped organic material. The homogenization temperatures are minimum trapping temperatures.

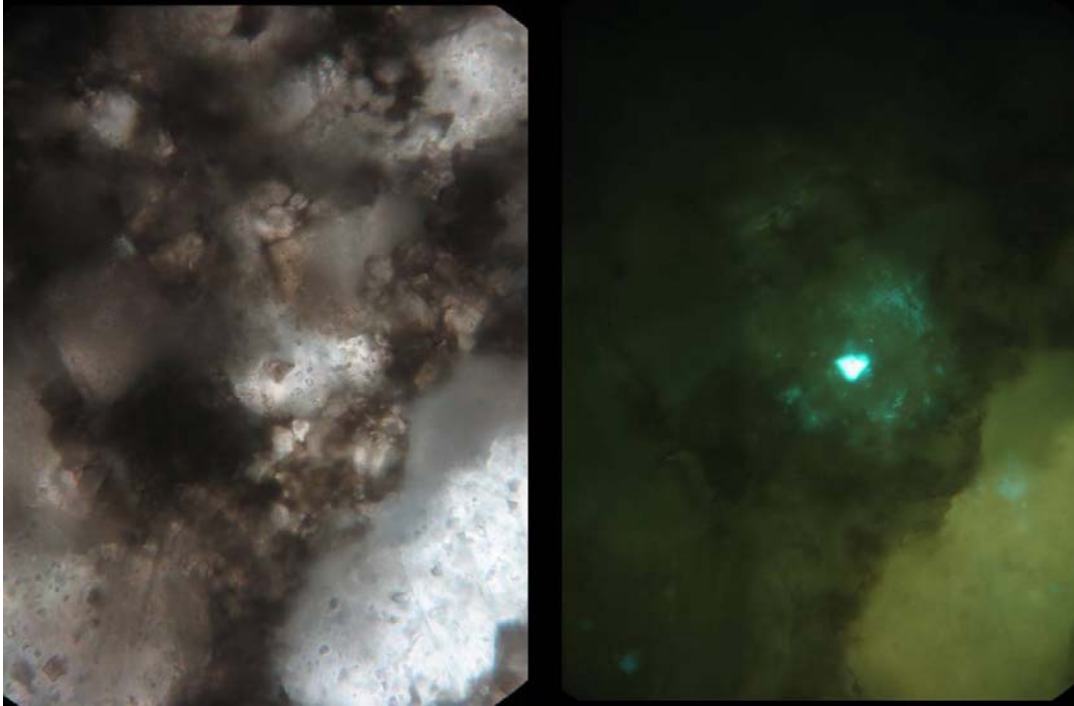


Figure 33. Primary oil inclusion in calcite from the Lisbon No. D-616 well at 8356 feet. Right-hand image taken under fluorescent light shows that the oil is live. Height of image is 0.3 mm.

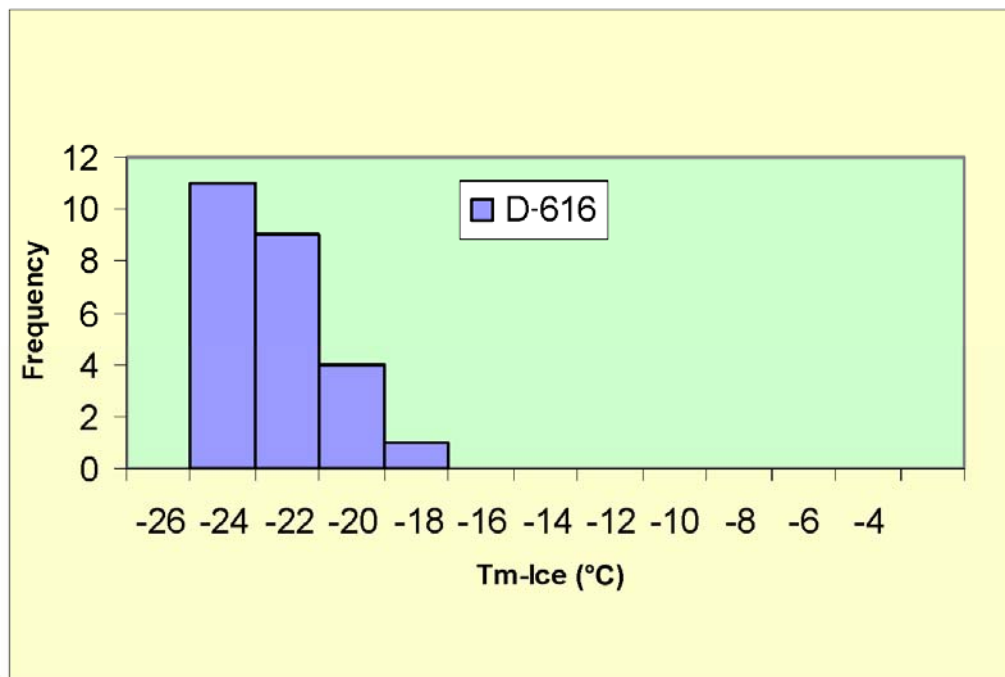


Figure 34. Ice-melting temperatures of fluid inclusions in early calcite from the Lisbon No. D-616 well at 8356 feet and 8372 feet.

Although the aqueous and oil inclusions appear primary in origin, they clearly could not have been present at the time the fossils were deposited. Furthermore, the phase relationships indicate the aqueous inclusions cannot be regarded as original inclusions that have stretched. The most likely explanation for the distribution and character of these calcite-hosted inclusions is that the original calcite has recrystallized and that the fluids were trapped during recrystallization. Oil inclusions in saddle dolomite suggest a similar history.

Fluid Inclusions in Dolomite

Dolomite fills voids and replaces early calcite. Early dolomite is typically fine grained; later saddle dolomite is coarser grained. Small fluid inclusions, most of which are less than a few micrometers in length, are common in dolomite (figure 35). These inclusions define growth zones, and consequently are interpreted as being primary in origin. Coarse-grained saddle dolomite frequently contains cloudy cores and clear rims.

Only aqueous inclusions were observed in the early fine-grained dolomite. Later saddle dolomite contains both aqueous and oil inclusions. Although many of the aqueous inclusions appear to contain only a single liquid phase, aqueous inclusions with variable liquid to vapor ratios are not uncommon. Reconnaissance measurements indicate that the two-phase (liquid plus vapor) inclusions commonly have homogenization temperatures ranging from 70 to 135°C (158-275°F), although inclusions having homogenization temperatures several tens of degrees higher are locally abundant. Fluid inclusions trapped during mineral growth at temperatures greater than 70°C (>158°F) will typically contain a vapor bubble. The common absence of a vapor bubble in many of the primary inclusions is inconsistent with dolomite formation at elevated temperatures and suggests that (1) the dolomite formed at temperatures of less than about 50°C (~122°F), (2) the fluid inclusions have re-equilibrated (necked, stretched, or refilled), and (3) the homogenization temperatures of the two-phase inclusions are meaningless.

Ice-melting temperatures of inclusions trapped in fine-grained dolomite from depths of 8372 feet (2552 m) in Lisbon No. D-616 well and 8444 feet (2574 m) in Lisbon No. D-816 well and from the clear rims of saddle dolomite from a depth of 9939 feet (3029 m) in Lisbon NW USA No. B-63 well are shown in figure 36.

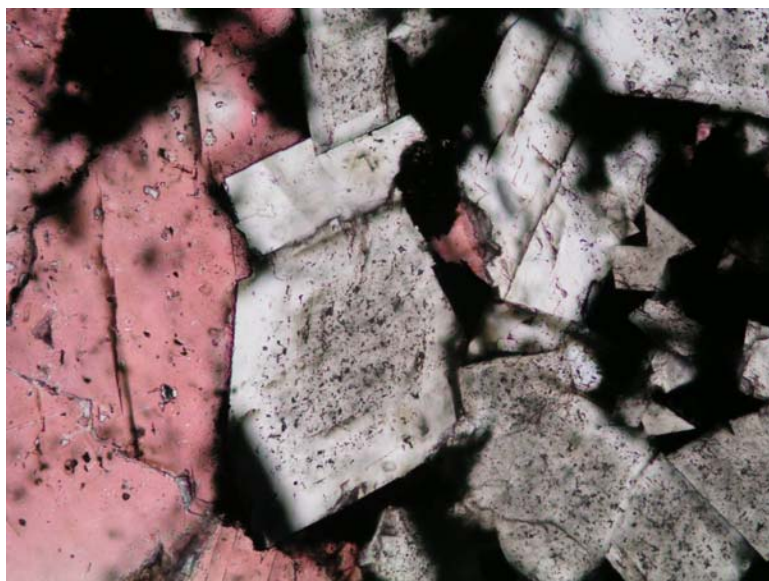


Figure 35. Dolomite (colorless) and calcite (red) from the Lisbon NW USA No. B-63 well at 10,004 feet. The cloudy appearance of the dolomite is due to abundant fluid inclusions. Saddle dolomites (center of photo) typically have cloudy cores and clear rims. Width of image is 3.3 mm.

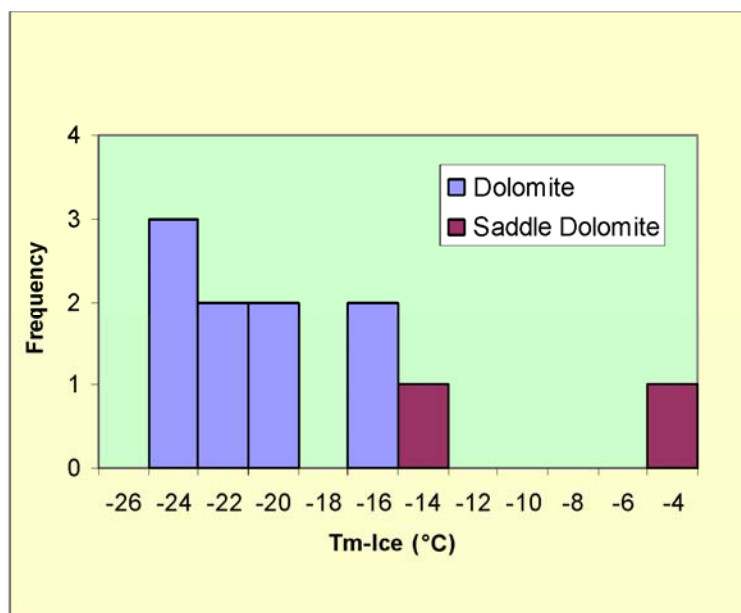


Figure 36. Ice-melting temperatures of dolomite-hosted fluid inclusions. Samples from depths of 8372 feet in the Lisbon No. D-616 well, 8444 feet in the Lisbon No. D-816 well, and from the clear rims of saddle dolomite from a depth of 9939 feet in the Lisbon NW USA No. B-63 well.

Oil inclusions occur in saddle dolomite from a depth of 9939 feet (3029 m) in Lisbon NW USA No. B-63 well (figure 37). The inclusions appear primary, occurring in light-colored portions of the crystal. Figure 38 shows that the early, dark-colored growth zones are truncated by the lighter colored dolomite, suggesting that the dolomite recrystallized during burial. These relationships indicate that the oil was trapped during recrystallization. Homogenization temperatures of the oil inclusions, which range from 60 to 70°C (140-158°F) (figure 39), provide a minimum temperature for this recrystallization.

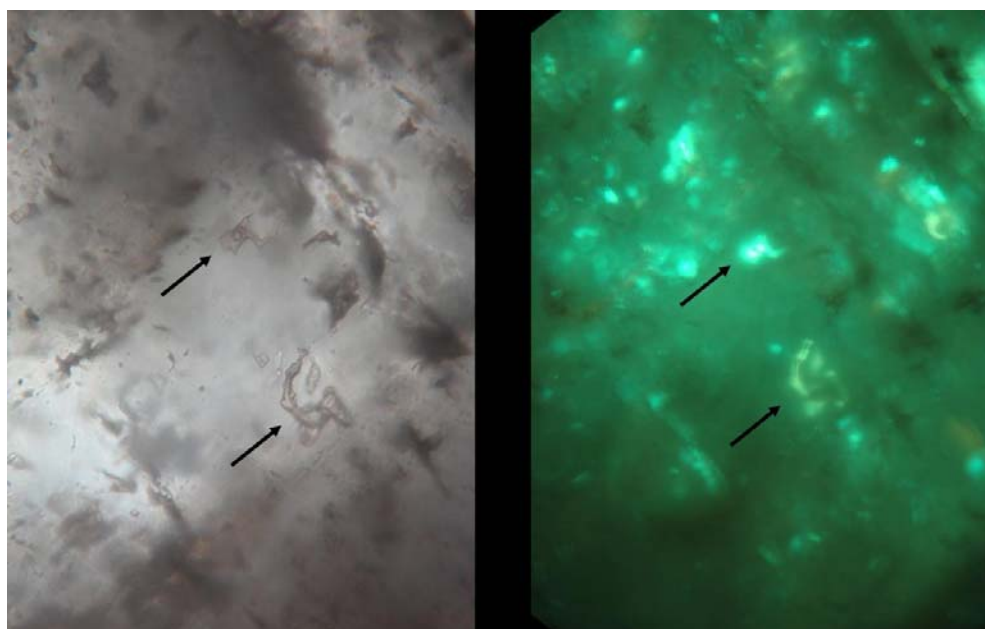


Figure 37. Oil inclusions in saddle dolomite from the Lisbon NW USA No. B-63 well at 9939 feet. Arrows point to two of the inclusions; others are apparent in the right-hand image taken under fluorescent light. Height of images is 0.3 mm.



Figure 38. Low-magnification image of saddle dolomite shown in figure 35. Dark growth zones are truncated near the left side of the oval. Oil inclusions in figure 35 occur in the light colored dolomite on right side of oval. Width of image is 0.7 mm.

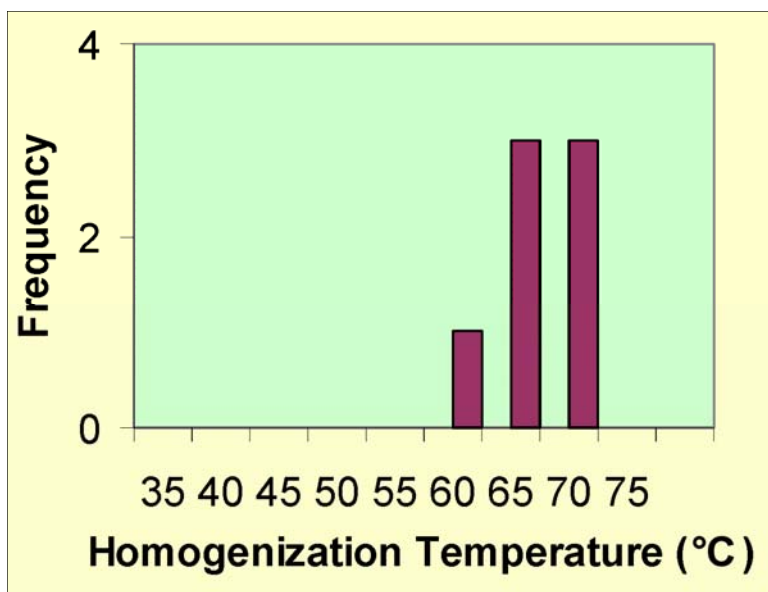


Figure 39. Homogenization temperatures of oil inclusions trapped in saddle dolomite from the Lisbon NW USA No. B-63 well at 9939 feet.

Fluid Inclusions in Quartz

Quartz occurs as fine- to medium-grained crystals that postdate dolomite. Figure 40 shows small quartz crystals filling cavities in dolomite. Larger euhedral quartz crystals encapsulate dolomite and anhydrite (figures 41 and 42). The anhydrite inclusions are frequently oriented and rounded, indicating they are remnants of large, partially dissolved crystals. Anhydrite has retrograde solubility (deposits as water is heated) whereas quartz has prograde solubility (deposits as fluids cool). These relationships suggest that the anhydrite formed from refluxing brines, whereas the later, laterally migrating or ascending cooling fluids that deposited quartz were undersaturated in anhydrite, leading to its dissolution.

The quartz crystals from a depth of 8356 feet (2547 m) in the Lisbon No. D-616 well commonly contain numerous two-phase aqueous inclusions; rarely, gas-rich and single-phase, liquid-rich inclusions are present. Figures 43 and 44 show quartz crystals containing primary liquid-rich inclusions. In figure 43, primary inclusions define a growth zone within the interior

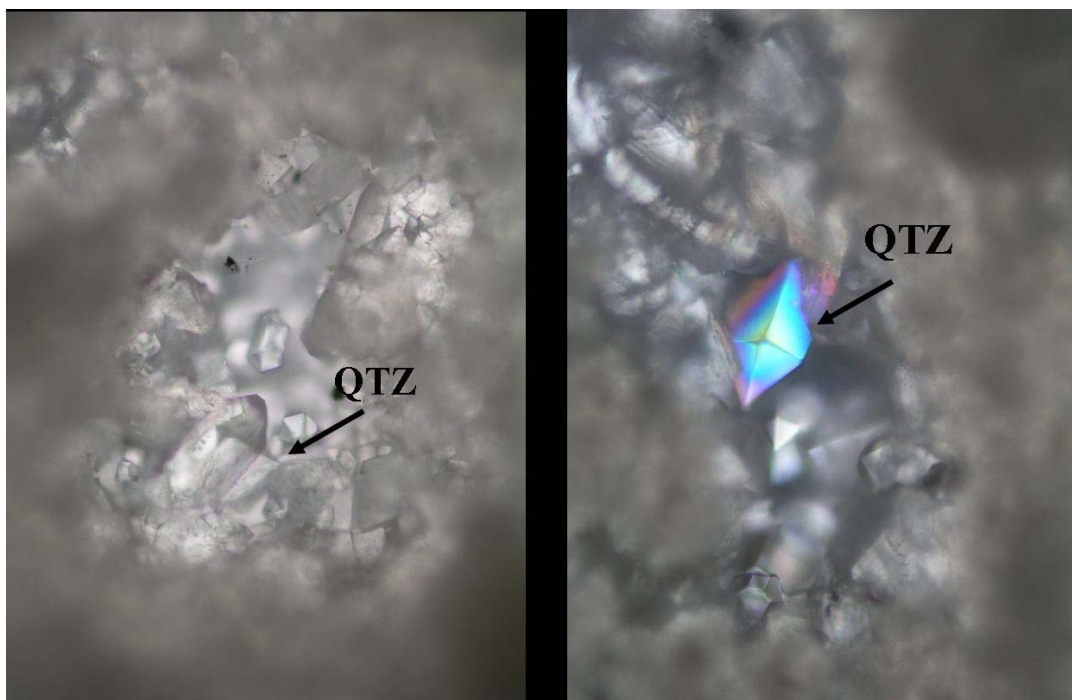


Figure 40. Quartz crystals partially filling a cavity in dolomite from the Lisbon NW USA No. B-63 well at 9981 feet. The right-hand image was taken under partially crossed nicols. Height of images 0.7 mm.

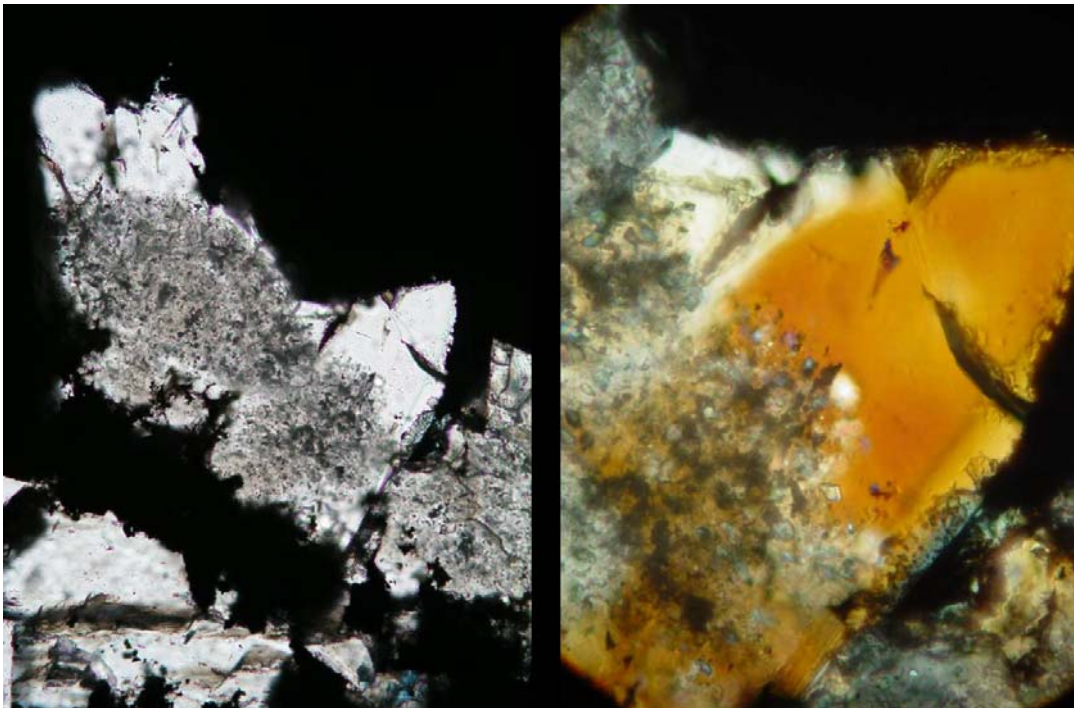


Figure 41. Quartz encapsulating dolomite from the Lisbon NW USA No. B-63 well at 10,004 feet. Height of images is 1.3 mm (left) and 0.7 mm (right). Right-hand image taken under crossed nicols.



Figure 42. *Relatively large quartz crystal from the Lisbon No. D-616 well at 8356 feet. Small oriented grains of anhydrite are encapsulated in the quartz. Width of image is 1.3 mm.*

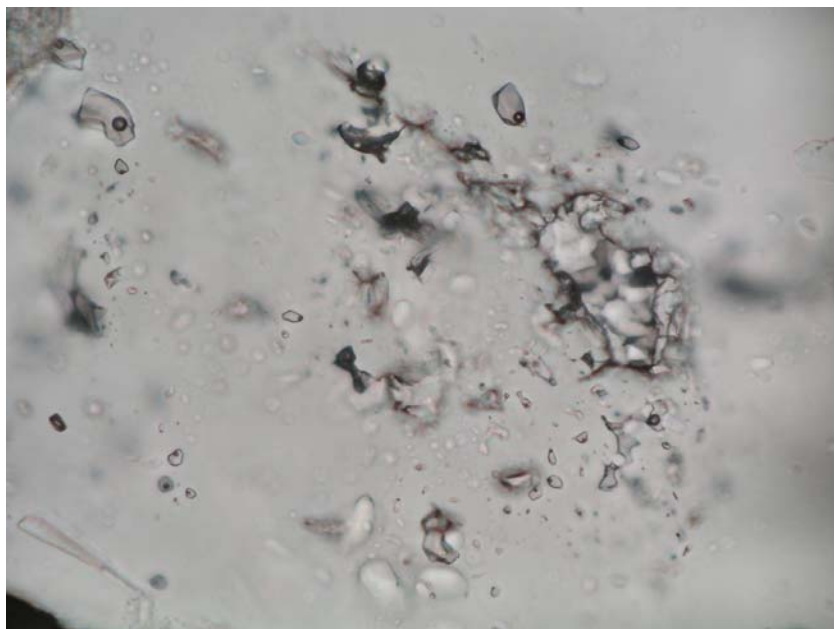


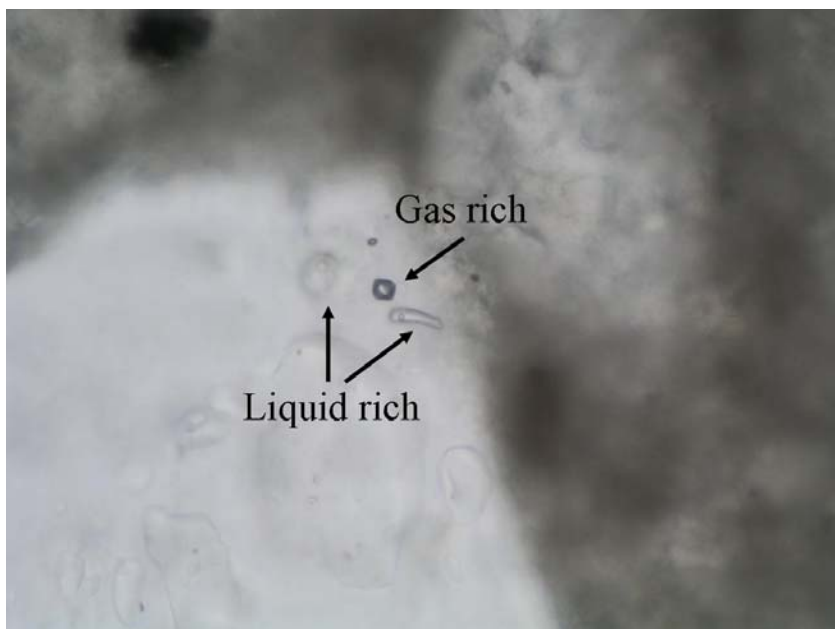
Figure 43. *Two-phase, liquid-rich inclusions defining a growth zone in the interior of a quartz crystal from the Lisbon No. D-616 well at 8356 feet. The large, irregular cavity on the right may have been initially filled with anhydrite. Width of image is 0.3 mm.*

of the crystal. Large isolated primary inclusions, up to 50 micrometers across, occur in the quartz crystals shown in figure 44. Coexisting liquid- and vapor-rich inclusions were observed in the crystal shown in figure 45. Because of the small size of the gas-rich inclusions, it was not possible to estimate their compositions from phase changes during freezing and heating. However, in this environment, the gas is probably methane-rich. No primary oil inclusions were observed in the quartz crystals.

Secondary aqueous inclusions that define healed fractures are common in some of the quartz crystals. The majority of these inclusions contain liquid and vapor at room temperature; rarely single-phase aqueous inclusions are present. As noted above, these single-phase inclusions could represent the local incursion of low-temperature (less than about 50°C [$\sim$ 122°F]) waters.



Figure 44. *Primary liquid-rich inclusions in quartz from the Lisbon No. D-616 well at 8356 feet. Height of image is 0.3 mm. Irregularly shaped inclusions are anhydrite.*



Homogenization and ice-

Figure 45. *Coexisting primary liquid- and gas-rich inclusions in quartz from the Lisbon No. D-616 well at 8356 feet. Width of image is 0.3 mm.*

melting temperatures of quartz-hosted inclusions were measured (figure 46). Primary inclusions yielded homogenization temperatures ranging from 118 to 133°C (244-271°F) and ice-melting temperatures of -20.5 to -22.8°C (-4.9 to -9°F). Secondary inclusions yielded lower homogenization temperatures but a much broader range of ice-melting temperatures that overlapped those of the primary inclusions.

The presence of coexisting gas- and liquid-rich inclusions is particularly significant because this suggests that the homogenization temperatures closely approximate the true trapping temperatures (see discussion in Goldstein and Reynolds, 1994). The quartz-hosted inclusions provide the best measure of the maximum burial temperature and depth of any of the minerals studied.

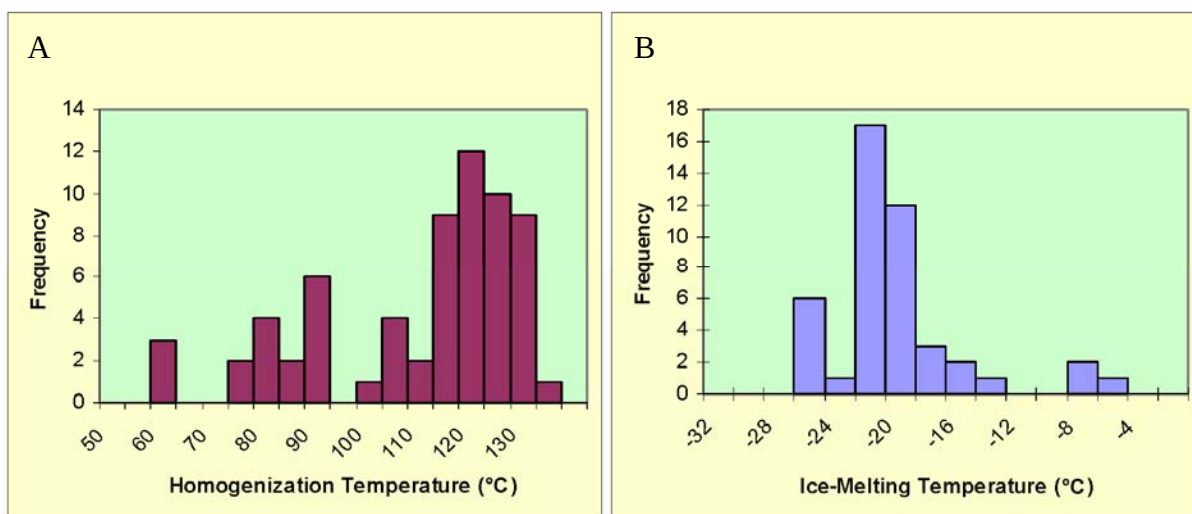


Figure 46. Homogenization (A) and ice-melting (B) temperatures of quartz-hosted aqueous inclusions from the Lisbon No. D-616 well at 8356 feet.

Fluid Inclusions in Late Calcite

Late calcite from depths of 9936 feet, 9991 feet, and 10,005 feet (3028 m, 3045 m, and 3049 m) in Lisbon NW USA No. B- 63 well was studied. The calcite encapsulates dolomite (figure 47) and fills vugs. The relationships between dolomite, quartz, and calcite are shown in figure 48. These textural relationships imply that the calcite also postdates quartz. As shown in figure 47, dissolution of dolomite occurred prior to calcite deposition.

Secondary aqueous and oil inclusions occur in the late calcite. All of the aqueous inclusions display variable liquid to vapor ratios indicative of necking. Ice-melting temperatures of the aqueous inclusions are shown in figure 49; see figure 50 for comparison of ice-melting temperatures of fluid inclusions in calcite vs quartz. The majority of the inclusions from depths of 9936 feet and 10,005 feet (3029 m and 3049 m) yielded comparatively high ice-melting temperatures ranging from -5.5 to about -12°C (22.1~10 °F), corresponding to salinities

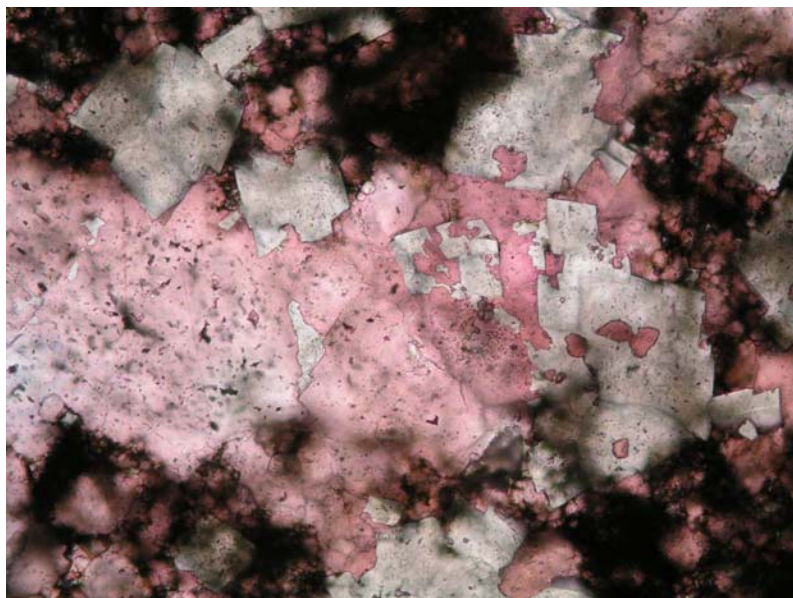


Figure 47. Corroded and dissolved dolomite (white) encapsulated in calcite (pink) from in the Lisbon No. D-616 at 8372 feet. Width of image is 1.3 mm.

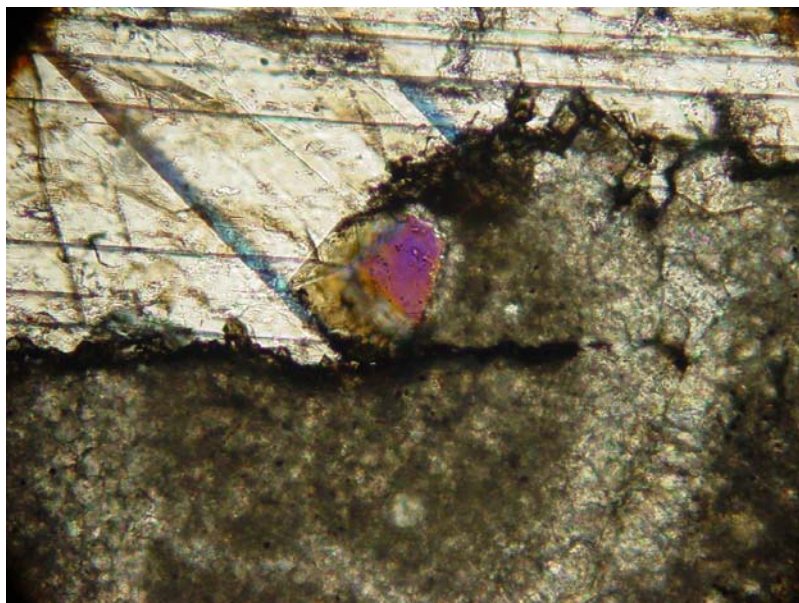


Figure 48. Coarse calcite (upper half of image) that appears to postdate quartz (purple crystal in center) and dolomite (lower half of image). Lisbon NW USA No. B-63 well at 10,004 feet. Width of image is 0.7 mm.

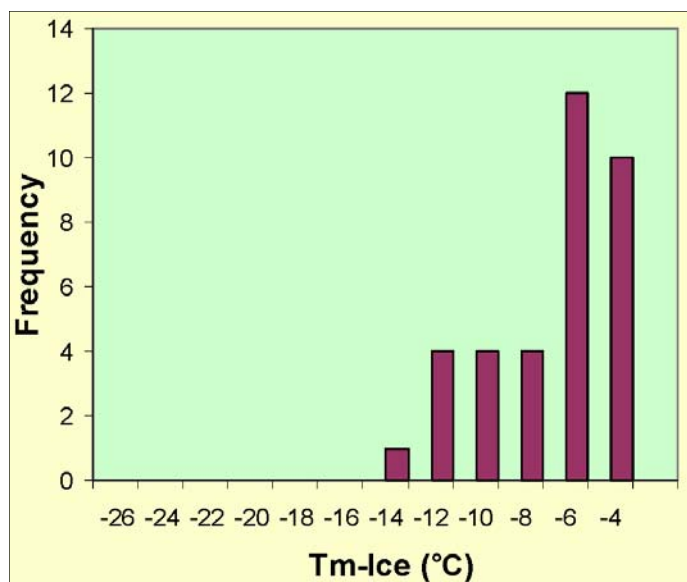


Figure 49. Ice-melting temperatures of late, calcite-hosted fluid inclusions from the Lisbon NW USA No. B-63 well.

of 8.6 to 16 weight percent NaCl equivalent. Inclusions from a depth of 9991.8 feet (3045 m) had higher salinities, up to 18 weight percent NaCl equivalent. These relationships suggest that at least two distinct groups of fluids interacted with the rocks from the Lisbon NW USA No. B-63 well.

Late Oil Inclusions

The youngest significant diagenetic event recorded in the rocks is represented by the presence of the bitumen observed in numerous thin sections (see Chidsey and others, 2005). Secondary inclusions trapped in late calcite from a depth of 9936 feet (3028 m) in the Lisbon NW USA No. B-63 well provide unequivocal evidence for a mobile oil phase that postdates calcite deposition. The oil inclusions shown in figure 51 display variable liquid to vapor ratios caused by necking. The oil is fluorescent with an estimated API gravity of 35 to 45°, based on

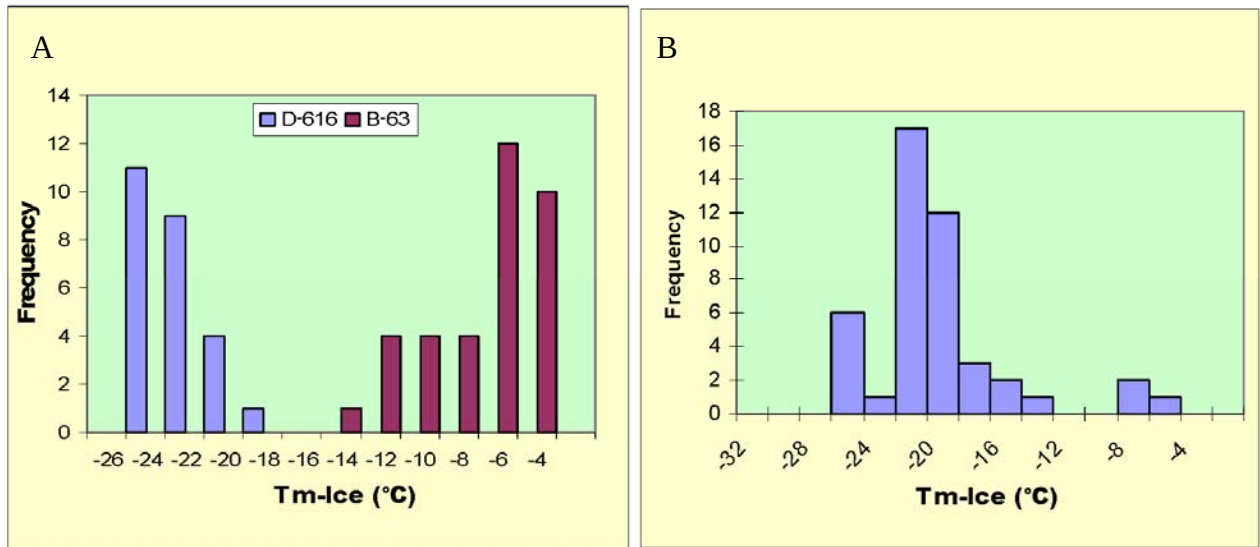


Figure 50. Comparison of ice-melting temperatures of fluid inclusions in early calcite (A) and quartz (B) from the Lisbon No. D-616 well.

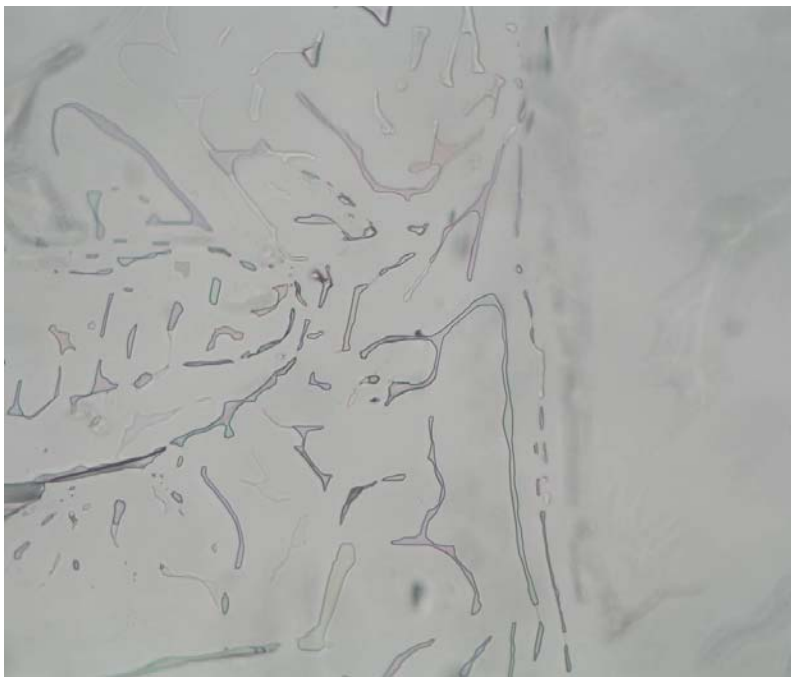


Figure 51. Secondary oil inclusions in late calcite from the Lisbon NW USA No. B-63 well at 9936 feet. The inclusions are necked. The large brown inclusion at bottom center contains only liquid; others contain variable ratios of liquid and gas. Width of image is 0.7 mm.

its color. Similar-appearing secondary oil inclusions were observed in calcite from a depth of 8372 feet (2552 m) in the Lisbon No. D-616 well (figure 52), although it is not possible to uniquely assign an age to these inclusions. These inclusions yielded consistent homogenization temperatures ranging from 39 to 43°C (102-109°F) (figure 53). For comparison, homogenization temperatures of primary oil inclusions are also shown in figure 53; see figure 54 for comparison of homogenization temperatures of oil inclusions in calcite versus saddle dolomite.

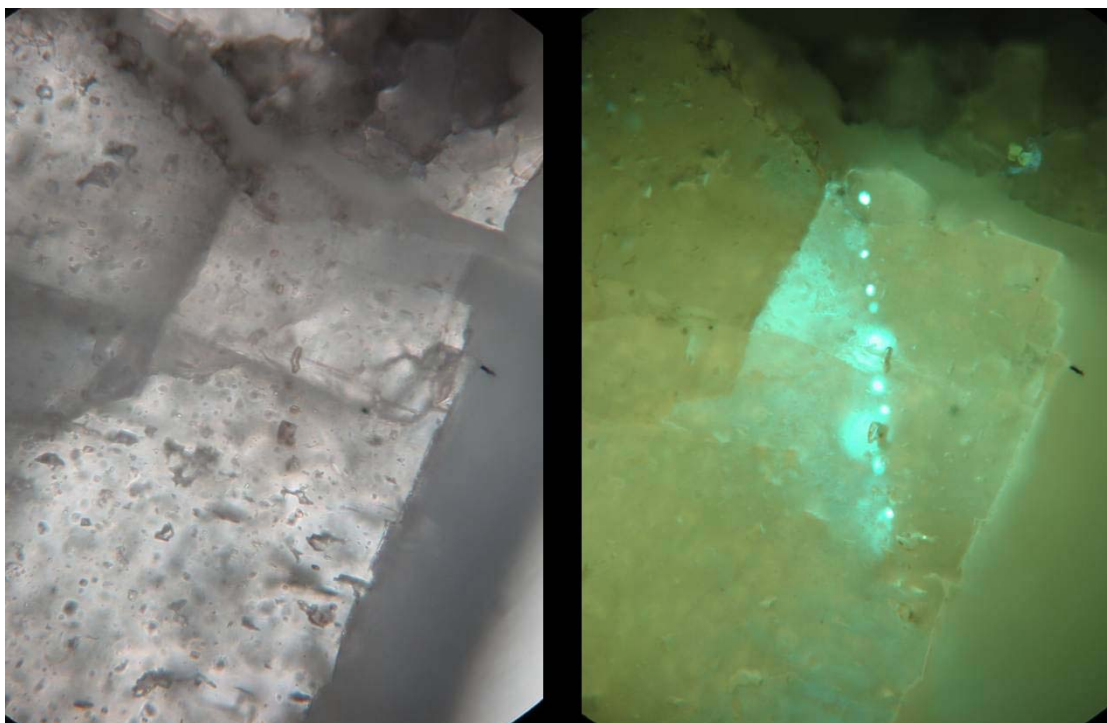


Figure 52. Secondary oil inclusions in calcite from the Lisbon No. D-616 well at 8372 feet. The height of each image is 0.3 mm. Right-hand image was taken under fluorescent light.

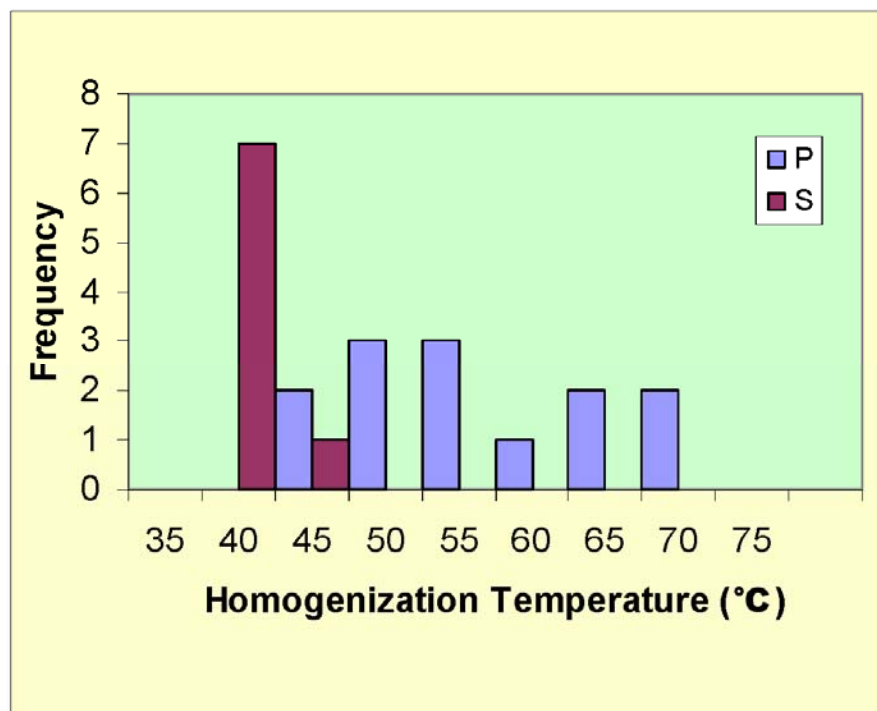


Figure 53. Comparison of homogenization temperatures of primary (P) and secondary (S) oil inclusions in calcite.

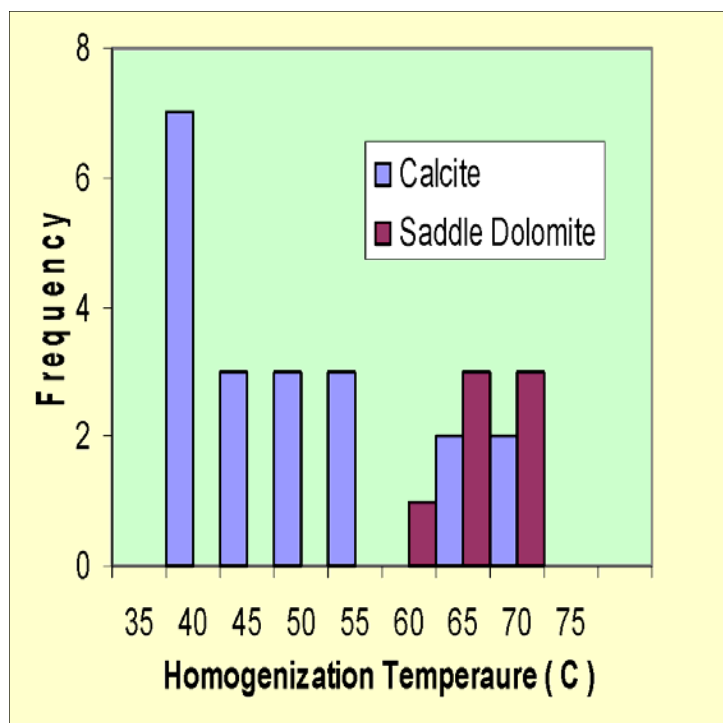


Figure 54. Comparison of homogenization temperatures of oil inclusions in calcite and saddle dolomite. All inclusions are primary except 35 to 40°C inclusions in calcite.

LEADVILLE ISOTOPIC GEOCHEMISTRY

Stable Carbon and Oxygen Isotope Analysis

Introduction

Modification of rock fabrics and porosity within the Leadville Limestone in Lisbon field is quite complex. Diagenesis played a major role in the development of reservoir heterogeneity. Diagenetic processes started during deposition and continued throughout burial history (figure 9).

Stable isotope geochemistry has been used in recent years to provide insights into the chemical differences between preserved remnants of depositional components and the various diagenetic events in carbonate rocks, as recognized from core examination and thin section petrography. Figure 55 shows a graph of carbon versus oxygen isotope compositions for a range of carbonate rock types from various published sources compiled by Roylance (1990). Broad fields of carbon and oxygen isotope compositions for various carbonate rock settings are indicated, including modern marine (“subsea”) cements, various marine skeletons and sediments, deep-water (“pelagic”) limestone, Pleistocene carbonates, and meteoric carbonates (“speleothems and veins”).

Methodology

Isotopic composition analyses for stable carbon and oxygen, as well as strontium, were completed on a variety of diagenetic phases from Lisbon field core samples (table 2). Individual samples were collected as powdered rock using a Dremel drill equipped with precision bits.

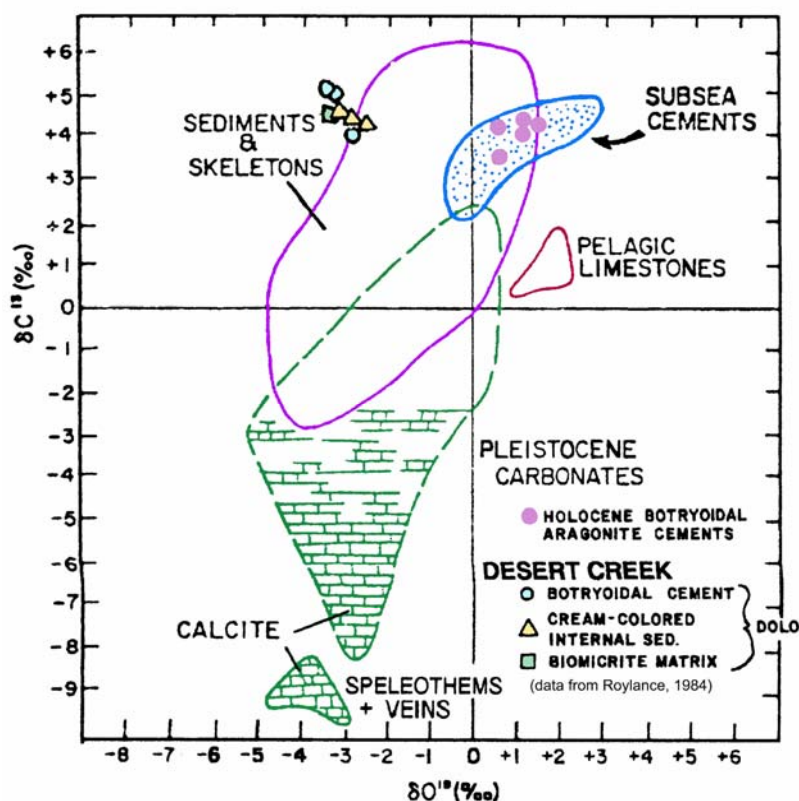


Figure 55. Graph of carbon versus oxygen isotope compositions. Other compositional facies compiled from various published work (modified from James and Ginsburg, 1979, by Roylance, 1984, 1990).

All analyses were completed at the Colorado School of Mines (CSM) Stable Isotope Laboratory, Golden, Colorado. The CSM lab possesses the capabilities of analyzing the stable isotopes of hydrogen, carbon, nitrogen, oxygen, and sulfur (H, C, N, O, and S) from a wide array of sample matrices. The GV Instruments IsoPrime mass spectrometer (figure 56) is the keystone around which several on-line preparation devices operate. Traditional dual-inlet applications (waters, carbonates, off-line prepared gases) are prepared with a MultiPrep auto sampler capable of performing carbon dioxide (CO₂) and H₂ equilibration on water samples, and acid digestion of carbonate samples (figure 57). A 50-port manifold can also be fitted for dual-inlet analysis of off-line gases. The IsoPrime mass spectrometer is also interfaced with continuous-flow preparation devices, including two elemental analyzers and a trace-gas preconcentrator. The elemental analyzers use combustion or pyrolysis to generate gases, which are then carried in an inert stream of helium to the mass spectrometer for analysis of H, C, N, O, and S. Common applications include analysis of phosphates, nitrates, waters, organics, soils, plant and animal matter, sulfides, sulfates, and oils. The trace-gas preconcentrator cryogenically focuses trace quantities of gases for isotopic analysis. Common applications include analysis of methane, carbon dioxide, and nitrous oxide from atmospheric and soil-gas samples.

The internal standard used in the CSM lab is the University of California at Los Angeles (UCLA) Carrara marble. The accepted values for this internal standard were matched consistently during the analysis of the Leadville core samples selected for this study. All isotopic compositions are reported relative to PeeDee Belemnite (PDB) (see Land, 1980, figure 6 for definition relative to Standard Mean Ocean Water [SMOW]).

Table 2. Stable carbon and oxygen isotope data from the Mississippian Leadville Limestone, Lisbon field core samples.

Sample No.	Well	Depth (ft)	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	Comments
1	B-63	9960.6	-2.441	-6.830	Late calcite
2	B-63	9960.6	-1.918	-1.435	Syngenetic dolomite
3	B-63	10,004-05	-6.092	-11.297	Late calcite
4	D-816	8444-45	-2.696	-3.069	Dolomite cement
5	D-816	8444-45	-2.648	-2.441	Replacement dolomite
6	D-816	8444-45	-3.008	-2.287	Matrix dolomite
7	D-816	8421	-2.584	-3.699	Dolomite cement
8	D-816	8421	-2.978	-4.265	Replacement dolomite
9	D-616	8356-57	-3.709	-4.613	Saddle dolomite in fractures
10	D-616	8356-57	-2.793	-4.422	Limestone matrix/crinoids
11	D-816	8433	-2.815	-3.375	Late replacement matrix dolomite
12	B-610	7897	-2.951	-0.963	White, tight early dolomite
13	B-610	7897	-3.348	-2.808	Black, porous late dolomite
14	B-610	7886	-3.294	-2.601	White, tight early dolomite
15	B-610	7886	-3.126	-2.890	Black, porous late dolomite
16	D-616	8559	-2.851	-3.313	Black, porous late replacement dolomite
17	D-616	8682	4.407	-2.086	Syngenetic dolomite
18	B-63	9935.6	-2.795	-4.012	Dolomite (possible cross-cutting karst sediment fill)
19	B-63	9935.6	-2.785	-5.564	Limestone, peloidal/skeletal grainstone; sampled only black non-skeletal grains which appear microporous
20	D-616	8308-09	-4.418	-3.038	Dolomitized sediment within karst cavity
21	D-616	8308-09	-2.783	-4.147	Limestone country rock
22	B-63	9991.8	-3.510	-7.668	Late calcite, poiklotopic
23	B-63	9939	-3.499	-7.644	Saddle dolomite
24	B-63	9909	-4.794	-12.255	Late calcite
25	D-616	8308	-4.224	-2.694	Karst-fill dolomite

Stable Carbon and Oxygen Isotopes for Leadville Samples at Lisbon Field

Carbon isotopic compositions for the 25 Leadville Limestone (limestone and dolomite) samples from Lisbon field (table 2 and figure 58) cluster in a very narrow range around the mean value of -2.95‰ PDB; the range is -1.92 to -6.09‰ PDB (one notable exception of $+4.4\text{‰}$ was excluded). Oxygen isotopic compositions for these samples, however, are more wide spread (table 2 and figure 58). The range is -0.96 to -12.26‰ PDB; the mean value is -4.61‰ PDB.



Figure 56. The CSM Stable Isotope Laboratory's GV Instruments IsoPrime stable isotope ratio mass spectrometer. Several peripheral devices are interfaced with the IsoPrime for both dual-inlet and continuous flow applications.

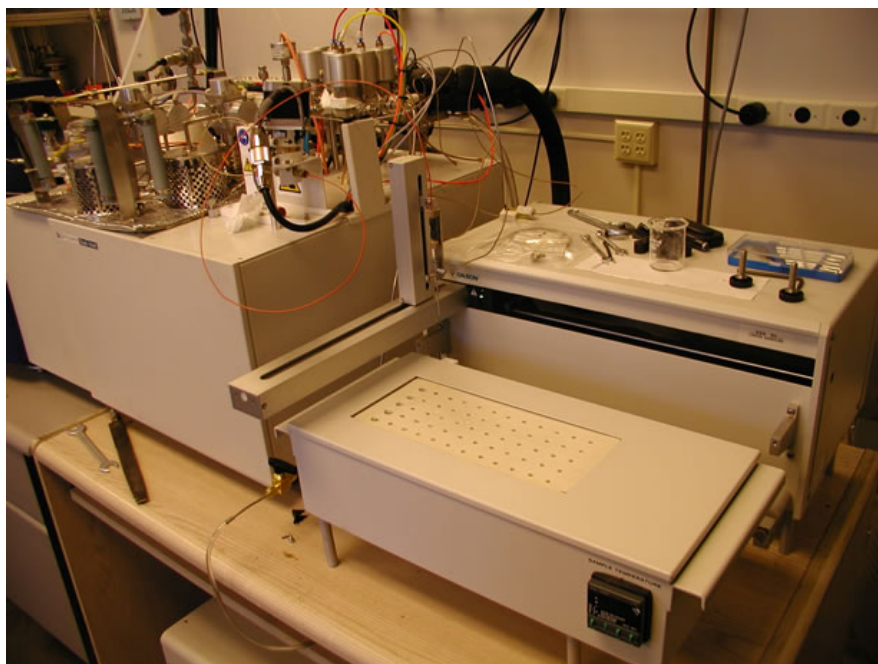


Figure 57. MultiPrep intended for high-precision dual-inlet analysis of carbon and oxygen isotopes of carbonate samples, and oxygen isotopes for waters by traditional equilibration techniques. Sample sizes for carbonates range from 10 to 100 ug – water samples are 200 ul.

Stable carbon and oxygen isotope data indicate that all Lisbon Leadville dolomites were likely associated with brines whose composition was enriched in $\delta^{18}\text{O}$ compared with Late Mississippian seawater. Stable oxygen isotope analyses of dolomites show a linear trend with a fairly narrow range of carbon isotope values (figure 58). Figure 59 shows a cross plot of the same $\delta^{13}\text{C}/\delta^{18}\text{O}$ Leadville data from Lisbon field with the regions of dolomite temperatures of formation suggested by Allan and Wiggins (1993), based upon their interpretation of many ancient dolomites. Note that most of the Leadville data points plot in the region that Allan and Wiggins (1993) have called the “overlap of low and high temperature dolomites.”

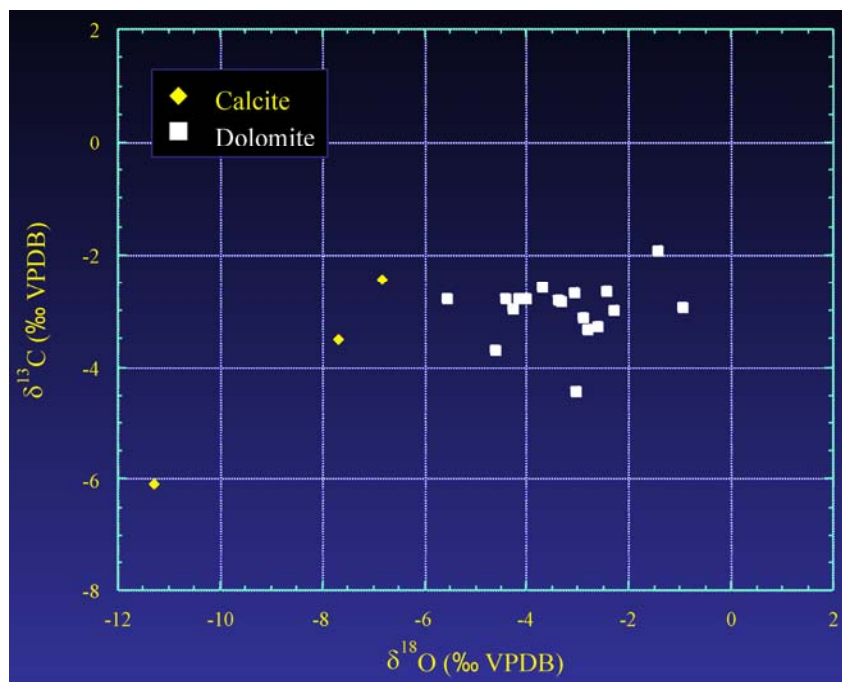


Figure 58. Graph of stable carbon versus oxygen isotopic compositions for Leadville dolomite and calcite from Lisbon field. Sample number 24 not shown.

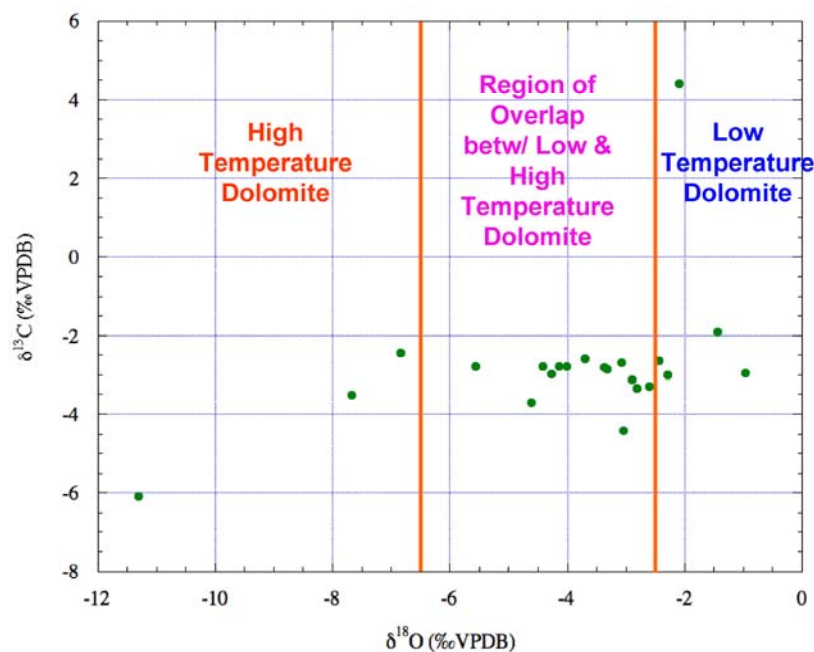


Figure 59. Cross plot of the $\delta^{13}\text{C}/\delta^{18}\text{O}$ Leadville data from Lisbon field with the regions of dolomite temperatures of formation suggested by Allan and Wiggins (1993).

Stable oxygen isotopes for Mississippian seawater were in the range of -2 to -1‰ (Veizer and others, 1999). Dolomitizing fluid compositions enriched with respect to $\delta^{18}\text{O}$ are thought to be heavier than normal Mississippian seawater (bracketed by the yellow arrows on figure 60). Leadville reflux dolomitization likely resulted from evaporated brines, several per mil heavier than normal seawater (for example modern Arabian Gulf water in the range of 2.5 to 4‰ (Wood and others, 2002). Assuming similar oxygen enrichment of Mississippian seawater values gives a dolomitizing fluid in the range of 0.5 to 3‰ . This factor, coupled with Leadville dolomite isotope values, constrain Leadville replacement dolomitization temperatures to between 60 - 90°C (140 and 194°F) (figure 60). Saddle dolomite cements were precipitated at temperatures greater than $>90^\circ\text{C}$ (194°F).

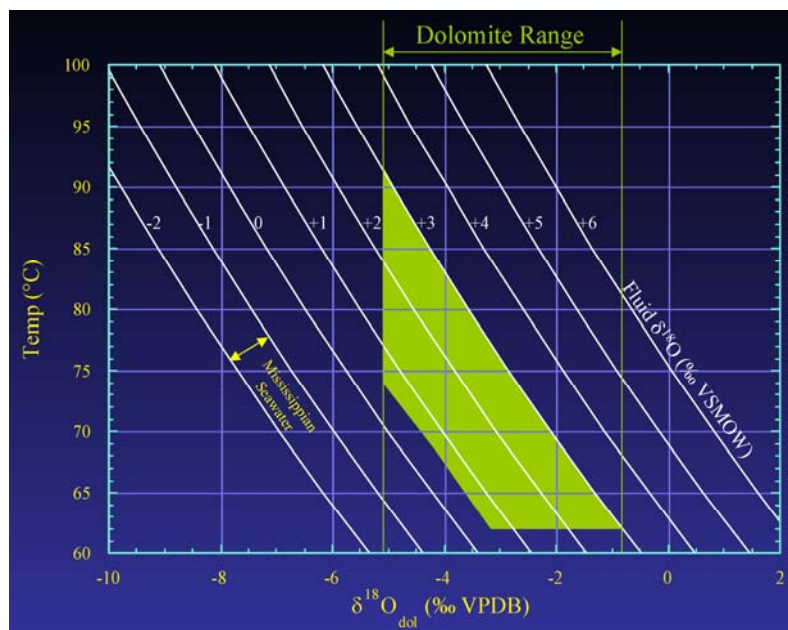


Figure 60. Graph of dolomite stable oxygen isotope values versus temperature data. The green field shows our estimate of $\delta^{18}\text{O}$ of dolomitizing fluids at between 0.5 and 3.0‰. Precipitation temperatures were up to about 90°C (~194°F).

Strontium Isotope Analysis

Introduction

Strontium (Sr) isotope analysis was used to assist with the diagenetic interpretation of different subsurface mineral phases within Leadville Limestone samples from Lisbon field. The interpretation of these analyses will be discussed after the following comments about the nature of the Sr isotope analysis, as well as a description of the analytical technique and laboratory used.

Applications and Background

Strontium isotope analysis is used most frequently as an age-dating tool in marine carbonates. The Sr composition of ancient seawater and its variation through geologic time have been determined from common marine carbonate minerals, especially calcite, aragonite, and dolomite (Brass, 1976; Burke and others, 1982; Allan and Wiggins, 1993).

Among the four known isotopes of Sr, the ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ is the most useful for tracking the secular changes of seawater Sr. These two isotopes come from separate sources in the earth. Strontium 87 is radiogenic (from the radioactive decay of rubidium 87 with a half-life of about 50 billion years), while ^{86}Sr is non-radiogenic (Faure and Powell, 1972; Faure, 1977). These secular changes in the Sr ratio of seawater are the result of the interplay of tectonism and erosion versus seafloor spreading (Allan and Wiggins, 1993). In general, erosion resulting from increased tectonism increases the ratio of $^{87}\text{Sr}/^{86}\text{Sr}$; during times of high seafloor spreading the ratio is decreased. The assumed reason for these changes is that continental (sialic) crustal rocks (for example granites, gneisses, and their derivatives such as arkoses) contribute radiogenic Sr ratios (that is relatively high Sr isotopic numbers). On the other hand, mantle (simatic) rocks (for example basalts, other volcanic, undifferentiated basic rock types, and their derivatives such as lithic sandstones) are much less radiogenic (that is relatively low

Sr isotopic ratios). The high contribution of Sr into the oceans from highly radiogenic continental materials and less radiogenic mantle minerals, combined with the rapid mixing rate of the oceans and the long oceanic residence time of Sr, have allowed the Sr isotope ratio of seawater to be the same globally at any given time. For useful discussions and explanations of these factors, see Veizer (1989); and Allan and Wiggins (1993, p. 49-52).

Strontium Isotope Age Curve for Marine Carbonate Rocks

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a carbonate mineral can be measured with great precision (that is to five significant figures). Workers at the Mobil (Oil) Field Research Lab successfully constructed a reference curve that traced the secular change in the Sr isotopic composition of seawater through all of Phanerozoic time (Burke and others, 1982; Elderfield, 1986; McArthur and Howarth, 2004; see figure 61). Index fossil samples were used to construct and constrain the original curve. Originally, the curve served as a reference for Sr isotope dating of marine carbonates without diagnostic index fossils. Cenozoic marine limestones and cherts can be dated with very small margins of error (for example DePaolo and Ingram, 1985; DePaolo, 1986; DePaolo and Finger, 1991) because of the availability of Cenozoic index fossils in good condition and the very steep, monotonic nature of the curve during this time period (figure 61). For older marine carbonates, dating is less accurate due to poor preservation of fossils as well as the oscillating trends of the Sr isotope age curve (figure 61). The amplitudes and high frequency of these oscillations over geologic time is probably the result of climatic, tectonic-erosional, and seafloor-spreading cycles (Allan and Wiggins, 1993). The Sr isotope curve is most useful for age dating during geologic time intervals when the curve is unidirectional and steep (for instance, during the Permian).

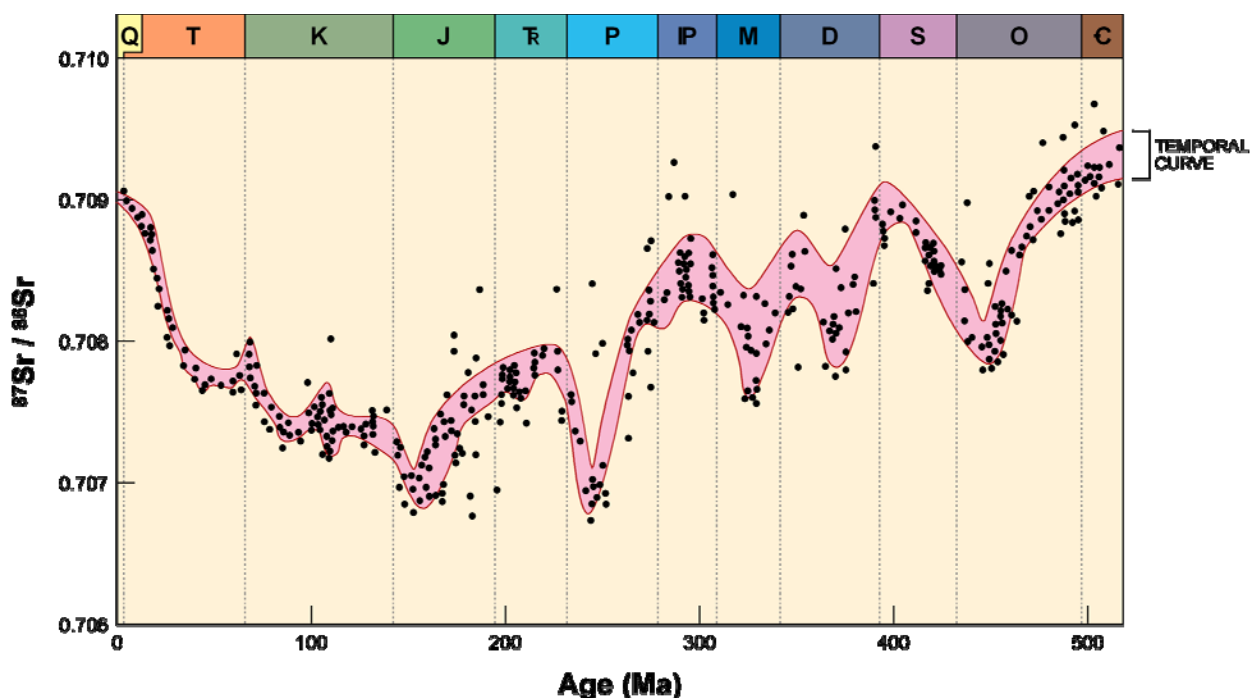


Figure 61. Strontium isotope seawater composition curve (from Burke and others, 1982; Elderfield, 1986; Allan and Wiggins, 1993).

Strontium Isotopes as Tracers for Diagenetic Fluids

Strontium isotopes can have significant value in tracing subsurface fluid movement (Burtner, 1987; Allan and Wiggins, 1993). Marine waters throughout geologic time apparently displayed a relatively narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios - from about 0.7078 to 0.7095 (figure 61). Any ratios from carbonates that are significantly above or below this range of Phanerozoic seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate contribution by diagenetic waters in carbonate minerals that are of non-marine origin. Higher Sr isotope values indicate addition of radiogenic (high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio) contaminants from crystalline (granitic or sialic) basement rocks or potassic feldspar-rich siliciclastic sediments (see, for instance, Burtner, 1987). Lower Sr isotope values indicate contributions from mafics, ultramafics, and lithic sandstones with calcic plagioclase feldspar (see, for instance, Schultz and others, 1989).

Strontium is a doubly charged cation which easily substitutes into the carbonate crystal lattice (Allan and Wiggins, 1993). When Sr is released by diagenetic processes, it is partitioned into dolomites and carbonate cements in various subsurface settings (figure 62). Therefore, Sr analysis is an excellent tool for identifying hydrothermal dolomite.

Strontium Isotopic Ratios for Leadville Samples at Lisbon Field

Three samples of different diagenetic mineral phases were selected for Sr isotopic analysis. Mineral separates were carefully drilled or plucked out of a conventional core segment from the Lisbon NW USA No. B-63 well in Lisbon field (figure 7) at a depth of 9939 feet (3030 m). One sample each of (1) replacement, brownish “sucrosic” (rhombic euhedral) dolomite, (2) coarse, white saddle dolomite, and (3) coarse, clear to white calcite spar cement (figure 63 is a thin section photomicrograph showing the same mineral phases from 9991.8 feet

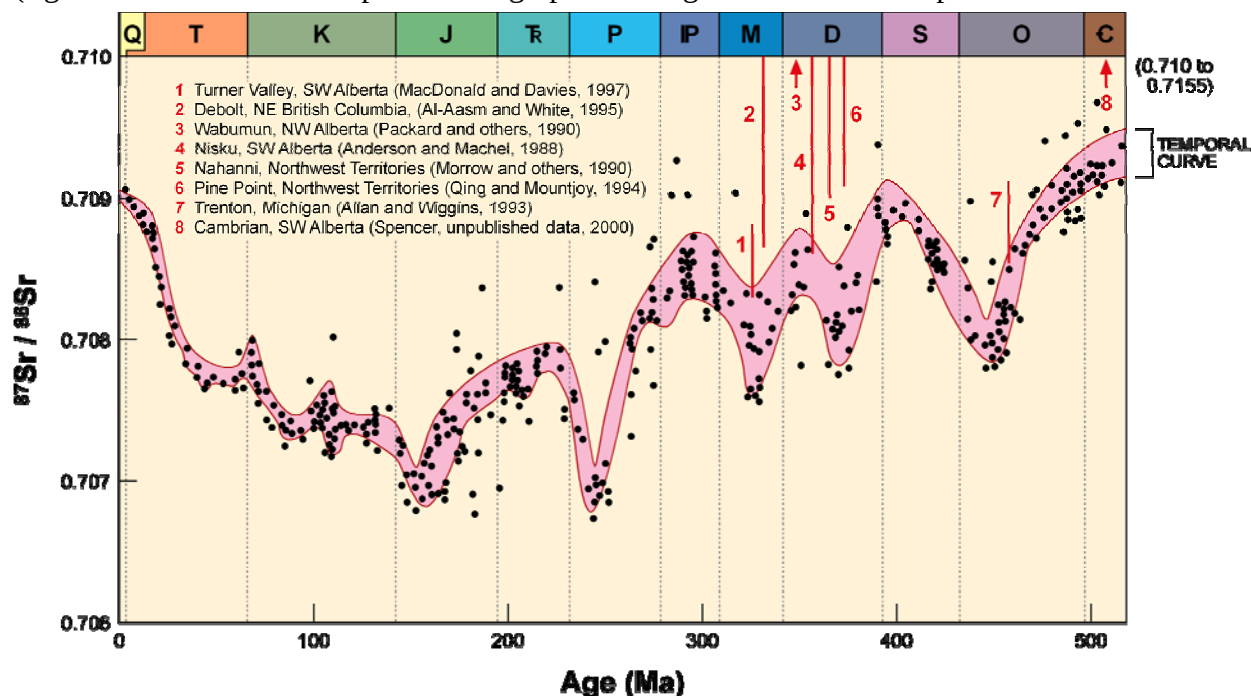


Figure 62. Strontium isotope compositions of saddle dolomites from the Canadian Rockies and Michigan Basin (from McArthur and Howard, 2004).

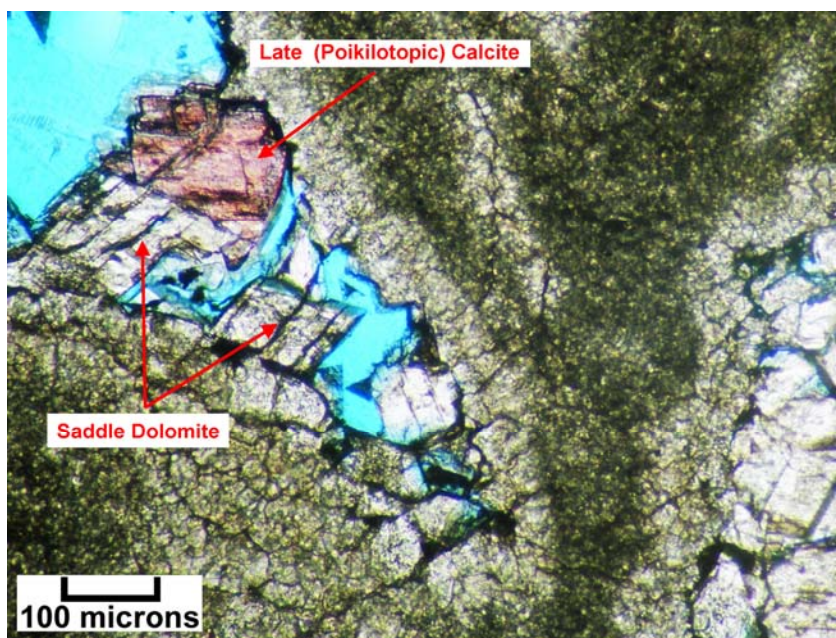


Figure 63. Photomicrograph (plane light) showing coarse, white saddle dolomite crystals and coarse, clear calcite spar cement (stained red) filling a portion of a large dissolution pore (blue) in a finely crystalline, sucrosic replacement dolomite matrix - the same diagenetic mineral phases found at the 9939-foot Sr sample depth. Lisbon NW USA No. B-63 well (figure 7), 9991.8 feet, porosity = 6.2 percent, permeability = 0.3 mD.

Table 3. Strontium isotopic data from the Leadville Limestone in the Lisbon NW USA No. B-63 well core samples.

Sample No.	Well	Depth (ft)	$^{87}\text{Sr}/^{86}\text{Sr}$	Comments
1	B-63	9939	0.712068	Late calcite
2	B-63	9939	0.711961	Saddle dolomite
3	B-63	9939	0.711464	Matrix sucrosic dolomite

[3045.4 m]), were analyzed by Geochron Laboratories (a Division of Krueger Enterprises, Inc., Cambridge, MA) for $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios (table 3). The precision of these analyses was reported to six significant figures (that is 0.00000X).

All three samples exhibit highly radiogenic Sr isotopic values, each in excess of 0.711. These values are far higher than the secular range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for marine carbonate fossils and rocks during the Mississippian or for any time during the Phanerozoic (Burke and others, 1982; Allan and Wiggins, 1993; Denison and others, 1994; Bruckschen and others, 1999; McArthur and Howarth, 2004). A plot of the Sr isotope composition for the three Leadville samples from Lisbon field, along with the Phanerozoic marine carbonate curve for Sr ratios, is shown in figure 64.

Discussion

It is apparent that the high Sr isotopic ratios for the three late (burial) diagenetic mineral phases indicate contributions from diagenetic waters enriched in ^{87}Sr that were derived from granitic or arkosic sandstone terrains. The most logical terrain for ^{87}Sr enrichment is either Precambrian basement rocks or the Devonian McCracken Sandstone. Both of these sources are at depths considerably below the Leadville reservoir rocks samples for this study. However, early Tertiary reactivation of basement-involved, high-angle normal faults associated with Precambrian tectonics may have allowed hot, deep-seated fluids from the granitic basement or

the McCracken Sandstone (figure 65) to communicate upwards with the Leadville carbonate section. Brines from evaporates in the Pennsylvanian Paradox Formation may also have entered the Leadville along the large fault bounding the northeast flank of Lisbon field (figures 7 and 65). It is interesting that these radiogenic fluids were involved in precipitation of replacement “sucrosic” dolomites, saddle dolomites, and late calcite spar cements.

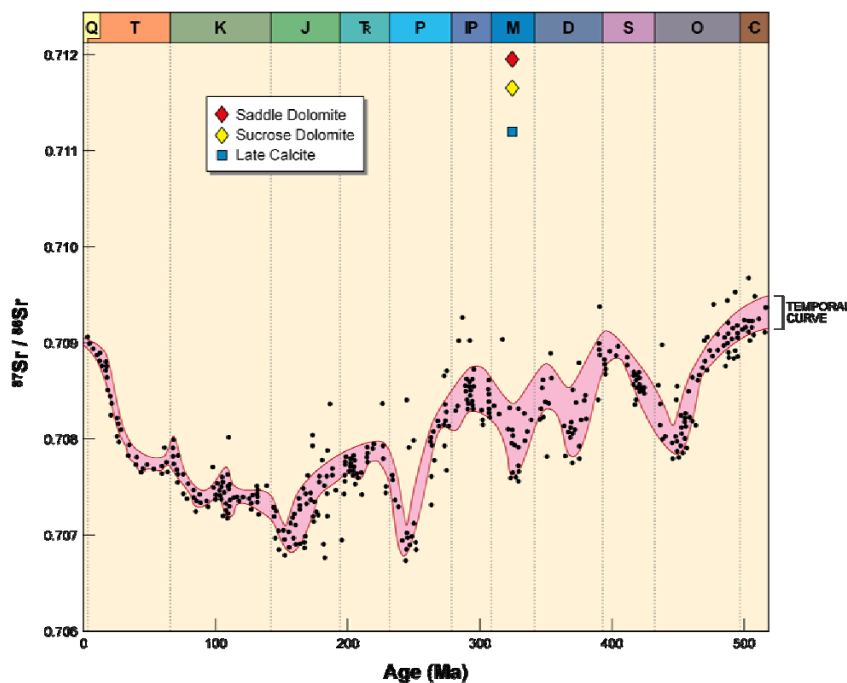


Figure 64. A plot of the Sr isotope composition for the three Leadville samples from Lisbon field along with the Phanerozoic marine carbonate curve for Sr ratios (modified from Allan and Wiggins, 1993).

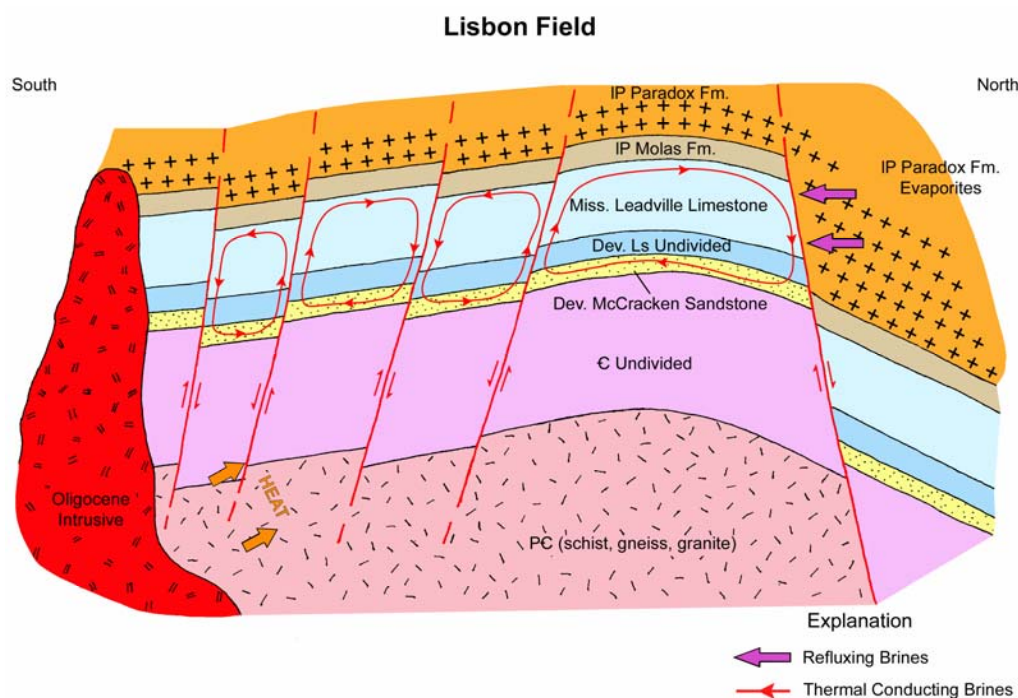


Figure 65. Possible heat sources and convection cells for late dolomitization of the Leadville Limestone in Lisbon field.

Strontium isotope compositions from many (but not all) burial replacement dolomites are radiogenic (Allan and Wiggins, 1993, p. 95). The high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is indicative of allochthonous dolomitizing brines that interacted with potassic feldspars from basement rocks or from arkosic siliciclastic sediments prior to dolomitization. For instance, matrix replacement and white saddle dolomites in Upper Devonian (Frasnian) pinnacle reefs, Alberta Basin, Canada, surrounded by deeper-water facies, contain radiogenic Sr well above the Sr isotope seawater curve (Anderson, 1985; Allan and Wiggins, 1993, figure 95). Burial replacement dolomites in the Ordovician Trenton Formation of southern Michigan, also have Sr isotope similarities to the Leadville at Lisbon field. Reactivation of a basement-involved, Precambrian, left-lateral wrench system allowed brines to migrate from the Silurian Salina Formation along faults and fractures into the Trenton (Allan and Wiggins, 1993). Strontium in Trenton limestone has Ordovician seawater values while dolomite has Silurian seawater values (figure 66).

SUMMARY AND CONCLUSIONS

Leadville reservoir quality at Lisbon field is greatly enhanced by dolomitization and dissolution of limestone. There are two basic types of dolomite: very fine, early dolomite and coarse, late dolomite. Early dolomitization preserves depositional fabrics and has limited porosity development, except for limited dissolution of fossils, and exhibits very low permeabilities. Late dolomitization has two morphologies: rhombic dolomites and saddle dolomites. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.

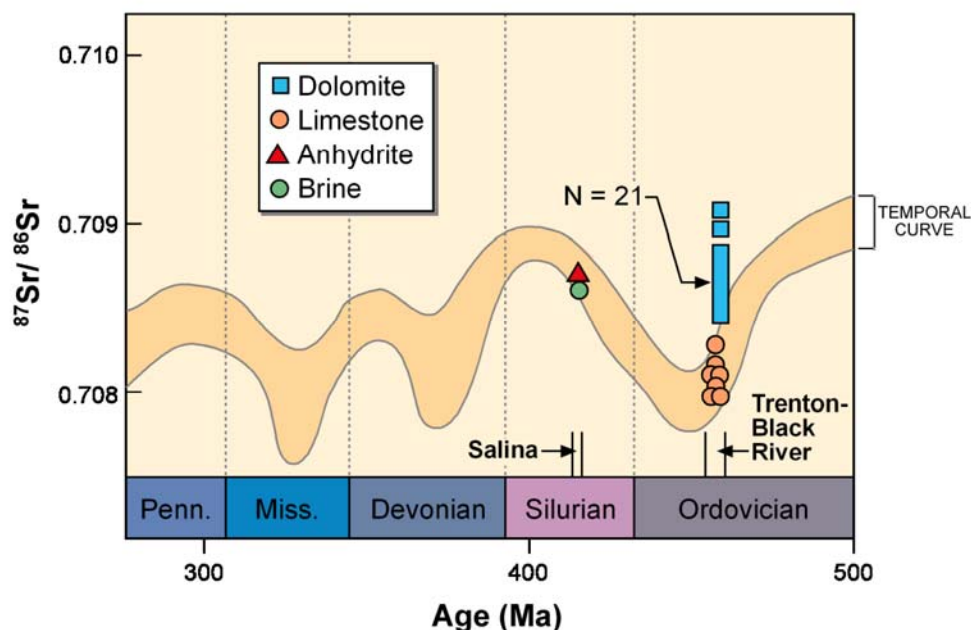


Figure 66. Strontium isotope values for limestone and dolomite of the Ordovician Trenton Formation and anhydrite and brine from the Silurian Salina Formation (from Allan and Wiggins, 1993).

Pyrobitumen coats most intercrystalline dolomite, as well as dissolution pores associated with the second type of dolomite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are relatively common throughout the upper third of the formation in the field. Other diagenetic products include syntaxial cement, sulfide minerals, anhydrite cement and replacement, and late macrocalcite.

Late dolomitization, saddle dolomite, and dolomite cement precipitation, as well as sulfides and brecciation, may have developed from hydrothermal events that can greatly improve reservoir quality. The result can be the formation of large, diagenetic-type, hydrocarbon traps. These conclusions were confirmed by the scanning electron microscopy, epifluorescence, cathodoluminescence, fluid inclusion, and isotope geochemical studies of samples from Lisbon field described in this report. The following sections summarize these studies and provide recommendations for independents exploring for Leadville targets.

Scanning Electron Microscopy

- Scanning electron microscopy demonstrates how Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of shallow water limestone. There are two basic types of dolomite: (1) very fine, early dolomite, and (2) coarse, late dolomite. Early dolomitization preserves depositional fabrics and has limited porosity development, except for limited dissolution of fossils, and has very low permeabilities. Late dolomitization has two morphologies: rhombic dolomites and saddle dolomites. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.
- Pyrobitumen coats most intercrystalline dolomite as well as dissolution pores associated with the second type of dolomite. Fractures enhance the permeability in several intervals. Minor euhedral quartz is present in several samples. Anhydrite and sulfide mineral(s) are present in moderate abundance.
- The general diagenetic sequence for these samples, based on SEM analysis, is (1) dolomitization, (2) dissolution, (3) dolomite cementation, (4) fracturing, (5) quartz cementation, (6) calcite cementation, (7) clay precipitation, (8) anhydrite cementation, (9) pyrobitumen emplacement, and (10) sulfide precipitation.

Epifluorescence

- Epifluorescence petrography makes it possible to clearly identify grain types and shapes, within both limestone and dolomite reservoir intervals in Leadville thin sections from cores examined in this study. In particular, peloids, skeletal grain types, and coated grains are easy to see in rocks where these grains have been poorly preserved, partially leached, or completely dolomitized.
- Depositional textures that are frequently occult or poorly preserved can often be

clearly distinguished using blue-light EF microscopy. In many limestones and finely crystalline dolomites of the Leadville reservoir at Lisbon field, the differences between muddy and calcarenitic fabrics can only be clearly appreciated with fluorescence lighting.

- Epifluorescence petrography clearly and rapidly images pore spaces that cannot otherwise be seen in standard viewing under transmitted polarized lighting. In addition, the cross-sectional size and shape of pores are easy to determine.
- Much of the Leadville porosity is very heterogeneous and poorly connected as viewed under EF. In particular, intercrystalline porosity within some of the reservoir in Lisbon field can be resolved much more clearly than with transmitted polarized lighting. The EF examination helps in seeing the origin of most types of porosity. Transmitted polarized lighting does not image intercrystalline porosity in carbonate samples very well, even though blue-dyed epoxy can be impregnated into even very small pores. In addition, opaque bitumen linings prevent light from passing through some of the pores to the observer. Without the aid of the EF view, the amount of visible open pore space would be underestimated in the plane-light image.
- Where dolomitization has occurred, EF petrography often shows the crystal size, shape, and zonation far better than transmitted plane or polarized lighting. This information is often very useful when considering the origin and timing of dolomitization as well as evaluating the quality of the pore system within the dolomite.
- Permeability differences within these dolomite and limestone samples are also easy to image because of the differential oil saturations between the tighter areas and the more permeable lithologies. Low-permeability carbonates from this study area show bright yellow fluorescence due to trapped live oil that is retained within tighter parts of the reservoir system. More permeable rocks show red fluorescence due to the epoxy fluorescence where oil has almost completely drained from the better quality portions of the reservoir.

Cathodoluminescence

- Cathodoluminescence imaging of samples nicely complements the types of information derived from EF of carbonate thin sections. Cathodoluminescence also displays original depositional textures and the outlines of original carbonate grains, and it distinctly images pore spaces. This information is often very useful when considering the origin and timing of dolomitization as well as evaluating the quality of the pore system within the dolomite.
- Cathodoluminescence shows a wide range of crystal size and growth habits within the dull-red-luminescing, matrix-replacing dolomite. The vast majority of the

dolomite within areas of fabric-selective dolomitization is a deep or intense red color. Between many of the grains, there is a lighter red luminescence where early cements have been dolomitized. Some of the coarser dolomite crystals appear to have an overgrowth of brighter red-luminescent material.

- The amount of open porosity under CL is considerably greater than that visible under plane-light microscopy. Between other grains, there are interparticle pores that are still open. In a few areas, these early pores have been solution-enlarged and lined with a later generation of coarse, rhombic dolomite.
- Examination of saddle dolomites in the Leadville can provide more information about these late, elevated temperature (often hydrothermal) mineral phases. For instance, saddle dolomites show nice growth banding. These saddle dolomites display dull, red luminescence in their core areas and slightly bright, orange-red luminescence toward their rim areas. In addition, CL makes it possible to see the growth bands in these coarse dolomite crystals due to slight luminescent differences between each growth zone.
- Cathodoluminescence imaging shows that the contact between the transported material related to karstification and the limestone country rock can be sharp, irregular, and corroded.

Fluid Inclusions

- The fluid inclusion and mineral relationships suggest the following sequence of events: (1) dolomite precipitation, (2) anhydrite deposition, (3) anhydrite dissolution and quartz precipitation, (4) dolomite dissolution and late calcite precipitation, (5) trapping of a mobile oil phase, and (6) formation of bitumen.
- Aqueous fluid inclusions in early calcite, which typically forms coarse-grained crystals, display a range of liquid to vapor ratios, suggesting they have necked. Primary oil inclusions studied in one calcite crystal from the Lisbon No. D-616 well, however, display consistent liquid to vapor ratios. These oil inclusions yielded homogenization temperatures ranging from 48 to 70°C (118-158°F). These temperatures represent the minimum temperature of oil formation, not of calcite deposition. The oil was generated in place by maturation of organic material. Both the oil inclusions and the common presence of two-phase, necked aqueous inclusions imply trapping at elevated temperatures. It is suggested trapping occurred when the original calcite recrystallized during burial.
- Fluid inclusions in dolomite have reequilibrated (stretched, necked, refilled) since trapping. The common presence of single-phase aqueous inclusions suggests that the fine-grained dolomite and cores of saddle dolomite were deposited at temperatures less than about 50°C (<~122 °F).

- Coarse-grained quartz crystals containing solid inclusions of anhydrite are found at a depth of 8356 feet in the Lisbon No. D-616 well. Homogenization temperatures of primary inclusions range from 120 to 130°C (~248-266°F). The presence of gas-rich inclusions in the quartz suggests these temperatures are close to the true trapping temperatures and possibly maximum burial temperatures.
- The low ice-melting temperatures of quartz and calcite-hosted inclusions from the Lisbon No. D-616 well, suggest chemically complex Ca-Mg-bearing brines associated with evaporite deposits were responsible for mineral deposition. Calcite from the Lisbon NW USA No. B-63 well trapped fluids with lower salinities (figure 48).
- Oil trapped in early calcite as primary inclusions, as secondary inclusions in calcite of undetermined age, and as “primary” inclusions in recrystallized portions of saddle dolomite fluoresces with a bluish green color, suggesting an API gravity of 35 to 40 °. Homogenization temperatures of primary inclusions in early calcite and saddle dolomite are similar and range from 48 to 70°C (118-158°F) (figure 52). The oil inclusions trapped in the white, recrystallized and inclusion-poor saddle dolomite indicate the temperature was at least 70°C (158°F) during oil deposition and recrystallization. Oil trapped in the saddle dolomite must represent oil that was mobile at this time.
- Oil deposited in healed fractures within late, pore-filling calcite has similar fluorescence as the primary inclusions but lower homogenization temperatures of about 40°C (~104°F). The lower temperatures of the secondary oil inclusions allow the possibility that the temperatures were decreasing, perhaps due to unroofing, prior to bitumen formation.
- It is possible live oil was preserved in the calcite and dolomite, but not in the main fractures, which now contain bitumen because the oil was not degassed.

Isotope Geochemistry

- Stable carbon and oxygen isotope data indicate that all Lisbon Leadville dolomites were likely associated with brines whose composition was enriched in $\delta^{18}\text{O}$ compared with late Mississippian seawater (several per mil heavier than normal seawater).
- Stable oxygen isotope analyses of the Leadville replacement dolomites indicate that temperatures of precipitation ranged from about 60 to 90°C (~140-194°F). Saddle dolomite cements were precipitated at temperatures greater than 90°C (>194°F).
- High Sr isotopic ratios for late burial diagenetic mineral phases at Lisbon field indicate contributions by waters enriched in ^{87}Sr that were derived from either granitic Precambrian basement rocks or the Devonian McCracken Sandstone.

- Early Tertiary reactivation of basement-involved, high-angle normal faults associated with Precambrian tectonics may have allowed hot, deep-seated fluids from the granitic basement or the McCracken Sandstone to communicate upwards with the Leadville carbonate section. Brines from evaporates in the Pennsylvanian Paradox Formation may have also entered the Leadville along the large fault bounding the northeast flank of the field.
- We recommend that any evaluation of the Leadville Limestone include stable carbon and oxygen isotope analysis of diagenetic components, strontium isotope analysis for tracing the origin of fluids responsible for different diagenetic events, and production of burial history and temperature profiles to help determine when the diagenetic events occurred.

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