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

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ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the second half of the fourth project year (April 1, 2007, through September 30, 2007), Budget Period II. Research consisted of identifying potential oil-prone areas based on hydrocarbon shows (using epifluorescence techniques).

Epifluorescence petrography makes it possible to clearly identify hydrocarbon shows in Leadville cuttings selected for study. It is a non-destructive procedure using a petrographic microscope equipped with reflected light capabilities, a mercury-vapor light, and appropriate filtering. Sample preparation is inexpensive and rapid. Cuttings from productive and dry exploratory wells penetrating the Leadville Limestone in the Utah part of the Paradox fold and fault belt were examined under a binocular microscope and selected for epifluorescence evaluation. Epifluorescence allows one to observe the presence or absence of any soluble hydrocarbons, especially in high porosity dolomite. The highest maximum and highest average epifluorescence readings from each well, based on a qualitative visual rating scale, were plotted and mapped.

A regional southeast-northwest trend of relatively high epifluorescence for Leadville cuttings parallels the southwestern part of the Paradox fold and fault belt. The northeastern part of the fold and fault belt shows a regional trend of low epifluorescence. As expected, productive Leadville wells have cuttings distinguished by generally higher epifluorescence readings. Hydrocarbon migration and dolomitization was associated with regional northwest-trending faults and fracture zones, which created potential oil-prone areas along the southwest trend. Hydrocarbons may have migrated from organic-rich shales in the Pennsylvanian Paradox Formation where they are in contact with the Leadville Limestone along faults. Hydrothermal alteration associated with these faults and related fracture zones may have generated late, porous dolomite and thus produced diagenetic traps. Hydrocarbons flushed out to the southwest by hydrodynamic processes may also account for the lack of significant epifluorescence in the northeast trend. In addition, these epifluorescence trends could be related to facies or karst development in the Leadville. Exploration efforts should be concentrated in suggested oil-prone areas along the southwest part of the Paradox fold and fault belt.

Technology transfer activities for the reporting period consisted of exhibiting a booth display of project materials at the 2007 Annual Convention of the American Association of Petroleum Geologists (AAPG), technical presentations, and publications. An abstract describing the surface geochemical survey and results was accepted for presentation at the October 2007 AAPG Rocky Mountain Section (RMS) meeting in Snowbird, Utah. A Leadville core workshop was also prepared for the RMS meeting. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Energy Technology Laboratory, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the second half of the fourth project year (April 1, 2007, through September 30, 2007), Budget Period II. Research consisted of identifying potential oil-prone areas based on hydrocarbon shows (using epifluorescence techniques).

Epifluorescence petrography makes it possible to clearly identify hydrocarbon shows in Leadville cuttings selected for study. It is a non-destructive procedure using a petrographic microscope equipped with reflected light capabilities, a mercury-vapor light, and appropriate filtering. Sample preparation is inexpensive and rapid. Cuttings from 32 productive and dry exploratory wells penetrating the Leadville Limestone in the Utah part of the Paradox fold and fault belt were examined under a binocular microscope. Over 900 samples of porous dolomite and some limestone were selected from various zones over the Leadville section for epifluorescence evaluation.

Epifluorescence allows one to observe the presence or absence of any soluble hydrocarbons, especially in high porosity dolomite. Samples displaying fluorescence represent areas where hydrocarbons may have migrated or accumulated. If no fluorescence is observed in porous dolomites, the samples are also good representatives of areas where hydrocarbons have not migrated or accumulated.

A qualitative visual rating scale (a range and average) based on epifluorescence evaluation was applied to the group of cuttings from each depth in each well. The highest maximum and highest average epifluorescence reading from each well were plotted and mapped. The maps show a regional southeast-northwest trend of relatively high epifluorescence for Leadville cuttings parallels the southwestern part of the Paradox fold and fault belt from Lisbon field to west of the town of Green River. The northeastern part of the fold and fault belt shows a regional trend of low epifluorescence, including a large area of essentially no epifluorescence centered around the town of Moab. As expected, productive Leadville wells have cuttings distinguished by generally higher epifluorescence ratings.

Hydrocarbon migration and dolomitization was associated with regional northwest-trending faults and fracture zones, which created potential oil-prone areas along the southwest trend. Hydrocarbons may have migrated from organic-rich shales in the Pennsylvanian Paradox

Formation where they are in contact with the Leadville Limestone along faults. Hydrothermal alteration associated with these faults and related fracture zones may have generated late, porous dolomite and thus produced diagenetic traps. Hydrocarbons flushed out to the southwest by hydrodynamic processes may also account for the lack of significant epifluorescence in the northeast trend. In addition, these epifluorescence trends could be related to facies or karst development in the Leadville. Exploration efforts should be concentrated in suggested oil-prone areas along the southwest part of the Paradox fold and fault belt.

Technology transfer activities for the reporting period consisted of a convention booth display, technical presentations, and publications. Project materials, plans, objectives, and results were displayed at the Utah Geological Survey booth during the American Association of Petroleum Geologists (AAPG) Annual Convention, April 1-4, 2007, in Long Beach, California. An abstract describing the surface geochemical survey and results was accepted for presentation at the October 2007 AAPG Rocky Mountain Section (RMS) meeting in Snowbird, Utah. A Leadville core workshop was also prepared for the RMS meeting. Presentations, made at both the AAPG Annual Convention and Eastern Section meeting, summarized Leadville project and the surface geochemical survey. Project team members published abstracts and a Semi-Annual Technical Progress Report detailing project work, results, and recommendations. The project home page was updated on the Utah Geological Survey Web site.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil/condensate from seven fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado (figure 1). All of these fields are currently operated by independent producers. There have been no significant new oil 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 km^2) 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.

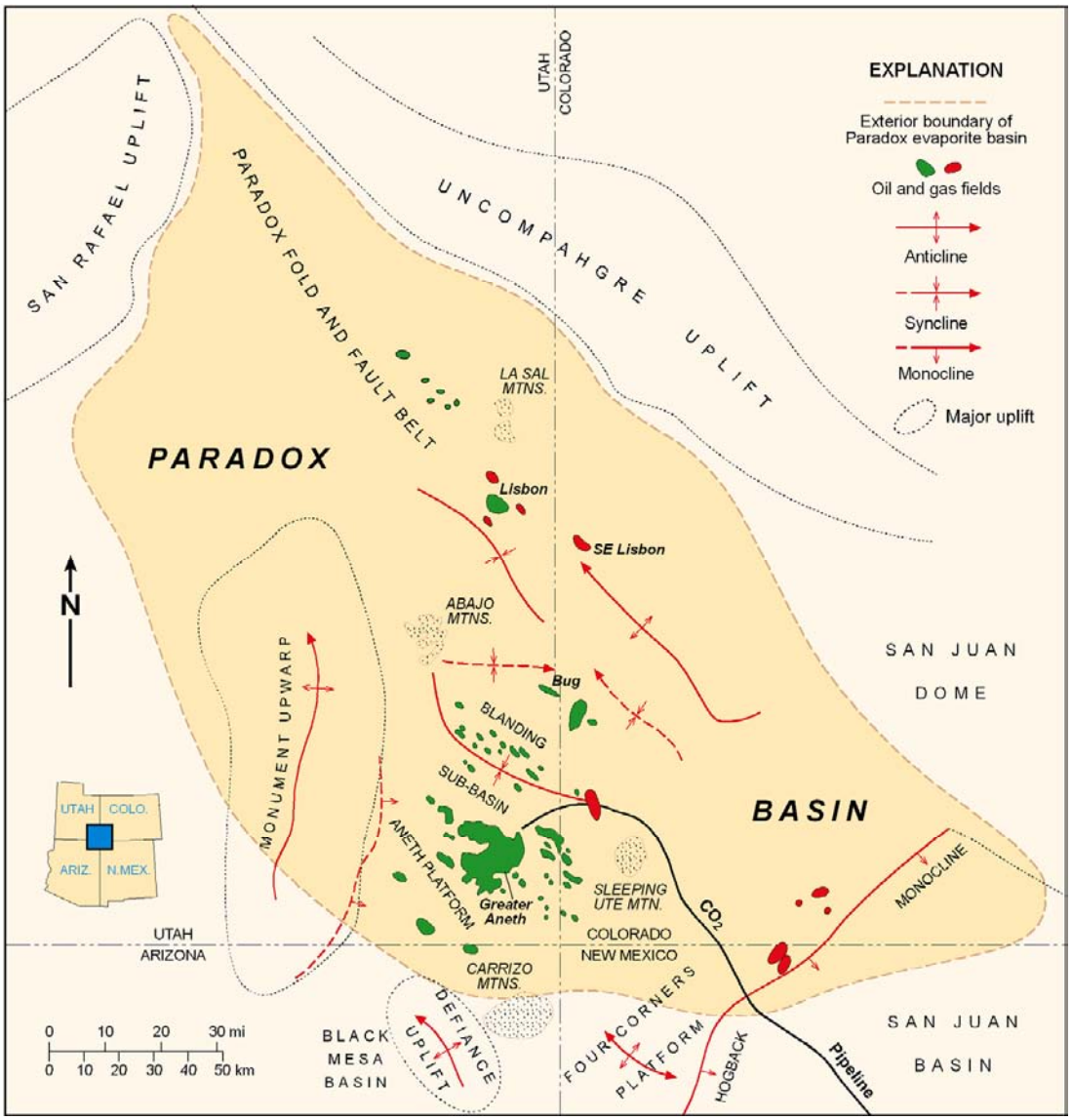

Figure 1. Oil and gas fields in the Paradox Basin of Utah, Colorado, Arizona, and New Mexico (modified from Harr, 1996).

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.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc. have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project is being conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I (Budget Period I). The objective of Phase I was to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville oil producer in the Paradox Basin), San Juan County, Utah, in order to understand the reservoir characteristics and facies that can be applied regionally. Phase I has been completed and Phase II (Budget Period II) approved by DOE. The first objective of Phase II is to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime) and surface geochemical anomalies, especially in environmentally sensitive areas. The second objective is to determine regional facies (evaluating cores, geophysical well logs, outcrop, and modern analogs), identify potential oil-prone areas, and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results are, or will be, publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results are, or will be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the second half of the fourth project year (April 1, 2007, through September 30, 2007), Budget Period II. Research consisted of identifying potential oil-prone areas based on hydrocarbon shows (using low-cost epifluorescence techniques).

Project Benefits and Potential Application

Exploring 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 often requires expensive, three-dimensional (3D) seismic acquisition, at times 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 using a new technique. For example, the independent would not likely attempt surface geochemical surveys without first knowing

they have been proven successful in the region. Our project proves geochemical surveys are an effective technique in environmentally sensitive areas, thus saving independents both time and money exploring for Leadville oil.

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. This project provides this information to save independents cash and manpower resources which they 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 potential environmental litigation, and therefore increase the chance of successfully finding new economic accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of this project's techniques and methods is a critical commonality.

IDENTIFYING POTENTIAL OIL-PRONE AREAS BASED ON SHOWS, SAN JUAN COUNTY, UTAH – RESULTS AND DISCUSSION

Paradox Basin – Overview

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with small portions in northeastern Arizona and the northwestern corner of New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian, about 330 to 310 million years ago (Ma). 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 one of two, major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2); minor amounts of oil are produced from the Devonian McCracken Sandstone at Lisbon field. Most Leadville production is from the Paradox fold and fault belt (figure 3).

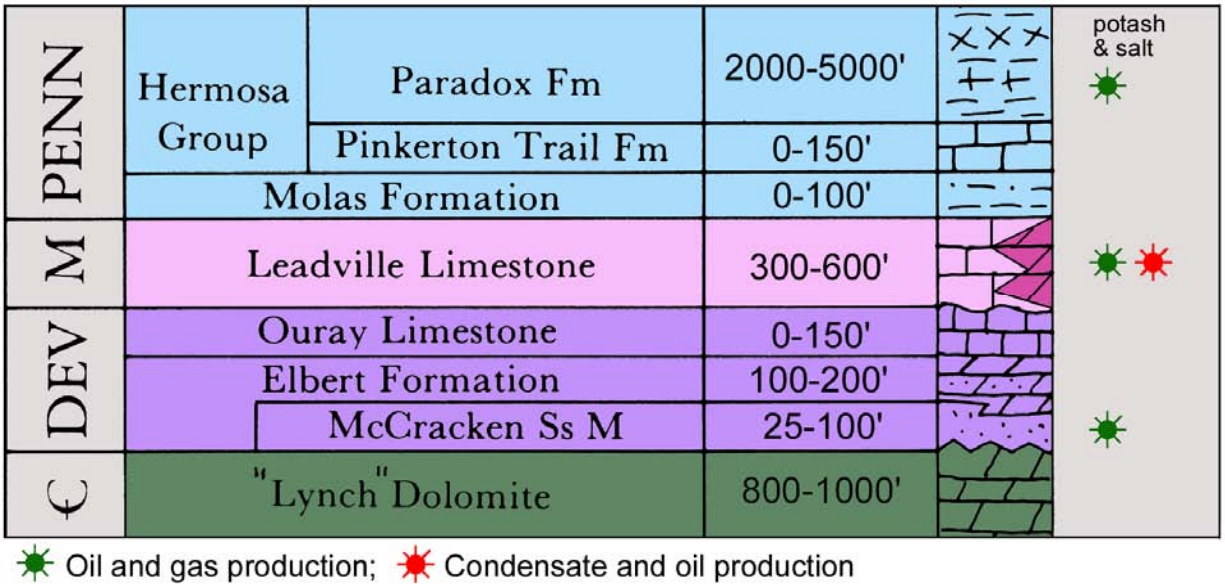

Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

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 1700 to 1600 Ma (Stevenson and Baars, 1986, 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 began in the Pennsylvanian when a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a consequence 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 (uplift) in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period.

The Uncompahgre Highlands are bounded along their southwestern flank by a large, basement-involved, high-angle reverse fault identified from seismic surveys and exploration drilling (Frahme and Vaughn, 1983). 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 present Paradox Basin includes or is surrounded by other uplifts that formed during the Late Cretaceous-early Tertiary Laramide orogeny, such as the Monument upwarp in the west-southwest, and the Uncompahgre uplift, corresponding to the earlier Uncompahgre Highlands, forming the northeast boundary (figure 1). Oligocene laccolithic intrusions form the La Sal and Abajo Mountains in the north and central parts of the basin in Utah while the Carrizo Mountains in Arizona, and the Ute, La Plata, and San Miguel Mountains in Colorado were intruded along the southeastern boundary of the basin (figure 1).

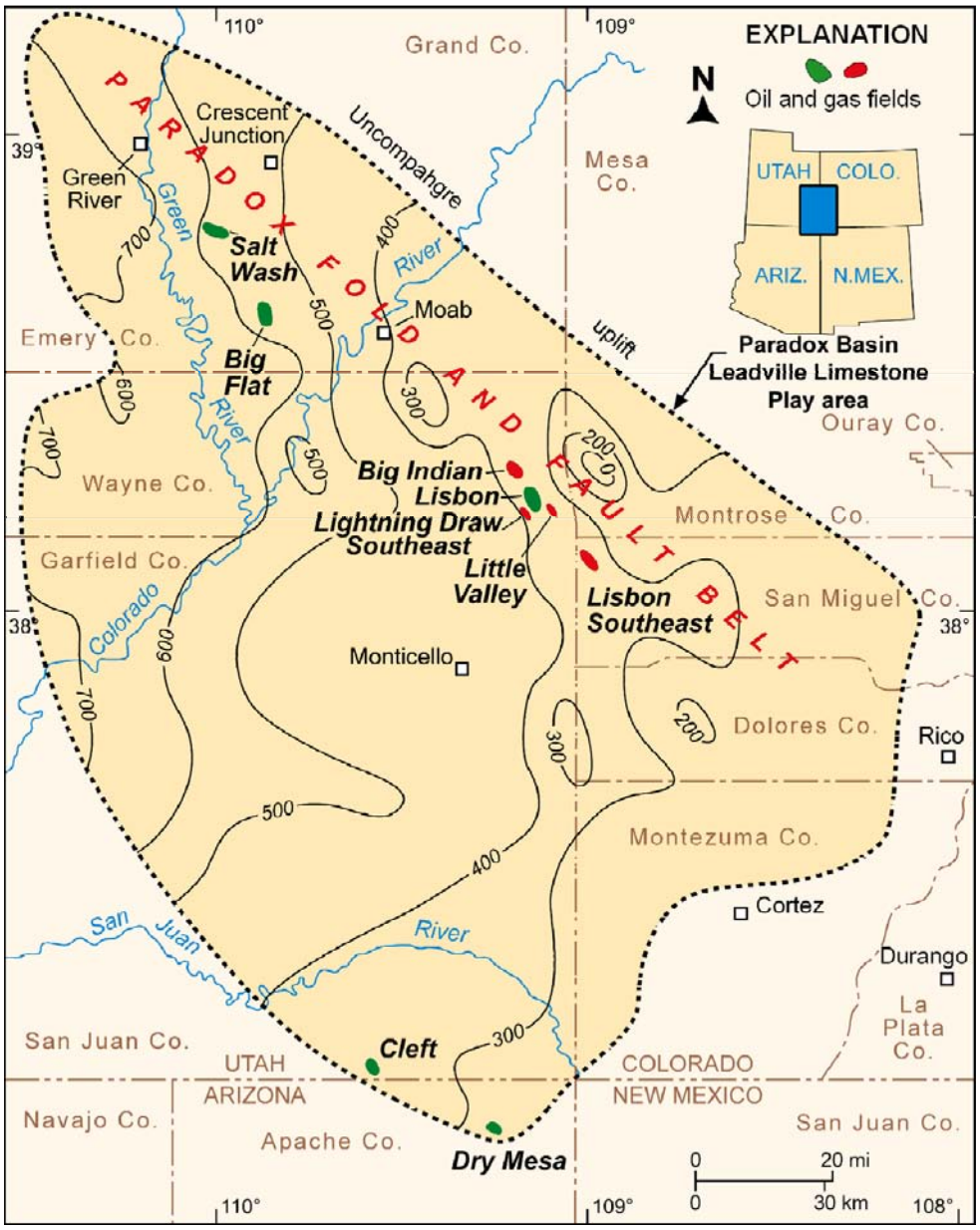

Figure 3. Location of fields that produce from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

The area now occupied by the Paradox fold and fault belt was also the site of greatest Pennsylvanian/Permian subsidence and salt deposition. Folding in the Paradox fold and fault belt began as early as the Late Pennsylvanian as sediments were laid down thinly over, and thickly in areas between rising salt (Doelling, 2000). The Paradox fold and fault belt was created during the Late Cretaceous through Quaternary by a combination of (1) reactivation of basement normal faults, (2) additional salt flowage followed by dissolution and collapse, and (3) regional uplift (Doelling, 2000). Outcrops ranging in age from Pennsylvanian through Cretaceous, with surficial Quaternary deposits, are found within the Paradox Basin.

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, Lightning Draw Southeast, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon or nearby fault zones. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

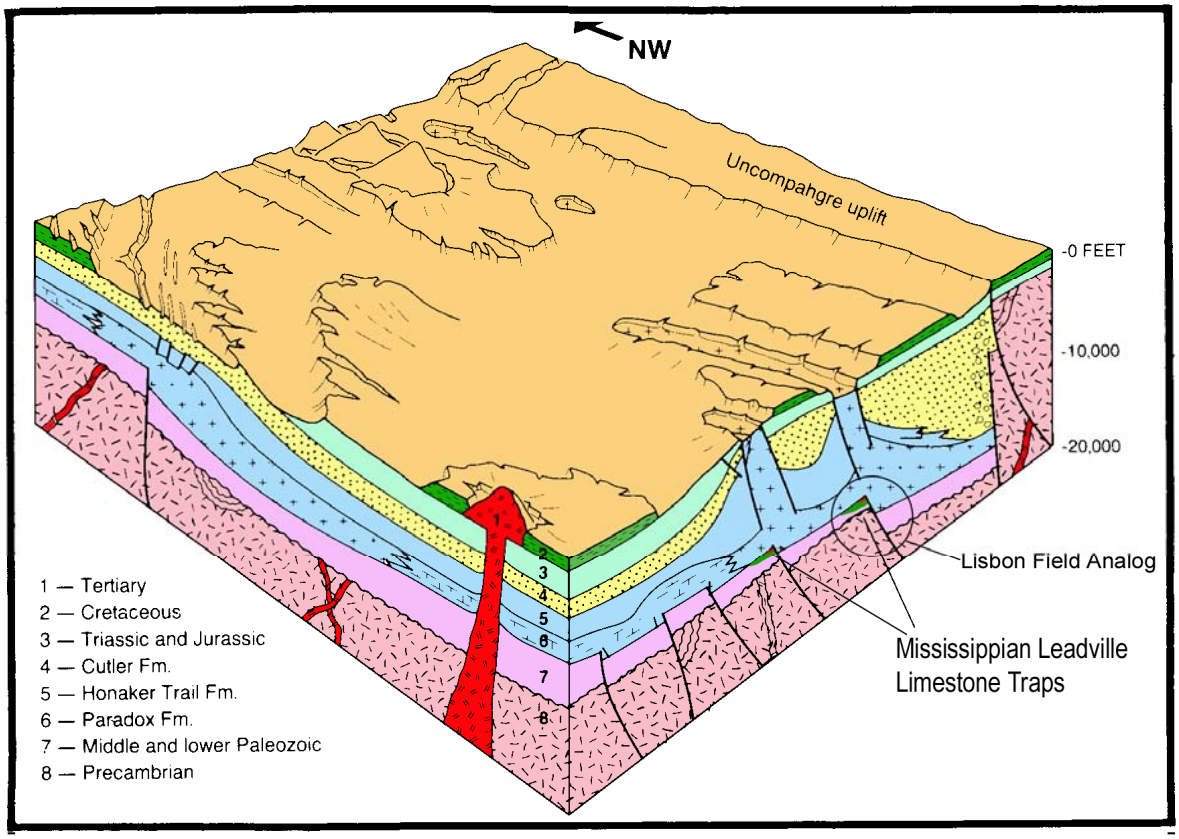

Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

Epifluorescence

Introduction

Epifluorescence (EF) microscopy is a technique that has been used in recent years to provide additional information on diagenesis, pore types, and organic matter (including "live" hydrocarbons) within sedimentary rocks. It is a rapid, non-destructive procedure that can be done using a petrographic microscope equipped with reflected light capabilities, a mercury-vapor light, and appropriate filtering. 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 Yurowicz, 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 5.

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

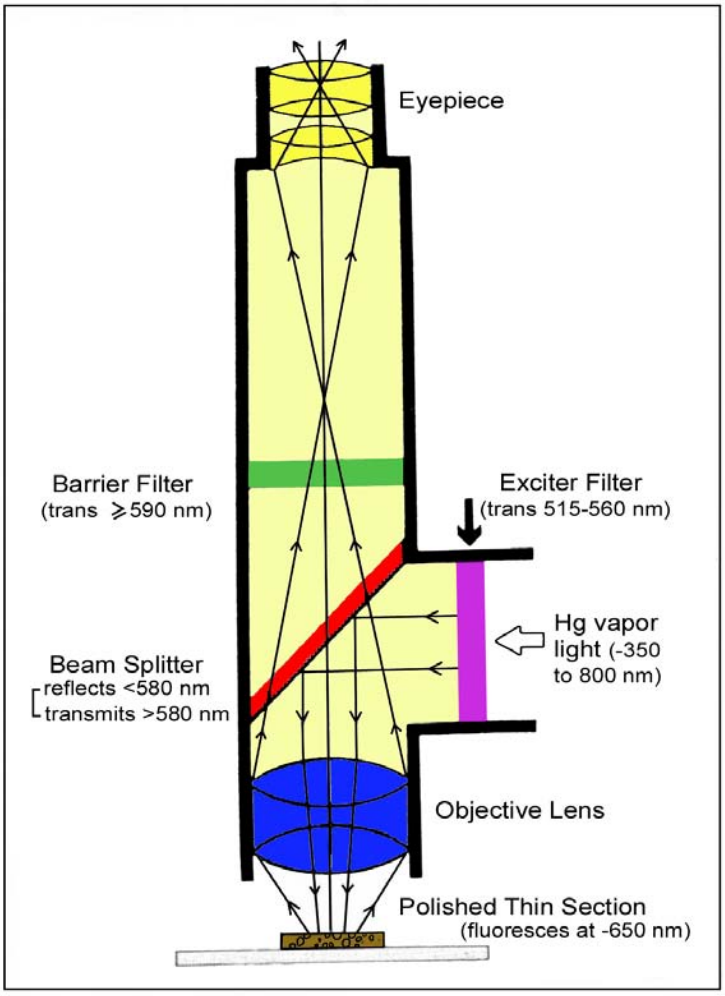

Figure 5. Generalized microscope optical configuration for observing fluorescence under incident light (modified from Soeder, 1990).

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.

Wells penetrating the Leadville Limestone in the Utah part of the Paradox fold and fault belt were plotted and all Leadville well cuttings available from the collection at the Utah Core Research Center were compiled. Cuttings were examined under a binocular microscope and porous samples of dolomite and some limestone were selected from various zones over the Leadville section (figure 6): generally four to ten samples per depth interval from each well. The cuttings were placed on Petrologs™, a small plastic, self-adhesive compartmentalized cutting storage unit, for EF examination (figure 7). (All Petrologs™ containing Leadville cuttings from the project are stored at the Utah Core Research Center and are available to the public.) Thus, sample preparation is inexpensive and rapid.

Approximately 900 cutting samples were selected from 32 wells penetrating the Leadville Limestone (six producing gas, condensate, and oil wells, as well as 26 non-productive wells) throughout the region (table 1). These cuttings display mainly intercrystalline porosity, occasional small vugs or molds, and other pore types (figure 8). Oil staining, bitumen, and stylolites are also observed (figure 8).

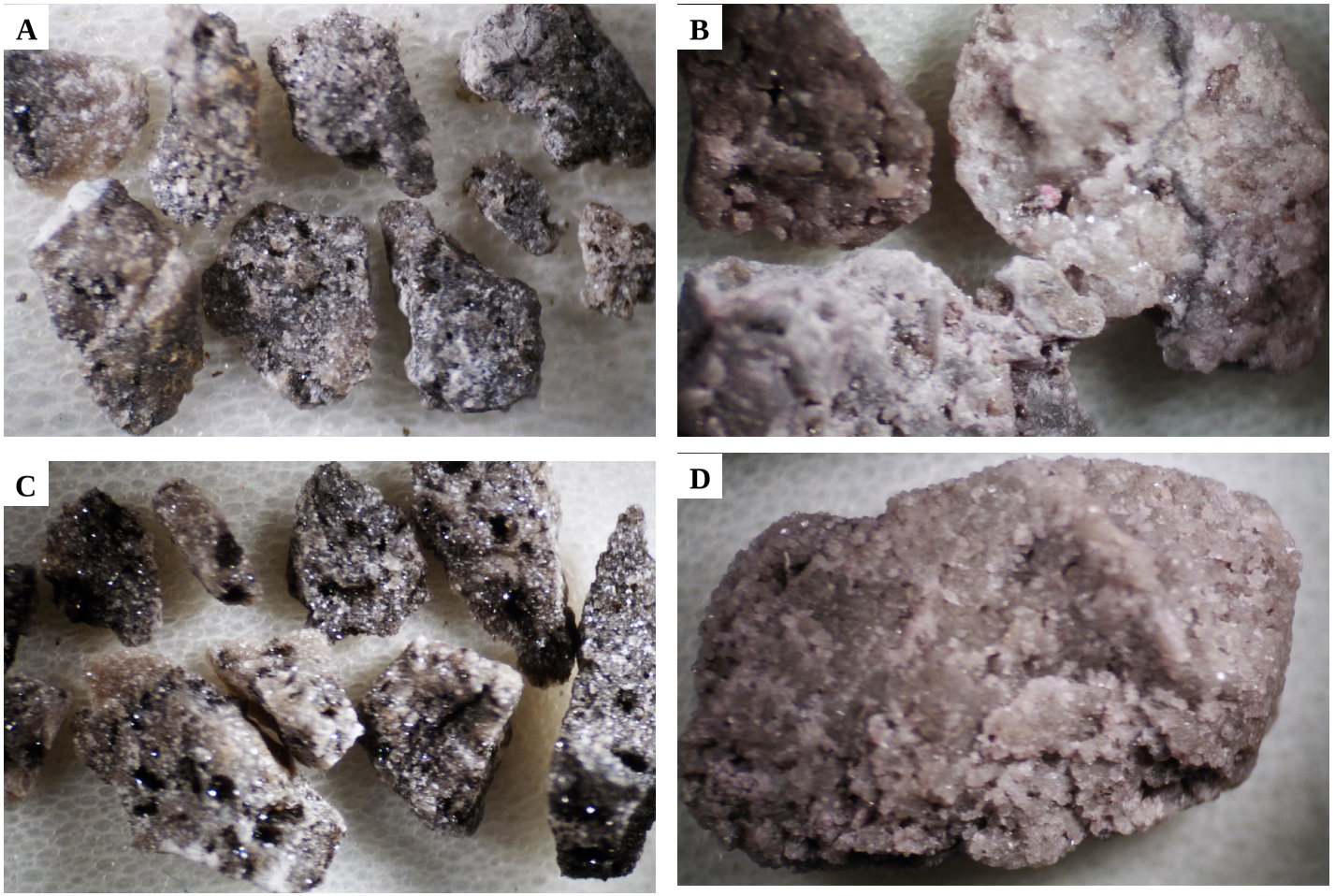

Figure 6. Examples of cuttings selected from various Leadville zones as observed with a binocular microscope. A – Overview of dolomite cuttings (16X) from 9410 to 9420 feet containing porosity and bitumen in the Pure Spiller Canyon State 1 well (SW1/4SW1/4 section 16, T. 30 S., R. 25 E., Salt Lake Base Line and Meridian [SLBL&M], San Juan County). B – Overview of dolomite cuttings (13X) from 7800 to 7810 feet containing porosity and stylolites in the Hatch Mesa 1 well (SE1/4SW1/4 section 22, T. 28 S., R. 21 E., SLBL&M, San Juan County). C – Overview of dolomite cuttings (12X) from 10,020 to 10,023 feet containing porosity and bitumen in the Pure USA Big Indian 1 well (SE1/4SE1/4 section 33, T. 29 S., R. 24 E., SLBL&M, San Juan County). D – Single white dolomite cutting (14X) with good intercrystalline porosity from 7790 to 7800 feet containing porosity and stylolites in the Hatch Mesa 1 well.

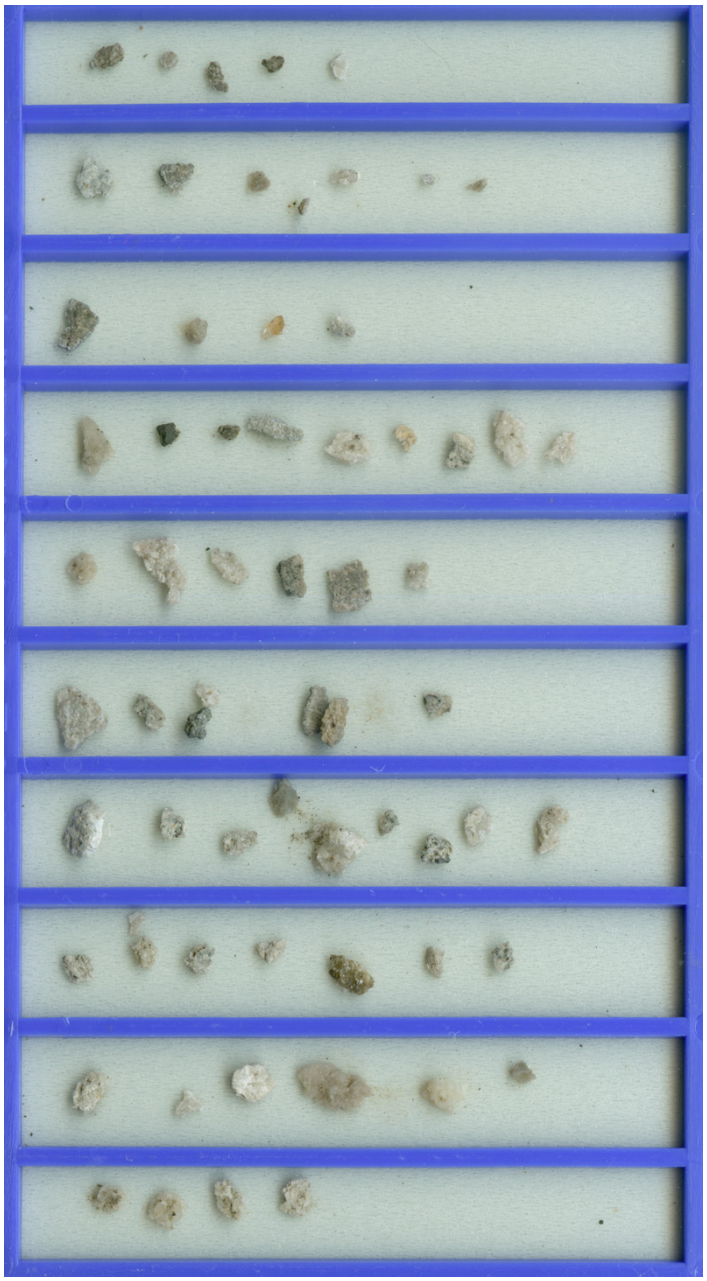

Figure 7. Example of cuttings selected from various Leadville zones between 6875 to 7075 feet, Pure Mineral Point 1 well (section 7, T. 26 S., R. 18 E., [SLBL&M], Grand County), placed on Petrologs™ for epifluorescence examination.

Table 1. Wells in the Paradox fold and fault belt, Utah, containing Leadville Limestone cuttings evaluated using epifluorescence techniques. N = number of samples.

Map #	Well Name	Location	County	Interval (ft)	N	Visual EF Rating	
						Highest Maximum	Highest Average
1	Woodside 1	SESE 12 19S 13E	Emery	6580-6750	23	1.5	1.2
2	Hatch Sphinx Unit 1-A	SWNW 35 19S 14E	Emery	8670-8715	45	1.0	0.8
3	Denison Mines 5-1	5 21S 14E	Emery	5830-5870	23	2.5	1.5
4	Salt Wash 22-34	34 22S 17E	Grand	10070-10085	16	0.2	0.1
5	Government Smoot 1	CSENE 17 23S 17E	Grand	8732-8737	16	2.5	2.0
6	Chaffin 1	NENW 21 23S 15E	Emery	7460-7540	26	1.5	1.2
7	Federal Hatt 1	SESE 19 23S 14 E	Emery	5905-6020	33	3.0	2.3
8	Gov 45-5	5 24S 15E	Emery	6899-6935	5	0.5	0.2
9	State 12-11	SWNW 11 24S 20E	Grand	11810-11850	50	1.0	0.7
10	Federal 31	NWSE 31 24S 23E	Grand	10450-10760	27	1.5	0.3
11	Gruvers Mesa 2	10 25S 16E	Emery	6750-6910	32	2.2	1.8
12	McRae Fed 1	SWSW 10 25S 18E	Grand	8485-8550	8	2.5	0.8
13	Bow Knot Unit 1	NESE 20 25S 17.5E	Grand	6075-6400	31	2.5	2.0
14	Big Flat/Bartlett Flat 1	NENE 26 25S 19 E	Grand	8560-8650	17	2.0	1.5
15	Lookout Point 1	SWSW 29 25S 16E	Emery	6380-6520	22	3.0	2.5
16	Fed Bowknoll 1	NESE 30 25S 18 E	Grand	7375-7390	12	2.5	1.8
17	Long Canyon 1	NENW 9 26S 20E	Grand	7560-7630	44	1.5	0.4
18	Mineral Point 1	7 26S 18E	Grand	6875-7075	65	2.5	2.0
19	Big Flat 3	NENE 23 26S 19E	Grand	7714-7725	51	1.0	0.8
20	Federal Ornsby 1	NWNE 3 27S 19E	Wayne	7740-7810	25	2.0	1.5
21	Gold Basin 1	NWNW 15 27S 24E	San Juan	14300-14410	37	2.0	0.8
22	Putnam 1	SENE 15 27S 22 E	San Juan	7410-7490	30	0.8	0.3
23	Unit 1 Bridger Sack Mesa	SESE 17 27S 22 E	San Juan	7030-7070	53	1.0	0.8
24	Muleshoe 1	2 28S 23E	San Juan	10240-10280	9	2.0	0.2
25	Lockhard Fed 1	SW 22 28S 20E	San Juan	5130-5050	37	2.5	2.0
26	Hatch Mesa 1	SESW 22 28S 21E	San Juan	7780-7820	23	2.5	1.0
27	USA Big Indian 1	NWSESE 33 29S 24E	San Juan	9960-10090	55	1.5	1.0
28	State 1	32 29.5S 24E	San Juan	9835-9852	16	3.0	2.5
29	NW Lisbon St. A	2 30S 24E	San Juan	9710-9725	12	2.0	1.0
30	Lisbon Valley C-1	NENW 9 30S 24E	San Juan	8765-70	20	1.5	1.0
31	Lisbon 814-A	CNWSW 14 30S 24E	San Juan	8870-8930	80	3.0	2.0
32	Spiller Canyon State 1	SWSW 16 30S 25E	San Juan	9080-9420	75	1.0	0.7

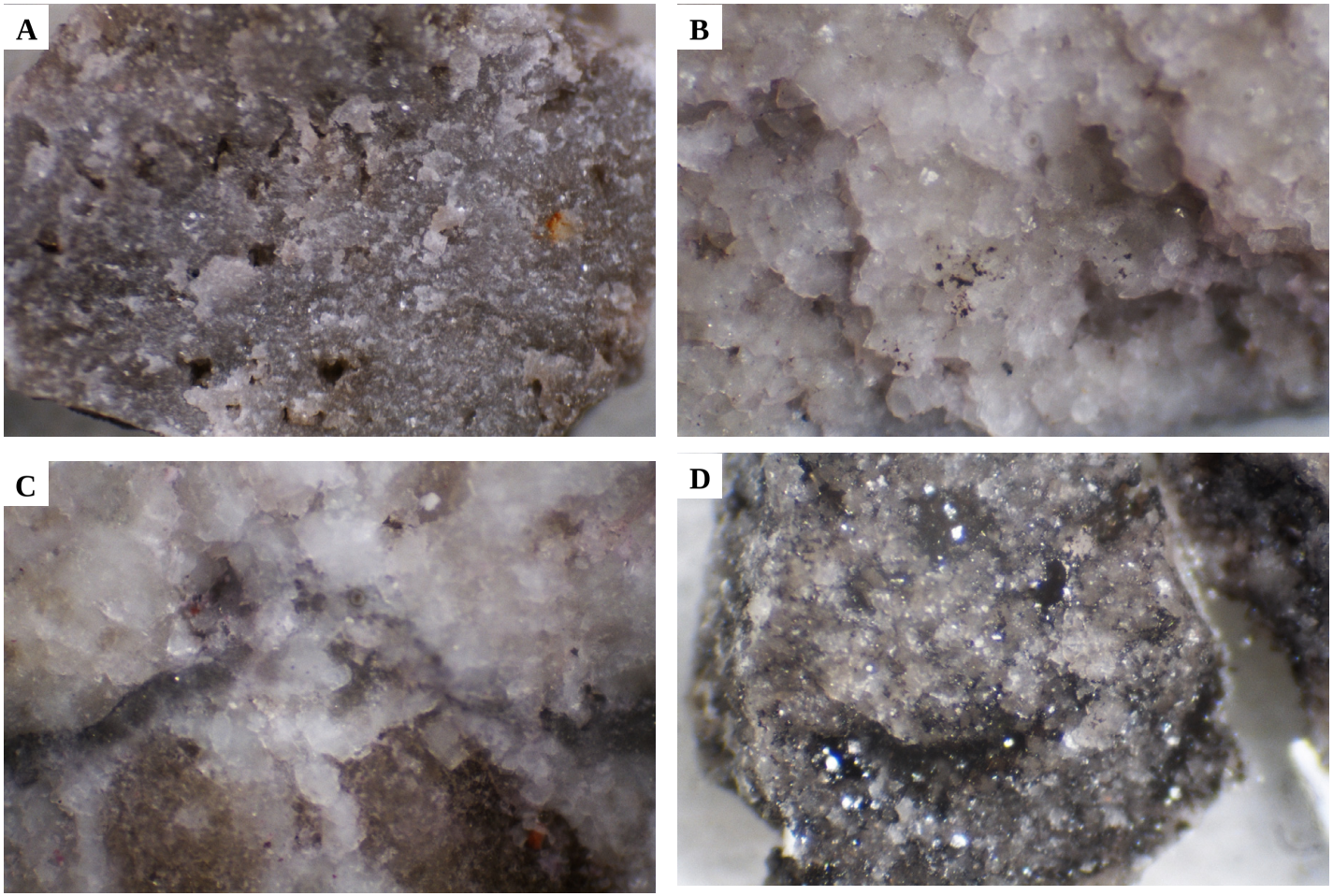

Figure 8. Close-up views of petrographic characteristics of Leadville cuttings as observed with a binocular microscope. A – Large, single sample of tight dolomite with widely spaced small vugs from 7780 to 7790 feet in the Hatch Mesa 1 well (SE1/4SW1/4 section 22, T. 28 S., R. 21 E., SLBL&M, San Juan County). B – Sample of white dolomite with good intercrystalline porosity from 7790 to 7800 feet contain porosity and bitumen in the Hatch Mesa 1 well; note possible sulfide replacement (opaque). C – Sample showing stylolite overprinted with dolomite replacement from 7800 to 7810 feet in the Hatch Mesa 1 well; note possible sulfide replacement. D – Sample showing dolomite containing small vugs and intercrystalline porosity lined with bitumen from 10,020 to 10,023 feet in the Pure USA Big Indian 1 well (SE1/4SE1/4 section 33, T. 29 S., R. 24 E., SLBL&M, San Juan County).

Examination of cuttings 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.

Epifluorescence petrography makes it possible to clearly identify hydrocarbon shows in Leadville cuttings selected for study. A qualitative visual rating scale (a range and average) based on EF evaluation was applied to the group of cuttings from each depth in each well (table 2 and figure 9). Using the qualitative visual rating scale, the highest maximum and highest average EF reading from each well were plotted and mapped (figures 10 and 11).

Discussion

Epifluorescence allows one to observe the presence of any soluble hydrocarbons. Samples displaying fluorescence represent areas where hydrocarbons may have migrated or accumulated. The best fluorescence, when present, was gold and occurred in high porosity (figure 9A), low permeability dolomites (thus the major reason the collection effort concentrated on porous dolomites). Pale-yellow fluorescence indicated possible high-gravity oil (figure 9B). If no fluorescence was observed in porous dolomites, the samples were also good representatives of areas where hydrocarbons had not migrated or accumulated. Bitumen (pyrobitumen) was common in many samples. It has no activity within the hydrocarbon molecules and therefore does not fluoresce (figure 9D).

As expected, productive Leadville wells (fields such as Lisbon and Salt Wash) have cuttings distinguished by generally higher EF readings (figures 10 and 11). However, a regional southeast-northwest trend of relatively high EF from Leadville cuttings parallels the southwestern part of the Paradox fold and fault belt from Lisbon field to west of the town of Green River. A visual reading of 2.0 to 3.0 for the highest maximum EF (figure 10) and 2.0 to 2.5 for the highest average EF (figure 11) occur in this region. The northeastern part of the fold and fault belt shows a regional trend of low EF including a large area of essentially no EF (a visual reading of less than 0.4 for the maximum highest average EF) centered around the town of Moab (figure 11).

These EF maps imply hydrocarbon migration and dolomitization was associated with regional northwest-trending faults and fracture zones, which created potential oil-prone areas along the southwest trend. Hydrocarbons may have migrated from organic-rich shales in the Pennsylvanian Paradox Formation where they are in contact with the Leadville Limestone along faults. Hydrothermal alteration associated with these faults and related fracture zones may have generated late, porous dolomite and thus produced diagenetic traps indicated by EF.

An alternative interpretation for the lack of significant EF in the northeast trend is the possibility that most hydrocarbons may have been flushed out to the southwest by hydrodynamic processes. A final explanation is that these EF trends could be related to facies or karst development in the Leadville Limestone. At any rate, the mapping of hydrocarbon shows based on EF indicates exploration efforts should be concentrated in suggested oil-prone areas along the southwest part of the Paradox fold and fault belt.

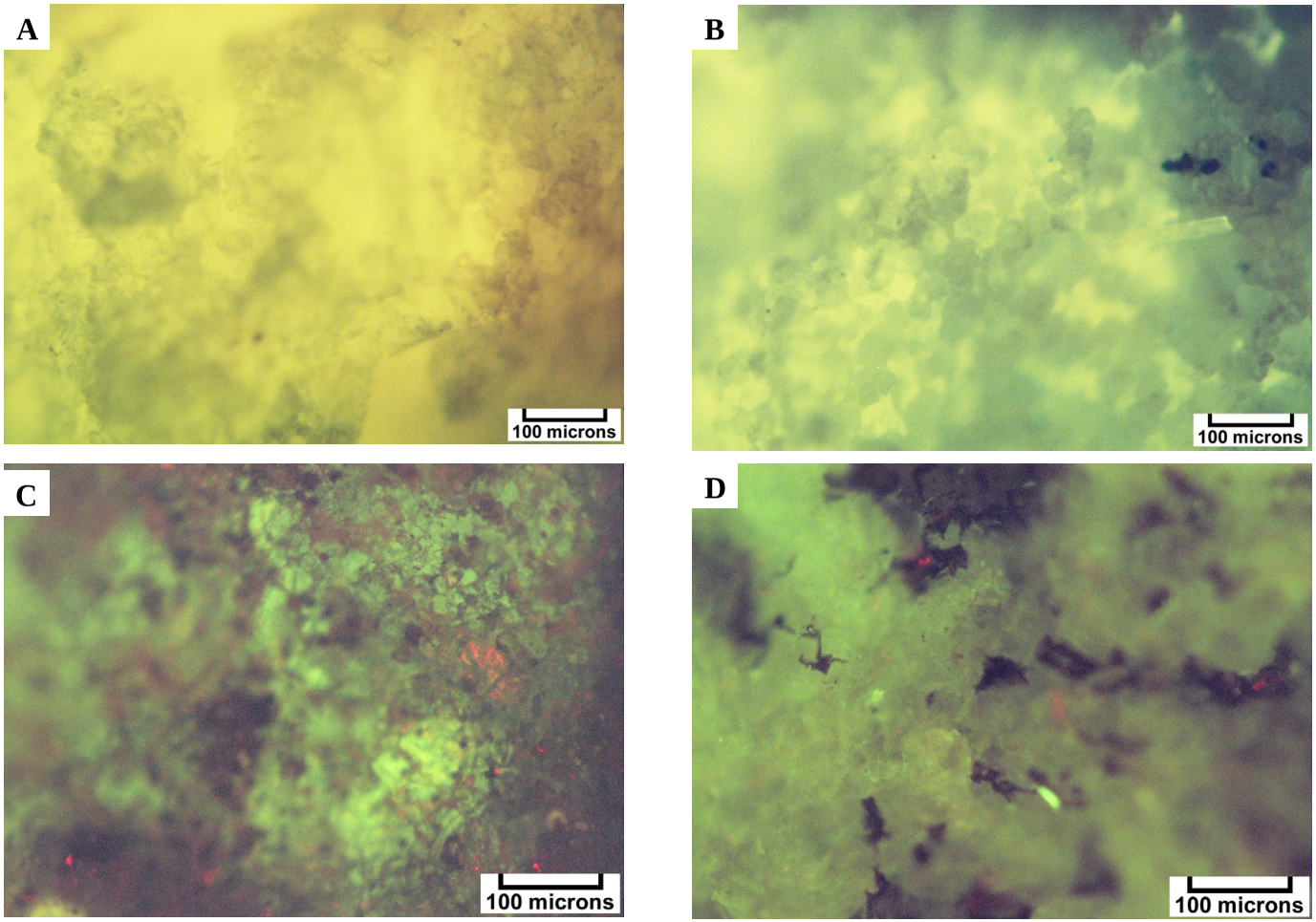

Figure 9. Photomicrographs under moderate magnification showing examples of visually rated epifluorescence. A – Bright fluorescence, rated 3.0, in medium crystalline dolomite with fair to good intercrystalline porosity from 5935 to 5945 feet in the Federal Hatt 1 well (SE1/4SE1/4 section 19, T. 23 S., R. 14 E., SLBL&M, Emery County). B – Moderate fluorescence, rated 2.0, fine to medium crystalline dolomite from 10,240 to 10,250 feet in the Gulf Muleshoe 1 well (section 2, T. 28 S., R. 23 E., SLBL&M, San Juan County). C – Weak fluorescence, rated 1.0, medium to coarsely crystalline dolomite with fairly good bitumen-lined, intercrystalline porosity from 9150 to 9160 feet in the Pure Spiller Canyon 1 well (SW1/4SW1/4 section 16, T. 30 S., R. 25 E., SLBL&M, San Juan County); note abundant iron distribution (red), bitumen is black. D – No to very weak fluorescence, rated 0.2, medium to coarsely crystalline dolomite containing bitumen and iron from 10,020 to 10,023 feet in the Pure USA Big Indian 1 well (SE1/4SE1/4 section 33, T. 29 S., R. 24 E., SLBL&M, San Juan County).

Table 2. Key to the epifluorescence qualitative visual "rating" scale.

Rating	Generalized Interpretation
0 – 0.5	No Fluorescence: Not capable of oil production. May be wet, if not a gas-bearing zone.
1.0 – 1.5	Weak Fluorescence: An "oil" show. Indicative of oil in the system, but not necessarily capable of production. Some dull or weak fluorescence may exist in a wet zone (especially if there is "speckled" fluorescence) or in a mixed oil/water zone.
2.0 – 2.5	Moderate Fluorescence: A good indication of oil within this zone. Probably capable of some oil production if there is adequate porosity and permeability.
3.0 – 3.5	Bright Fluorescence: A very good to excellent indication of oil within this zone. Should be capable of some oil production if there is adequate porosity and permeability.
3.5 – 4.0	Very Bright, Intense Fluorescence: Also a very good to excellent indication of oil within this zone. However, some very bright fluorescence may indicate very tight oil-bearing rocks or mature, oil-generating source rocks.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data.

Project materials, plans, objectives, and results were displayed at the UGS booth during the AAPG Annual Convention, April 1-4, 2007, in Long Beach, California. Four UGS scientists staffed the display booth at this event. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

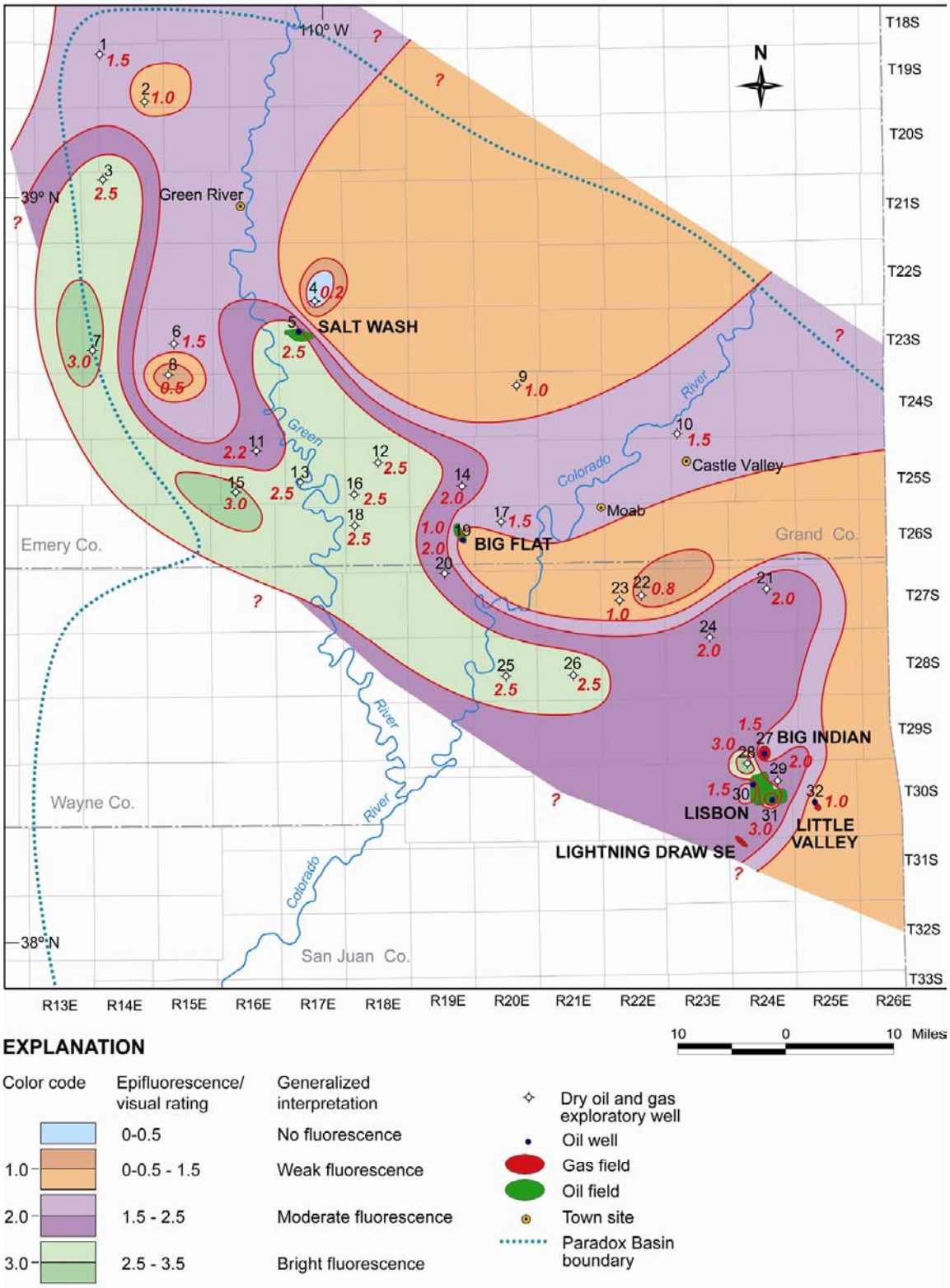

Figure 10. Map of the highest maximum epifluorescence based on visual rating of well cuttings, Paradox fold and fault belt, Utah.

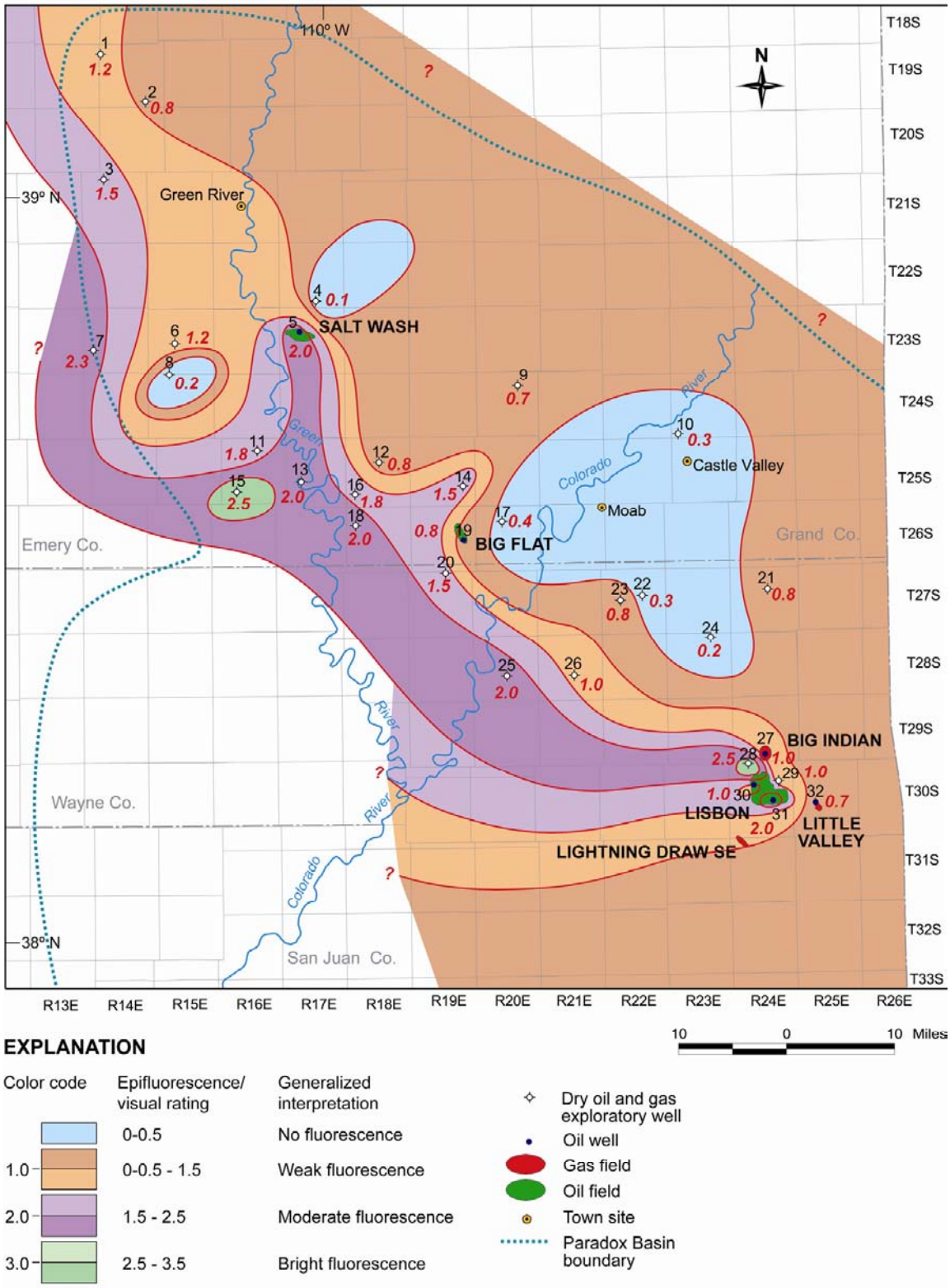

Figure 11. Map of the highest average epifluorescence based on visual rating of well cuttings, Paradox fold and fault belt, Utah.

An abstract describing the surface geochemical survey and results was accepted for presentation at the October 2007 AAPG Rocky Mountain Section (RMS) meeting at Snowbird, Utah. We also prepared a Leadville short course for the AAPG RMS meeting "Depositional Environments, Diagenesis, and Hydrothermal Alteration of the Mississippian Leadville Limestone Reservoir, Paradox Basin, Utah: A Core Workshop." This workshop is for geoscientists with interests in exploration and development of shallow-shelf carbonate reservoirs. This course is designed for geoscientists who wish to examine a large collection of carbonate core (both limestone and dolomite) presented within lithofacies, diagenetic, and petrophysical context. Representative core from Utah's Lisbon field will be examined. The core workshop is organized into two topical sessions: Leadville Facies/Fabrics and Leadville Burial Overprint. Participants will perform a series of group exercises using core, geophysical well logs, and photomicrographs from thin sections. These sessions include describing reservoir versus non-reservoir lithofacies; determining diagenesis, hydrothermal alteration, and porosity from core; recognizing barriers and baffles to fluid flow; correlating core to geophysical well logs; and identifying potential completion zones. Following the core sessions, we will present a summary lecture on our Leadville diagenetic/alteration interpretation based on geochemical analysis and petrographic techniques.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities. These presentations included an overview of the Leadville project and the results of the Lisbon area surface geochemical survey.

"New Techniques for New Discoveries – Results from the Lisbon Field Area, Paradox Basin, Utah" by David Seneshen, T.C. Chidsey, C.D. Morgan, and M.D. Vanden Berg, presented at the AAPG Annual Convention, in Long Beach, California, April 2, 2007.

"Gas and Oil in Utah: Potential, New Discoveries, and Hot Plays" by Thomas C. Chidsey, Jr., presented at the annual meeting of the International Oil Scouts Association in Park City, Utah, June 19, 2007.

"New Techniques for New Discoveries – Results from the Lisbon Field Area, Paradox Basin, Utah" by David Seneshen, T.C. Chidsey, C.D. Morgan, and M.D. Vanden Berg, presented at the AAPG Eastern Section meeting, in Lexington, Kentucky, September 17, 2007.

Project Publications

Chidsey, T.C., Jr., Morgan, C.D., Vanden Berg, M.D., and Seneshen, D.M., 2007, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period October 1, 2006 to March 31, 2007: U.S. Department of Energy, DOE/BC15424-7, 75 p.

Durham, L.S., 2007, Geochem offers Paradox option – lichens, free gas yield clues: American Association of Petroleum Geologists Explorer (August), v. 28, no. 8, p. 8-12.

Seneshen, D.M., Chidsey, T.C., Jr., Morgan, C.D., and Vanden Berg, M.D., 2007, New techniques for new discoveries – results from the Lisbon field area, Paradox Basin, Utah [abs.]: American Association of Petroleum Geologists Annual Convention Abstracts, v. 16, p. 126.

Seneshen, D.M., Chidsey, T.C., Jr., Morgan, C.D., and Vanden Berg, M.D., 2007, New techniques for new discoveries – results from the Lisbon field area, Paradox Basin, Utah [abs.]: American Association of Petroleum Geologists, Eastern Section Meeting Official Program.

We also prepared a manuscript on the Leadville surface geochemical survey, "New Techniques for New Discoveries – Surface Geochemical Results from the Lisbon Field Area, Paradox Basin, Utah," for inclusion in the Rocky Mountain Association of Geologists 2008 guidebook titled "Petroleum Geology of the Paradox Basin."

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

2. Epifluorescence petrography makes it possible to clearly identify hydrocarbon shows in Leadville cuttings selected for study. It is a non-destructive procedure that can be done using a petrographic microscope equipped with reflected light capabilities, mercury-vapor light, and appropriate filtering. Sample preparation is inexpensive and rapid.

3. Cuttings from 32 productive and dry exploratory wells penetrating the Leadville Limestone in the Utah part of the Paradox fold and fault belt were examined under a binocular microscope. Over 900 samples of porous dolomite and some limestone were selected from various zones over the Leadville section for EF evaluation.

4. Epifluorescence allows one to observe the presence or absence of any soluble hydrocarbons, especially in high porosity dolomite. Samples displaying fluorescence represent areas where hydrocarbons may have migrated or accumulated. If no fluorescence is observed in porous dolomites, the samples are also good representatives of areas where hydrocarbons has not migrated or accumulated.

5. A qualitative visual "rating" scale (a range and average) based on EF evaluation was applied to the group of cuttings from each depth in each well. The highest maximum and highest average EF reading from each well were plotted and mapped.

6. The maps show a regional southeast-northwest trend of relatively high EF for Leadville cuttings parallels the southwestern part of the Paradox fold and fault belt from Lisbon field to west of the town of Green River. The northeastern part of the fold and fault belt shows a regional trend of low EF including a large area of essentially no EF centered around the town of Moab. As expected, productive Leadville wells have cuttings distinguished by generally higher EF readings.

7. Hydrocarbon migration and alteration dolomitization was associated with regional northwest-trending faults and fracture zones, which created potential oil-prone areas along the southwest trend. Hydrocarbons may have migrated from organic-rich shales in the Pennsylvanian Paradox Formation where they are in contact with the Leadville Limestone along faults. Hydrothermal alteration associated with these faults and related fracture zones may have generated late, porous dolomite and thus produced diagenetic traps. Hydrocarbons flushed out to the southwest by hydrodynamic processes may also account for the lack of significant EF in the northeast trend. In addition, these EF trends could be related to facies or karst development in the Leadville.

8. Exploration efforts should be concentrated in suggested oil-prone areas along the southwest part of the Paradox fold and fault belt.

ACKNOWLEDGMENTS

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James Parker, Sharon Wakefield, and Thomas Dempster of the UGS drafted figures, compiled maps, and collected well cuttings from the Utah Core Research Center; Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David E. Tabet and Robert Ressetar of the UGS.

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