Carbon Dioxide in Mississippian Rocks of the Paradox Basin and Adjacent Areas, Colorado, Utah, New Mexico, and Arizona

U.S. GEOLOGICAL SURVEY BULLETIN 2000–H

On the Front Cover: View south toward the LaSal Mountains along the Colorado River between Cisco and Moab, Utah. Fisher Towers in center is composed of Permian Cutler Formation and capped by Triassic Moenkopi Formation. The prominent mesa at left center is capped by Jurassic Kayenta Formation and Wingate Sandstone and underlain by slope-forming Triassic Chinle and Moenkopi Formations. The Chinle-Moenkopi contact is marked by a thin white ledge-forming gritstone. The valley between Fisher Towers and Fisher Mesa in the background is part of Richardson Mesa, part of Professor Valley. Photograph by Omer B. Raup, U.S. Geological Survey.

Carbon Dioxide in Mississippian Rocks of the Paradox Basin and Adjacent Areas, Colorado, Utah, New Mexico, and Arizona

By James A. Cappa *and* Dudley D. Rice

EVOLUTION OF SEDIMENTARY BASINS—PARADOX BASIN
A.C. Huffman, Jr., Project Coordinator

U. S. GEOLOGICAL SURVEY BULLETIN 2000–H

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

A multidisicplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Cappa, James A.
Carbon dioxide in Mississippian rocks of the Paradox Basin and adjacent areas, Colorado, Utah, New Mexico, and Arizona / by James A. Cappa and Dudley D. Rice
p. cm.—(Evolution of sedimentary basins—Paradox basin : H) (U.S. Geological Survey bulletin : 2000)
Includes bibliographic references.
Supt. of Docs. no. : I 19.3:2000–H
1. Limestone—Paradox Basin. 2. Carbon dioxide. 3. Geology, Stratigraphic—Mississippian. I. Rice, Dudley D. II. Title. III. Series. IV. Series: Evolution of sedimentary basin—Paradox Basin : ch. H.
QE75.B9 no. 2000–H
[QE471.15.L5]
557.3 s—dc20
[552'.58]
95–2
CIP

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ABSTRACT

Six gas samples and two core samples were obtained from the Mississippian Leadville Limestone in the McElmo field, Colorado, and the Lisbon field, Utah. Gas samples from the McElmo field contain 97–98 percent CO_2 and have CO_2 $\delta^{13}C$ values of –3.8, –4.2, –4.4, and –11.8‰. The $\delta^{13}C$ value for calcite from the reservoir is –0.64‰, almost identical to that for calcite from normal marine limestones (–0.02‰).

Produced gas from the Lisbon field contains 18–36 percent CO_2; hydrocarbon gases and helium make up the rest. Carbon dioxide $\delta^{13}C$ values for the gas are –11.1 and –9.5‰ and for the methane range from –42.3 to –42.1‰, whereas values for the calcite and organic carbon of the reservoir core sample are 0.34 and –27.06‰, respectively.

The high amounts of carbon dioxide in both fields result mainly from the thermal decomposition of calcite in carbonate reservoirs, predominantly the Leadville Limestone, during a period of elevated geothermal gradients in early to mid-Tertiary time. The McElmo field is 5 mi north of the Ute Mountain laccolith, and the Lisbon field is 15 mi south of the La Sal Mountains laccolith. In contrast, the associated hydrocarbon gases in the Lisbon field were generated from interbedded organic-rich shale at intermediate levels of thermal maturity (oil generation window).

INTRODUCTION

The Paradox Basin of the Four Corners area (fig. 1) is a paleotectonic depression of late Paleozoic age that has been structurally deformed at various times. The last and most obvious major deformation was during the Laramide orogeny of Late Cretaceous to early Tertiary age. The zones of deformation during the Laramide event in part reflect older Precambrian structures (Baars and Stevenson, 1981). Although the basin is generally defined as the area of salt deposition in the Middle Pennsylvanian Paradox Formation, the rock units discussed in this report are of Mississippian age and extend far beyond the boundaries of the Paradox Basin.

In this report we review published literature on the depositional setting of the Mississippian Leadville Limestone in the Paradox Basin and discuss the nature, distribution, and origin of carbon dioxide in the Leadville Limestone. Geophysical well logs were used to construct subsurface stratigraphic sections and structure sections (plates 1–5, fig. 1) that illustrate the stratigraphic variation of the Leadville Limestone in the Paradox Basin. Particular attention is given to the McElmo field in Colorado and the Lisbon field in Utah because of their economic importance. The McElmo field has produced more than 1,345 billion cubic feet (BCF) of CO_2 through 1992, and the Lisbon field has produced approximately 50 million barrels of oil (BO) and 581 BCF of gas that includes about 25 percent CO_2. The U.S. Geological Survey supplied a data set of 941 wells in the Paradox Basin that intersected the Leadville Limestone; 21 of these (fig. 1) were used to construct the stratigraphic and structure sections . Isopach and structure contour maps (plates 6 and 7, respectively; fig. 1) of the Mississippian Leadville Limestone were generated from the data set by assigning grid values to the data using the program SURFER and converting the data to an ARC/INFO grid format. Contours, other line data, and location names were generated, edited, and plotted using ARC/INFO, a GIS software package. Corrections of the picks of the top and base of the Leadville Limestone were made to the U.S. Geological Survey data set based on our interpretation of the well logs used in the sections. Corrections to the depth of the top of the Leadville Limestone were made for eight of the wells; most of the corrections were on the order of 10–20 ft, and the

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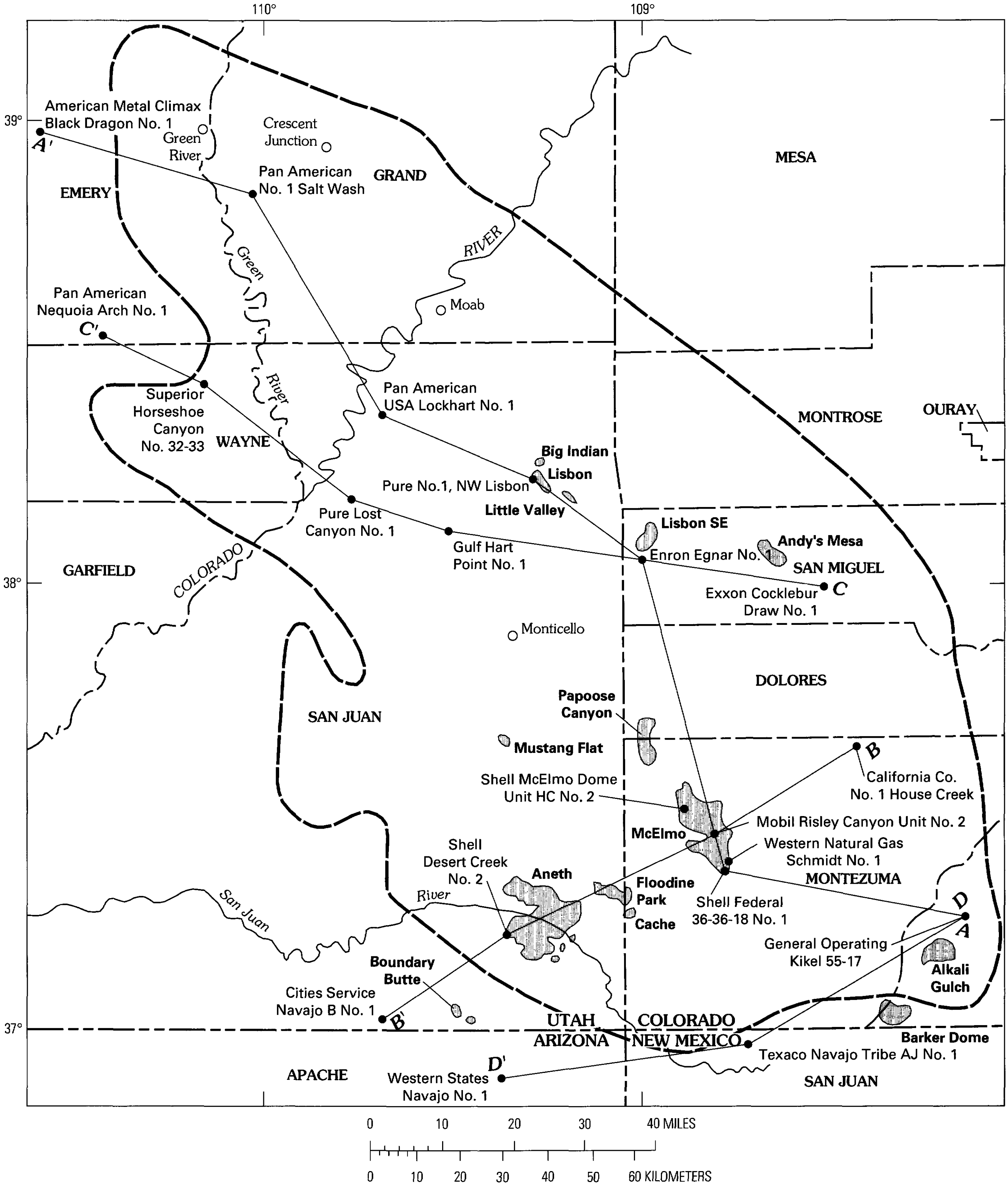

Figure 1. Map showing location of the Paradox Basin, as defined by the approximate limit of the halite facies in the Pennsylvanian Paradox Formation (dashed line), and location of gas reservoirs from which there has been more than 5 BCF production as of December 31, 1991 (areas enclosed by light solid lines). Oil or gas wells mentioned in text are indicated by solid circle and name. Lines of sections (plates 1–5) are also shown. Modified from Raup and Hite (1992).

greatest was 70 ft. The base of the Leadville, the top of the Upper Devonian Ouray Formation, is much more difficult to pick in well logs because of the similar rock types. Corrections as much as 250 ft were made to the depth of the base of the Leadville Limestone in 11 wells. The isopach and structure contour maps of the Leadville Limestone were compiled using the corrected data set.

NOMENCLATURE

Eldridge (1894) named the Leadville Limestone for outcrops of limestone and dolomite in the Leadville mining district, Lake County, Colorado (Parker and Roberts, 1963). Bass (1944) applied the term "Leadville Limestone" to outcrops of Mississippian carbonate rocks in the San Juan Mountains of southwestern Colorado. Parker and Roberts (1963) suggested that it would be more appropriate to use the term "Redwall Limestone" for these outcrops because there is a direct correlation from the type section of the Redwall Limestone in the Grand Canyon to the subsurface of the Paradox Basin. Baars (1966) reviewed some of the correlation problems in tracing a prominent chert marker in the Redwall Limestone to the eastern Paradox Basin and San Juan Mountains and suggested the continued use of Leadville Limestone for the Paradox Basin. The ages of the Redwall Limestone and the Leadville Limestone are the same, dominantly Kinderhookian and Osagean (Craig, 1972). Both formations are correlated on the basis of their endothyrid fauna (Baars, 1966).

Most workers agree that Mississippian carbonate deposition in the central Rocky Mountain region was continuous and widespread, with only minor thinning across uplifted Precambrian blocks (Parker and Roberts, 1963; Baars and See, 1968).

LITHOLOGY AND STRATIGRAPHY

The Leadville Limestone is composed of densely crystalline dolomite throughout much of its areal and stratigraphic extent (Baars, 1966). The upper part of the formation locally contains significant sections of limestone. The thickness of the Leadville Limestone in the Paradox Basin varies from approximately 100 ft in the eastern part of the basin in San Miguel County, Colorado, to more than 800 ft in the northwestern part of the basin in western Grand County, Utah (plate 7).

Baars and Ellingson (1984) believed that the lower contact of the Leadville Limestone with the Upper Devonian Ouray Formation is gradational. Armstrong and Mamet (1977) indicated, however, that compelling faunal evidence exists for a long hiatus between the highest conodont fauna in the Ouray Formation and the lowest diagnostic foraminifera fauna in the Leadville Limestone. They picked the contact of the Leadville Limestone and the Ouray Formation at the Rockwood Quarry, La Plata County, Colorado, within the same stratigraphic horizon as reported by Kindle (1909) as "5–10 feet of drab or rusty shale and early limestone." The highest beds in the Ouray Limestone that contain a diagnostic Devonian fauna are 15 ft below the contact. The lowest diagnostic Mississippian foraminifers in the Leadville Limestone are 70 ft above the contact. The Ouray Formation is, in most outcrop and subsurface core locations, a fine-grained dolomite that has sedimentary structures suggestive of an intertidal to subtidal depositional environment, and the lower beds of the Leadville Limestone are similar in lithology and depositional environment. The contact between the Ouray Formation and the Leadville Limestone is commonly difficult to discern, especially on geophysical logs used in subsurface correlation. In surface stratigraphic sections the following criteria are used to distinguish the two formations (Armstrong and Mamet, 1977):

1. A color change from brownish gray in the Ouray to gray to light gray in the Leadville
2. A decrease in argillaceous material in the Leadville relative to the Ouray
3. The presence of intraformational conglomerate in the Leadville
4. Strongly developed stromatolites, laminations, and maroon shale in the Leadville
5. Evidence of vadose weathering beneath the maroon shale of the Leadville, on a supposed Devonian (and Early Mississippian) surface

The upper contact of the Leadville Limestone with the overlying Molas Formation is usually very distinct and abrupt. The Molas Formation is thought to be a regolith derived from the underlying carbonate rocks of the Leadville Limestone under karst-forming, subtropical weathering conditions (Merril and Winar, 1958).

The Leadville Limestone in the subsurface of the Paradox Basin was informally divided into a lower and upper member by Baars (1966) on the basis of a prominent intraformational disconformity. This break corresponds to the disconformity between the Thunder Springs and Mooney Falls Members of the Redwall Limestone in the Grand Canyon. The lower member was defined in the type well, Pure Oil Co. No. 1 Northwest Lisbon (sec. 10, T. 30 S., R. 24 E., San Juan County, Utah), as the interval between the disconformity at 7,762 ft and the top of the Ouray Formation at 7,998 ft (plate 1) (Baars, 1966). The lower member is composed of a basal, finely crystalline dolomite unit overlain by more coarse grained dolomite. Generally, the lower member has poorly developed porosity except where it contains crinoidal fragments that leach out and create porosity and permeability.

The upper member, which extends from the top of the Mississippian Leadville Limestone at 7,520 ft to the disconformity at 7,762 ft in the Pure Oil Co. No. 1 Northwest Lisbon well, has variable lithology comprising limestone and dolomite. The base of the upper member is commonly marked by a zone of intraclastic carbonate representing the initial phase of sedimentation after the regression that caused the disconformity. Miller (1985) suggested that the intraformational conglomerates that mark the disconformity are solution collapse breccias. The most prominent lithofacies is crinoidal biomicrite (crinoidal biogenic bank deposits). Almost all of the Mississippian petroleum occurrences in the Paradox Basin, such as the Lisbon, Salt Wash, and Big Flat fields in Utah and the McIntyre Canyon field in Colorado (Miller, 1985), are in these crinoidal biomicrite deposits. Reservoir rocks resulted from dolomitization of micritic mud to a saccharoidal texture and leaching of the crinoids to form a highly porous and permeable rock.

Another prominent lithofacies of the upper member is a grain-supported oolitic pelsparite that is stratigraphically equivalent to the crinoidal biomicrite. The pelsparite may represent higher energy shoal areas as compared to the relatively quieter biogenic bank deposits. The third and most widespread lithofacies of the upper member is micrite (lithified carbonate mud).

The Leadville Limestone in the adjoining San Juan Basin of northwestern New Mexico and southwestern Colorado is a series of upward-shoaling carbonate cycles. In this region the Leadville Limestone was deposited in a complex range of environments including tidal to nearshore shelf (indicated by the presence of a unique crinoid-bryozoan-brachiopod wackestone believed to have formed in less than 230 ft of water); tidal deltas and channels; frontal beaches and dunes; restricted platform, intertidal, and supratidal lagoons; and dunes and sabkhas similar to those in the modern-day Persian Gulf (Armstrong and Holcomb, 1989, fig. 5).

RESERVOIR CHARACTERISTICS AND DEVELOPMENT

The Lisbon field was discovered with the completion of the Pure Oil Company No. 1 Northwest Lisbon well in January 1960 (fig. 1). Initial flow was 170 BO per day and 4,376 thousand cubic feet of gas (MCFG) per day from the Mississippian sequence and 586 BO per day from the Upper Devonian McCracken Sandstone Member of the Elbert Formation. The produced gas (table 1) contains 17–35 percent CO_2 and averages 26.0 percent CO_2. Estimated ultimate recovery is 42,850,000 BO and 250,000 million cubic feet (MMCF) of gas (Clark, 1978).

The major factors responsible for the development of porosity and permeability in the Leadville Limestone at the Lisbon field are dolomitization, leaching, and fracturing (Miller, 1985). The average porosity is 5 percent, and the average permeability is 22 millidarcies. The dominant type of porosity in the dolomite is intercrystalline and moldic. Porosity is developed in zones 5–25 ft thick that are separated by impermeable zones. The impermeable zones are usually related to early cementation or to stylolitization-cementation. Detrital clay near the upper and lower contacts of the permeable zones also reduces permeability.

Geological evidence from core studies of the Leadville Limestone at the Lisbon field suggests that there were multiple periods of dolomitization (Miller, 1985). The first period was probably coeval with deposition of carbonate material in the intertidal and supratidal facies. Ground-water circulation in the carbonate sediments probably caused two or three later periods of diagenesis that formed fine-grained dolomite from the micritic fraction of the biomicrite. A still later period of dolomitization, probably related to uplift and erosion in Pennsylvanian time, caused leaching of the crinoids and other bioclastic material in the biomicrites and led to development of the widespread vuggy porosity.

There are two credible hypotheses for the origin of the petroleum in Mississippian carbonate rocks in the Lisbon field: (1) the oil originated in surrounding sedimentary rocks and migrated into the reservoir rocks, or (2) the oil originated within the Mississippian rocks and migrated to suitable reservoir rocks. Parker (1968) suggested that oil in Mississippian rocks at the Lisbon field is not indigenous to either Devonian or Mississippian rocks but migrated into these rocks from Pennsylvanian shale, carbonate, and sandstone by way of hydraulic movement along major fractures. Organic-rich black shale in the Middle and Upper Pennsylvanian Hermosa Group contains as much as 25 percent total organic carbon (Clayton and Chen, 1993). Miller (1985) and V. Nuccio (U.S. Geological Survey, 1992, oral commun.) suggested, on the basis of geological and geochemical evidence, that petroleum in Mississippian reservoir rocks of the Lisbon field was derived from the same Mississippian rocks and migrated into porous and permeable facies during Middle to Late Pennsylvanian time. Nuccio reported total organic carbon values of more than 1 percent in Leadville Limestone drill cuttings from the Paradox Basin supplied by American Stratigraphic Company.

Carbon dioxide at the McElmo field was discovered in 1948 during the drilling of the Western Natural Gas-Byrd Frost Schmidt No. 1 well in sec. 24, T. 36 N., R. 18 W., Montezuma County, Colorado (Gerling, 1983) (fig. 1). In 1976, Shell Western E&P, Mobil Producing Co., and New Mexico, Inc., began a 21-well development program. An additional 13 wells were drilled in a later program during 1980 and 1981.

The Leadville Limestone is about 300 ft thick throughout the McElmo field. The contact between carbon dioxide and the underlying water dips to west at about 50–60 ft/mi. The underlying water has a salinity of 50,000 ppm. The reservoir rock is dolomite, and the average reservoir thickness is 70 ft. The average porosity is 11 percent. Permeability measured in well tests averages 23 millidarcies; however, permeability values of more than 200 millidarcies have been measured in core samples (Gerling, 1983).

The proven productive area at McElmo field is 203,714 acres. The estimated carbon dioxide in place is 17,000,000,000 MCF (Gerling, 1983). In 1992, the Colorado Oil and Gas Conservation Commission reported that the cumulative carbon dioxide production through 1991 at McElmo field was 1,345,366,330 MCF.

In the San Juan Basin, to the south of the Paradox Basin (fig. 1), Osagean carbonate rocks of the Leadville Limestone contain a persistent 100–250-foot-thick zone of replacement dolomite. Relic textures indicate that the original rock was a crinoidal biomicrite. Several oil shows and noncommercial oil and gas pools are known from the Leadville Limestone in the San Juan Basin (Armstrong and Holcomb, 1989).

GAS ANALYSES FROM OIL AND GAS WELLS

Gas analyses from geological formations of all ages in the Paradox Basin were compiled from collections by the U.S. Bureau of Mines and are shown in table 1 (Moore and Sigler, 1987a, b, 1988; Hamak and Sigler, 1989, 1990, 1991). The U.S. Bureau of Mines compilations list analyses for methane, ethane, propane, butane, pentane, hexane, carbon dioxide, nitrogen, oxygen, argon, helium, hydrogen, hydrogen sulfide, specific gravity, and BTU. A lower limit of 10 percent CO_2 was used in selecting samples for inclusion in table 1. Many of the samples in the compilation are from the same well and geological formation and differ only in the depth and date of the sample. Because of this duplication, the actual number of wells sampled is small.

CARBON DIOXIDE PRODUCTION DATA

The State of Utah does not publish statistical data showing the volumes of nonflammable gases produced in the State. Personal communication with the production staff of Union Oil at the Lisbon field indicates that most of the pensroduced inert gas from the field is stripped from the gas stream and reinjected into the reservoirs.

The McElmo field in Montezuma County, Colorado, produces most of the carbon dioxide in the Paradox Basin. Approximately 98 percent of the gas from Mississippian reservoirs in the McElmo field is carbon dioxide. According to records of the Colorado Oil and Gas Conservation Commission, two companies produce carbon dioxide. Shell Western E&P Company is by far the largest producer, having produced 206,497,043 MCF in 1991. All of Shell's carbon dioxide is transported by pipeline to Utah and west Texas oil fields to be used in enhanced oil recovery programs. The other producer, AIRCO Industrial Gases, produced 1,024,755 MCF in 1991. Production data for McElmo field from 1970 to 1992 are shown in table 2. The substantial increase in production of carbon dioxide from McElmo field in 1985 was the result of the completion in 1984 of a 500-mile-long pipeline to the west Texas oil fields. A minor amount of natural gas, 3,769 MCF in 1991, is produced at the McElmo field from the Upper Triassic Shinarump Member of the Chinle Formation.

OTHER INERT GASES

The concentrations of several inert gases in samples from oil and gas wells in the Paradox Basin are shown as a function of depth (figs. 2–5, table 1). A graph of the nitrogen content (fig. 2) of all gas samples from table 1 shows a wide scatter of values; however, the percentage of nitrogen probably decreases with depth. These data suggest that all of the nitrogen did not have a deep-seated source, such as the Precambrian basement rocks, lower crust, or mantle. Levorsen (1967, p. 220) suggested that the nitrogen in natural gases represents the nitrogen content of air trapped in sediments at the time of deposition, as well as some additions from igneous sources and the decomposition of nitric organic compounds. It is probable that the nitrogen in the Leadville Limestone had mixed sources; however, a definitive source is not indicated.

Ratios between nitrogen and argon do not affirm an atmospheric source for either nitrogen or argon (fig. 3). The present-day atmospheric ratio of N_2/A is 84. Values of this ratio from the data base vary from almost 1 to more than 320, and there is no indication of a preferred value near 84.

Graphs of helium in all samples (fig. 4) and in only Mississippian-age samples (fig. 5) show poorly defined paterns of decreasing helium values with depth that suggest the helium did not have a deep-seated source. Casey (1983) suggested that the helium in Devonian and Mississippian carbonate reservoirs of the Four Corners area was derived from igneous rocks, not from surrounding sedimentary rocks. Alkalic igneous rocks, which are present throughout the Four Corners area (La Sal Mountains, La Plata Mountains, Carrizo Mountains), do contain higher concentrations of rare earth elements and uranium and thorium, which are parent elements of helium in the uranium-lead decay series, than do calc-alkaline igneous rocks (Murphy and others, 1978). Helium contents are sufficiently high at the Lisbon field to warrant a commercial production facility (Union Oil Co., oral commun., 1992).

Table 1. Gas analyses from oil and gas wells in the Paradox Basin, Arizona, Colorado, New Mexico, and Utah.
[Data from Moore and Sigler (1987a, b, 1988) and Hamack and Sigler (1989, 1990, 1991). Depth is in feet. Abbreviations of ages: D, Devonian; M, Mississippian; ℙ, Pennsylvanian; P, Permian; TR, Triassic; J, Jurassic. Abundance of gases in percent. Leaders (--) indicate no data or not detected]

State	County	Oil or gas field	API number	Location	Well name
Arizona	Apache	Boundary Butte E.	02 001 90053	Sec. 3, T. 41 N., R. 28 E.	Boundary Butte E No. 2
Arizona	Apache	Boundary Butte E.	02 001 90054	Sec. 4, T. 41 N., R. 28 E.	Navajo Tribal No. 1
Arizona	Apache	Dineh Bi Keyah	02 001 20017	Sec. 8, T. 35 N., R. 30 E.	Navajo Tract 140 No. 1
Arizona	Apache	Dineh Bi Keyah	02 001 20025	Sec. 23, T. 36 N., R. 29 E.	Navajo Tract 87 No. 1
Arizona	Apache	Dineh Bi Keyah	02 001 20055	Sec. 25, T. 36 N., R. 29 E.	Navajo Tract 88 No. 2
Arizona	Apache	Dineh Bi Keyah	02 001 20055	Sec. 25, T. 36 N., R. 29 E.	Navajo Tract 88 No. 2
Arizona	Apache	Teec Nos Pos	02 001 90070	Sec. 23, T. 41 N., R. 30 E.	Navajo Tribal O
Arizona	Apache	Tohache Wash	02 001 90071	Sec. 36, T. 41 N., R. 30 E.	Navajo Z No. 1
Arizona	Apache	Tohache Wash	02 001 90071	Sec. 36, T. 41 N., R. 30 E.	Navajo Z No. 1
Arizona	Apache	Tohache Wash	02 001 90071	Sec. 36, T. 41 N., R. 30 E.	Navajo Z No. 1
Arizona	Apache	Tohache Wash	02 001 90071	Sec. 36, T. 41 N., R. 30 E.	Navajo Z No. 1
Colorado	Dolores	Doe Canyon	05 033 05065	Sec. 13, T. 40 N., R. 18 W.	Doe Canyon No. 1
Colorado	Dolores	Doe Canyon	05 033 05065	Sec. 13, T. 40 N., R. 18 W.	Doe Canyon No. 1
Colorado	Dolores	Glade Canyon	05 033 05007	Sec. 13, T. 40 N., R. 17 W.	Glade Canyon Unit No. 1
Colorado	La Plata	Barker Creek	05 067 05177	Sec. 15, T. 32 N., R. 13½ W.	Delhi No. 2
Colorado	La Plata	Barker Creek	05 067 05819	Sec. 14, T. 32 N., R. 13½ W.	Delhi No. 3
Colorado	La Plata	Barker Creek	05 067 06052	Sec. 11, T. 32 N., R. 14 W.	Barker Dome No. 1
Colorado	Montezuma	McElmo	05 083 05231	Sec. 24, T. 36 N., R. 18 W.	Schmidt No. 1
Colorado	Montezuma	McElmo	05 083 05237	Sec. 13, T. 36 N., R. 18 W.	Dean Dudley No. 2
Colorado	Montezuma	McElmo	05 083 05237	Sec. 13, T. 36 N., R. 18 W.	Dean Dudley No. 2
Colorado	Montezuma	McElmo	05 083 05237	Sec. 13, T. 36 N., R. 18 W.	Dean Dudley No. 3
Colorado	Montezuma	McElmo	05 083 05250	Sec. 27, T. 37 N., R. 17 W.	J.A. Fulks No. 1
Colorado	Montezuma	McElmo	05 083 05250	Sec. 27, T. 37 N., R. 17 W.	J.A. Fulks No. 1
Colorado	Montezuma	McElmo	05 083 05250	Sec. 27, T. 37 N., R. 17 W.	J.A. Fulks No. 1
Colorado	Montezuma	McElmo	05 083 05250	Sec. 27, T. 37 N., R. 17 W.	J.A. Fulks No. 1
Colorado	Montezuma	McElmo	05 083 06189	Sec. 19, T. 38 N., R. 18 W.	McElmo Dome Unit 19–38–18
Colorado	Montezuma	McElmo	05 083 06189	Sec. 19, T. 38 N., R. 18 W.	McElmo Dome Unit 19–38–18
Colorado	Montezuma	McElmo	05 083 06253	Sec. 12, T. 37 N., R. 19 W.	McElmo Dome Unit 12–37–19
Colorado	Montezuma	McElmo	05 083 06256	Sec. 24, T. 36 N., R. 18 W.	Schmidt No. 2
Colorado	San Miguel	McIntyre Canyon	05 113 05012	Sec. 30, T. 44 N., R. 19 W.	Egnar Unit No. 1
Colorado	San Miguel	McIntyre Canyon	05 113 05012	Sec. 30, T. 44 N., R. 19 W.	Egnar Unit No. 1
Colorado	San Miguel	McIntyre Canyon	05 113 05012	Sec. 30, T. 44 N., R. 19 W.	Egnar Unit No. 1
New Mexico	San Juan	Barker Creek	30 045 11342	Sec. 21, T. 32 N., R. 14 W.	Ute No. 9
New Mexico	San Juan	Barker Creek	30 045 11382	Sec. 21, T. 32 N., R. 14 W.	Southern Union Barker No. 19
New Mexico	San Juan	Barker Creek	30 045 11426	Sec. 16, T. 32 N., R. 14 W.	Barker Creek No. 11
New Mexico	San Juan	Hogback	30 045 08082	Sec. 19, T. 29 N., R. 16 W.	U.S.G. No.13
New Mexico	San Juan	Hogback	30 045 08082	Sec. 19, T. 29 N., R. 16 W.	U.S.G. No.13
New Mexico	San Juan	Hogback	30 045 08082	Sec. 19, T. 29 N., R. 16 W.	U.S.G. No.13
New Mexico	San Juan	Hogback N	30 045 09003	Sec. 31, T. 30 N., R. 16 W.	Navajo K No. 2
New Mexico	San Juan	Pajarito	30 045 07747	Sec. 31, T. 29 N., R. 17 W.	Navajo Tract 20 No. 1
New Mexico	San Juan	Rattlesnake	30 045 08887	Sec. 1, T. 29 N., R. 19 W.	Rattlesnake No. 135
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1

Formation	Age	Depth	CO_2	N_2	A	He	H_2S	Methane	Ethane	Propane	Butane	Pentane	Hexane
Paradox	IP	4,974	15.4	8.6	0.1	1.10	--	70.8	3.0	0.1	0.3	0.20	0.1
Paradox	IP	4,806	13.8	8.2	0.1	1.00	0.1	70.3	3.6	1.7	0.8	0.3	0.2
Aneth	D	4,663	11.1	78.7	0.8	5.23	--	3.4	0.5	0.2	0.2	--	--
McCracken	D	5,223	10.6	78.8	0.8	5.58	--	3.1	0.4	0.2	0.1	--	--
McCracken	D	--	12.6	78.1	0.8	5.16	--	2.7	0.4	0.1	0.2	--	--
McCracken	D	4,626	13.3	77.3	0.8	5.17	--	2.7	0.4	0.1	0.3	--	--
Ismay	IP	5,122	11.1	11.2	0.1	1.20	--	69.1	3.7	1.9	0.8	0.5	0.3
Leadville	M	6,270	22.1	54.1	0.7	5.91	--	14.7	1.0	0.5	0.3	0.4	0.2
Leadville	M	6,270	23.0	53.0	0.6	5.99	--	14.8	1.1	0.4	0.3	0.4	0.3
Leadville	M	--	23.5	53.1	0.6	5.84	--	14.6	1.0	0.4	0.4	0.2	0.2
Leadville	M	6,270	22.3	53.4	0.7	6.08	--	15.1	1.1	0.6	0.4	0.4	0.2
Leadville	M	8,366	90.4	6.8	0.1	0.88	--	1.5	0.1	0.1	--	--	--
Leadville	M	8,366	92.6	5.2	0.1	0.65	--	1.1	0.1	0.1	--	--	0.1
Leadville	M	9,140	95.8	2.5	--	0.30	--	1.0	0.2	--	--	--	--
Paradox	IP	--	11.6	1.6	--	0.22	--	84.1	1.1	0.4	0.3	--	--
Paradox	IP	9,654	12.1	1.4	--	0.21	--	84.0	1.2	0.4	0.2	0.2	--
Barker Creek	IP	9,281	14.9	1.4	--	0.00	--	81.7	1.1	0.4	0.2	0.1	0.2
Leadville	M	6,745	81.9	15.4	--	0.55	--	0.3	0.8	--	--	--	--
Leadville	M	6,940	96.0	3.3	--	0.28	--	0.3	--	--	--	--	--
Leadville	M	6,608	96.2	3.2	--	0.10	--	0.2	0.3	--	--	--	--
Leadville	M	6,700	97.5	2.0	--	0.10	--	0.1	--	--	--	--	--
Leadville	M	7,797	97.8	1.8	--	0.09	--	0.1	0.1	--	--	--	--
Leadville	M	7,768	97.7	1.9	--	0.10	--	0.1	0.1	--	--	--	--
Leadville	M	8,364	97.5	2.1	--	0.00	--	0.2	--	--	--	--	--
Leadville	M	7,690	97.5	2.1	--	0.10	--	0.1	0.1	--	--	--	--
Leadville	M	8,357	98.5	1.2	--	0.09	--	0.2	--	--	--	--	--
Leadville	M	8,284	98.6	1.0	--	0.08	--	0.2	0.1	--	--	--	--
Leadville	M	8,000	97.9	1.7	--	0.09	--	0.2	--	--	--	--	--
Leadville	M	6,700	97.6	1.9	--	0.09	--	0.1	--	--	--	--	--
Leadville	M	9,120	10.1	11.9	--	0.94	--	69.2	3.7	1.7	1.4	0.6	0.5
Leadville	M	9,030	10.6	10.4	--	1.00	--	69.6	3.8	1.7	1.6	0.7	0.6
Leadville	M	9,100	10.0	11.8	--	0.90	--	69.2	4.1	1.8	1.3	0.4	0.3
Barker Creek	IP	8,443	10.4	0.1	--	0.23	--	86.7	2.4	--	--	--	--
Barker Creek	IP	8,885	15.5	1.7	--	0.20	--	80.2	1.2	0.5	0.2	0.3	--
Paradox	P	8,660	12.1	2.1	--	0.25	--	78.7	6.8	--	--	--	--
Leadville	M	6,930	20.0	63.5	0.5	5.10	--	6.1	0.9	1.5	0.9	1.1	0.4
Leadville	M	7,000	20.3	60.5	0.5	5.10	--	5.8	0.9	1.7	2.3	1.6	1.3
Leadville	M	6,930	19.3	58.4	1.1	5.05	--	5.8	5.9	2.7	1.2	0.5	0.2
Leadville	M	7,340	88.5	6.2	0.1	1.40	--	0.1	--	3.6	--	--	0.1
Paradox C	IP	7,198	12.9	22.2	0.3	1.20	--	40.7	9.9	7.3	4.0	1.2	0.3
Paradox	IP	6,602	14.4	1.1	--	0.10	--	71.0	5.9	4.3	2.0	0.9	0.4
Paradox	IP	8,248	28.5	1.7	--	0.20	1.5	67.3	0.5	--	0.2	--	0.1
Leadville	M	9,322	88.0	2.4	0.1	0.60	--	8.7	0.1	--	0.1	--	--
Leadville	M	9,466	88.0	2.4	0.1	0.50	--	8.6	0.1	0.2	--	--	--
Paradox	IP	8,762	31.2	1.7	--	0.30	1.3	64.7	0.5	--	0.2	--	0.1

Table 1. Gas analyses from oil and gas wells in the Paradox Basin, Arizona, Colorado, New Mexico, and Utah—Continued.

State	County	Oil or gas field	API number	Location	Well name
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1
New Mexico	San Juan	Ute Dome	30 045 10918	Sec. 10, T. 31 N., R. 14 W.	Ute Mountain Tribal D No. 1
New Mexico	San Juan	Wildcat	30 045 05267	Sec. 32, T. 26 N., R. 15 W.	Navajo Tract 27 No. 1
New Mexico	San Juan	Wildcat	30 045 05267	Sec. 32, T. 26 N., R. 15 W.	Navajo Tract 27 No. 1
New Mexico	San Juan	Wildcat	30 045 08885	Sec. 1, T. 29 N., R. 17 W.	Navajo C No. 1
New Mexico	San Juan	Wildcat	30 045 09871	Sec. 5, T. 30 N., R. 17 W.	Navajo No. 1
New Mexico	San Juan	Wildcat	30 045 09871	Sec. 5, T. 30 N., R. 17 W.	Navajo No. 1
New Mexico	San Juan	Wildcat	30 045 10317	Sec. 27, T. 31 N., R. 17 W.	Navajo No. 1
New Mexico	San Juan	Wildcat	30 045 10774	Sec. 15, T. 31 N., R. 20 W.	Navajo E No. 1
New Mexico	San Juan	Wildcat	30 045 11151	Sec. 36, T. 32 N., R. 18 W.	Aztec Navajo A No. 1
New Mexico	San Juan	Wildcat	30 045 11151	Sec. 36, T. 32 N., R. 18 W.	Aztec Navajo A No. 1
Utah	Emery	Federal Mounds	43 015 10825	Sec. 11, T. 16 S., R. 11 E.	Federal Mounds No. 1
Utah	Emery	Federal Mounds	43 015 10825	Sec. 11, T. 16 S., R. 11 E.	Federal Mounds No. 1
Utah	Emery	Federal Mounds	43 015 10825	Sec. 11, T. 16 S., R. 11 E.	Federal Mounds No. 1
Utah	Emery	Not given	43 015 30206	Sec. 33, T. 19 S., R. 12 E.	Toledo-Vukasovich No. 3–TV
Utah	Emery	Wildcat	43 015 05139	Sec. 27, T. 16 S., R. 12 E.	Govt.-Wheatley No. 1
Utah	Emery	Wildcat	43 015 10350	Sec. 12, T. 18 S., R. 12 E.	Packsaddle No. 1
Utah	Emery	Woodside	43 015 10505	Sec. 12, T. 19 S., R. 13 E.	Fed. No. 44–12
Utah	Emery	Woodside	43 015 10505	Sec. 12, T. 19 S., R. 13 E.	Fed. No. 44–12
Utah	Emery	Woodside	43 015 10505	Sec. 12, T. 19 S., R. 13 E.	Fed. No. 44–12
Utah	Grand	San Arroyo	43 019 15885	Sec. 22, T. 16 S., R. 25 E.	San Arroyo Govt. No. 2
Utah	Grand	San Arroyo	43 019 15886	Sec. 23, T. 16 S., R. 25 E.	San Arroyo Govt. No. 3
Utah	Grand	San Arroyo	43 019 15886	Sec. 23, T. 16 S., R. 25 E.	San Arroyo Govt. No. 3
Utah	Grand	San Arroyo	43 019 15888	Sec. 25, T. 16 S., R. 25 E.	San Arroyo Govt. No. 5
Utah	Grand	San Arroyo	43 019 15888	Sec. 25, T. 16 S., R. 25 E.	San Arroyo Govt. No. 5
Utah	Grand	San Arroyo	43 019 15889	Sec. 21, T. 16 S., R. 25 E.	San Arroyo Unit No. 6
Utah	Grand	San Arroyo	43 019 16532	Sec. 26, T. 16 S., R. 25 E.	San Arroyo Govt. No. 1
Utah	Grand	San Arroyo	43 019 16532	Sec. 26, T. 16 S., R. 25 E.	San Arroyo Govt. No. 1
Utah	San Juan	Big Indian	43 037 16219	Sec. 33, T. 29 S., R. 24 E.	Big Indian U.S.A. No. 1
Utah	San Juan	Big Indian	43 037 16219	Sec. 33, T. 29 S., R. 24 E.	Big Indian U.S.A. No. 1
Utah	San Juan	Big Indian	43 037 16219	Sec. 33, T. 29 S., R. 24 E.	Big Indian U.S.A. No. 1
Utah	San Juan	Bluff	43 037 15864	Sec. 4, T. 40 S., R. 23 E.	Bluff Unit No. 3
Utah	San Juan	Bluff	43 037 15864	Sec. 4, T. 40 S., R. 23 E.	Bluff Unit No. 3
Utah	San Juan	Bluff Unit	43 037 06193	Not given	Shell Bluff Unit No. 1
Utah	San Juan	Boundary Butte N.	43 037 15870	Sec. 33, T. 42 S., R. 24 E.	Boundary Butte N. No. 1
Utah	San Juan	Boundary Butte N.	43 037 15870	Sec. 33, T. 42 S., R. 24 E.	Boundary Butte N. No. 1
Utah	San Juan	Boundary Butte N.	43 037 16517	Sec. 28, T. 42 S., R. 24 E.	No. 43–28
Utah	San Juan	Coalbed Canyon	43 037 10430	Sec. 20, T. 35 S., R. 26 E.	Coalbed Canyon Unit No. 2
Utah	San Juan	Desert Creek	43 037 93059	Sec. 2, T. 42 S., R. 23 E.	Desert Creek No. 1
Utah	San Juan	Gothic Area	43 037 10533	Sec. 36, T. 40 S., R. 21 E.	Navajo-Gothic No. 2
Utah	San Juan	Gothic Mesa	43 037 10537	Sec. 7, T. 41 S., R. 22 E.	Navajo Tract No. 30–1
Utah	San Juan	Lime Ridge	43 037 15588	Sec. 28, T. 40 S., R. 20 E.	U.S. Lime Ridge No. 1
Utah	San Juan	Lisbon	43 037 06362	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon B No. 2
Utah	San Juan	Lisbon	43 037 06362	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon B No. 2
Utah	San Juan	Lisbon	43 037 15049	Sec. 16, T. 30 S., R. 24 E.	Belco State No. 2

Formation	Age	Depth	CO_2	N_2	A	He	H_2S	Methane	Ethane	Propane	Butane	Pentane	Hexane
Paradox	ℙ	9,141	33.7	2.5	0.1	0.41	0.1	62.0	0.5	0.1	0.2	0.2	0.2
Paradox	ℙ	8,644	30.9	1.7	--	0.30	1.3	65.0	0.5	--	0.2	--	0.1
Leadville	M	10,120	96.2	2.0	--	0.43	--	1.1	0.1	--	--	--	--
Leadville	M	10,079	95.3	2.2	--	0.45	--	1.2	0.1	0.1	0.1	0.1	0.2
Leadville	M	6,950	38.2	40.8	0.5	2.10	--	11.8	0.8	4.3	0.4	0.4	0.7
Hermosa	ℙ	6,779	17.9	19.5	0.3	3.09	--	49.8	4.9	0.2	1.1	0.7	0.3
Hermosa	ℙ	6,779	16.7	22.7	0.3	3.16	--	47.2	5.0	2.2	1.4	0.7	0.4
Hermosa	ℙ	7,278	10.8	10.8	0.1	0.66	--	73.1	4.7	2.6	2.0	1.2	0.6
Leadville	M	6,810	19.2	56.5	--	6.60	--	14.4	1.2	0.9	0.3	0.1	0.1
Paradox	ℙ	7,604	10.5	0.9	--	0.16	0.4	85.0	1.4	0.9	0.4	0.1	0.2
Paradox	ℙ	7,623	10.3	0.4	--	0.16	0.7	81.1	1.5	3.6	0.7	0.7	0.8
Deseret	M	8,369	26.8	70.5	0.4	0.54	--	1.5	0.1	--	--	--	--
Deseret	M	8,520	24.2	73.0	0.4	0.55	--	1.6	0.1	--	--	--	--
Deseret	M	8,276	27.3	70.2	0.3	0.52	--	1.5	0.1	--	--	--	--
Moenkopi	TR	2,184	80.9	16.4	--	0.08	--	1.5	0.5	0.2	0.2	0.1	--
Sinbad	TR	3,501	91.2	7.0	0.1	0.13	--	1.4	0.1	--	--	--	--
Kaibab	PM	2,309	94.7	4.5	--	0.10	--	0.5	--	--	--	--	--
Kaibab	P	--	31.7	61.0	--	1.31	--	0.0	5.7	--	--	--	--
Kaibab	P	3,341	33.0	64.4	0.2	1.51	--	0.2	0.1	--	0.2	0.2	0.1
Kaibab	P	3,341	33.2	64.4	0.2	1.36	--	0.2	0.2	0.1	0.3	0.1	0.1
Entrada	J	6,635	24.5	24.4	0.1	0.90	--	45.1	2.4	1.5	0.7	0.1	0.1
Entrada	J	5,414	22.7	24.5	0.1	0.90	--	46.8	2.0	1.8	0.5	0.3	0.3
Entrada	J	5,440	23.4	23.7	0.1	1.00	--	46.8	2.1	1.3	0.8	0.3	0.5
Entrada	J	4,814	19.7	27.1	0.2	0.50	--	47.2	2.3	1.4	0.9	0.3	0.4
Entrada	J	4,792	19.7	26.5	0.1	1.00	--	47.2	2.2	1.5	0.9	0.3	0.4
Entrada	J	6,490	23.9	17.1	0.1	0.46	--	51.4	2.3	1.5	0.9	0.7	0.2
Entrada	J	4,851	26.1	17.0	0.1	0.60	--	47.5	3.5	3.2	1.0	0.4	0.5
Entrada	J	4,851	19.6	26.5	0.1	0.90	--	47.9	2.2	1.5	0.5	0.3	0.2
--	--	9,800	23.5	4.9	--	0.05	0.7	49.1	13.3	5.5	2.0	0.6	0.2
Leadville	M	9,800	15.7	16.7	0.1	0.72	0.4	56.1	6.5	1.9	1.2	0.3	0.3
Leadville	M	9,956	15.8	15.8	--	0.80	--	56.7	6.9	2.0	1.2	0.4	0.3
Leadville	M	6,914	85.7	11.3	0.1	0.42	--	1.3	0.4	--	0.2	0.2	0.2
Leadville	M	6,940	86.6	10.8	0.1	0.40	--	1.2	0.4	--	0.2	0.2	0.2
--	--	7,527	92.5	5.9	0.1	0.28	--	0.7	0.1	0.2	0.1	--	0.1
Ouray	D	5,807	56.8	31.9	0.2	1.58	--	7.5	0.4	0.5	0.1	0.2	0.2
Hermosa	ℙ	4,662	19.3	7.5	--	0.23	--	52.5	8.2	6.7	3.3	1.5	0.4
Hermosa	ℙ	4,681	14.9	14.7	0.1	0.58	--	60.9	4.5	2.4	1.1	0.4	0.2
Leadville	M	--	62.3	24.2	0.3	0.30	--	7.4	0.7	--	0.2	0.1	0.1
Ouray	D	5,855	77.5	13.1	0.1	1.37	--	6.3	0.4	0.8	0.1	0.1	0.1
Leadville	M	6,706	93.4	3.9	0.1	0.38	--	1.0	0.2	--	0.1	0.7	0.1
Leadville	M	6,952	73.2	21.3	0.2	0.90	--	1.5	0.1	--	0.1	--	--
Hermosa	ℙ	1,088	17.9	13.3	0.2	0.70	3.9	49.1	11.9	0.6	0.1	0.1	--
Leadville	M	--	30.6	7.6	--	0.20	0.1	34.0	14.0	7.5	4.4	1.1	0.3
Leadville	M	8,536	21.1	15.9	--	0.90	--	37.7	7.2	13.2	1.6	0.6	0.3
Leadville	M	8,221	29.9	13.7	0.1	0.60	0.1	43.1	7.9	3.1	2.1	0.2	0.1

Table 1. Gas analyses from oil and gas wells in the Paradox Basin, Arizona, Colorado, New Mexico, and Utah—Continued.

State	County	Oil or gas field	API number	Location	Well name
Utah	San Juan	Lisbon	43 037 15049	Sec. 16, T. 30 S., R. 24 E.	Belco State No. 2
Utah	San Juan	Lisbon	43 037 15049	Sec. 16, T. 30 S., R. 24 E.	Belco State No. 2
Utah	San Juan	Lisbon	43 037 15123	Sec. 15, T. 30 S., R. 24 E.	Arnold No. 21–15
Utah	San Juan	Lisbon	43 037 15123	Sec. 15, T. 30 S., R. 24 E.	Arnold No. 21–15
Utah	San Juan	Lisbon	43 037 15769	Sec. 12, T. 30 S., R. 24 E.	Lisbon Fed. No. 1–12
Utah	San Juan	Lisbon	43 037 15769	Sec. 12, T. 30 S., R. 24 E.	Lisbon Fed. No. 1–12
Utah	San Juan	Lisbon	43 037 15769	Sec. 12, T. 30 S., R. 24 E.	Lisbon Fed. No. 1–12
Utah	San Juan	Lisbon	43 037 15769	Sec. 12, T. 30 S., R. 24 E.	Lisbon Fed. No. 1–12
Utah	San Juan	Lisbon	43 037 16241	Sec. 9, T. 30 S., R. 24 E.	Lisbon Valley No. C–1
Utah	San Juan	Lisbon	43 037 16241	Sec. 9, T. 30 S., R. 24 E.	Lisbon Valley No. C–1
Utah	San Juan	Lisbon	43 037 16241	Sec. 9, T. 30 S., R. 24 E.	Lisbon Valley No. C–1
Utah	San Juan	Lisbon	43 037 16249	Sec. 15, T. 30 S., R. 24 E.	NW Lisbon No. E–1
Utah	San Juan	Lisbon	43 037 16250	Sec. 4, T. 30 S., R. 24 E.	NW Lisbon No. C–1
Utah	San Juan	Lisbon	43 037 16250	Sec. 4, T. 30 S., R. 24 E.	NW Lisbon No. C–1
Utah	San Juan	Lisbon	43 037 16468	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon No. B–1
Utah	San Juan	Lisbon	43 037 16468	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon No. B–1
Utah	San Juan	Lisbon	43 037 16468	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon No. B–1
Utah	San Juan	Lisbon	43 037 16468	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon No. B–1
Utah	San Juan	Lisbon	43 037 16468	Sec. 14, T. 30 S., R. 24 E.	NW Lisbon No. B–1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16469	Sec. 10, T. 30 S., R. 24 E.	NW Lisbon No. 1
Utah	San Juan	Lisbon	43 037 16470	Sec. 3, T. 30 S., R. 24 E.	NW Lisbon No. C–3
Utah	San Juan	Lisbon	43 037 16470	Sec. 3, T. 30 S., R. 24 E.	NW Lisbon No. C–3
Utah	San Juan	Little Valley	43 037 15768	Sec. 21, T. 30 S., R. 25 E.	Lisbon Fed. No. 2–21–F
Utah	San Juan	Little Valley	43 037 15768	Sec. 21, T. 30 S., R. 25 E.	Lisbon Fed. No. 2–21–F
Utah	San Juan	Little Valley	43 037 15768	Sec. 21, T. 30 S., R. 25 E.	Lisbon Fed. No. 2–21–F
Utah	San Juan	Rolling Mesa	43 037 10522	Sec. 33, T. 40 S., R. 21 E.	Govt. Fehr-Lyon No. 1
Utah	San Juan	Wildcat	43 037 10842	Sec. 20, T. 37 S., R. 24 E.	Deadman Canyon No. 1
Utah	San Juan	Wildcat	43 037 11256	Sec. 20, T. 40 S., R. 24 E.	Navajo "D" No. 30
Utah	San Juan	Wildcat	43 037 11277	Sec. 9, T. 35 S., R. 25 E.	U.S.A. B No. 1

CARBON-DIOXIDE-RICH GASES

Six gas samples from producing intervals in carbon-dioxide-rich Mississippian reservoirs in the Paradox Basin were collected during the summer of 1992. Four samples were obtained from four wells in the McElmo field, and two samples were obtained from two wells in the Lisbon field. The main purpose of the sampling program was to obtain information on carbon isotope ratios. Sample descriptions and analytical results are given in table 3.

Two drill-core samples from the productive horizon of the Leadville Limestone in the McElmo field and the Lisbon field were donated by Shell Western E&P and Union Oil Company, respectively, for carbon isotope analysis. The objective of this part of the sampling program was to compare carbon isotope ratios for calcite and organic material from the drill-core samples with those for the produced carbon dioxide. Sample descriptions and analytical results are given in table 4.

Both oil and associated gas are produced at the Lisbon field. The oil is relatively light, 54° API gravity (Clark,

Formation	Age	Depth	CO_2	N_2	A	He	H_2S	Methane	Ethane	Propane	Butane	Pentane	Hexane
Leadville	M	8,548	30.2	8.4	--	0.40	--	37.3	11.5	8.0	3.3	0.7	0.2
Leadville	M	8,221	32.9	9.6	0.1	0.40	0.1	36.9	11.3	4.9	2.9	0.8	0.2
Leadville	M	8,098	26.3	9.8	0.1	0.40	--	33.5	11.5	6.0	7.7	3.2	1.1
Leadville	M	8,605	28.7	10.0	0.1	0.30	--	36.4	13.1	4.3	5.4	1.4	0.3
Leadville	M	8,434	26.6	6.9	--	0.30	--	34.5	11.6	9.8	6.0	3.0	1.3
Leadville	M	8,434	27.9	9.5	0.1	0.40	0.3	37.4	12.0	6.1	4.6	1.1	0.4
Leadville	M	8,434	17.7	0.0	0.1	0.00	1.0	9.1	18.9	25.3	19.9	5.6	1.2
Leadville	M	8,550	29.0	7.6	--	0.40	--	37.8	11.4	9.3	2.7	0.9	0.8
Leadville	M	8,808	31.3	6.7	--	0.30	--	36.1	10.7	10.2	2.9	1.1	0.7
Leadville	M	8,640	31.9	9.3	0.1	0.40	0.3	31.1	11.6	5.3	6.5	2.4	0.9
Leadville	M	8,640	29.6	9.1	0.1	0.30	0.2	30.4	11.0	5.7	8.0	4.0	1.5
Leadville	M	8,571	27.5	13.5	0.1	0.50	--	43.1	9.4	3.3	1.9	0.5	0.2
Leadville	M	8,296	28.3	13.9	0.1	0.60	0.1	41.6	10.4	2.4	1.7	0.6	0.3
Leadville	M	8,738	27.7	15.7	0.1	1.00	0.6	41.3	7.9	3.4	1.4	0.3	0.1
Leadville	M	8,339	22.3	17.2	--	1.00	--	43.6	7.6	5.7	1.6	0.5	0.2
Leadville	M	8,192	24.0	20.9	0.1	0.90	--	39.4	7.7	3.7	1.6	0.3	0.1
Leadville	M	8,192	32.2	2.3	0.1	0.03	0.6	22.6	20.3	12.4	7.2	1.7	0.2
Leadville	M	8,309	23.5	16.5	--	1.00	--	42.8	7.5	6.0	1.7	0.6	0.3
Leadville	M	8,160	25.5	9.9	0.1	0.30	0.2	38.0	12.2	5.9	4.9	2.0	0.6
Leadville	M	7,996	21.6	17.7	--	1.00	--	42.4	8.3	3.6	2.7	1.8	0.8
Leadville	M	7,590	35.6	2.9	--	0.10	1.0	33.2	14.0	9.6	2.8	0.5	0.2
Leadville	M	7,539	23.0	17.2	0.1	1.00	0.1	41.2	8.3	3.2	3.1	2.0	0.7
Leadville	M	7,829	22.5	15.9	--	1.00	0.2	42.1	7.9	6.4	2.1	1.1	0.4
Leadville	M	7,590	26.6	15.8	--	1.10	0.2	40.6	8.0	5.1	1.8	0.5	0.2
Leadville	M	--	25.8	15.2	--	1.10	0.2	42.0	8.0	5.5	1.5	0.3	0.2
Leadville	M	7,589	22.9	17.7	0.1	1.10	1.1	42.3	7.8	3.5	2.4	1.5	0.6
Leadville	M	--	26.7	15.5	0.1	1.00	--	40.1	8.5	5.2	2.1	0.8	0.1
Leadville	M	8,000	23.9	16.7	0.1	1.10	0.3	43.6	7.9	3.7	1.8	0.6	0.2
Leadville	M	9,269	15.5	9.6	--	0.68	0.2	65.8	5.1	1.7	0.9	0.2	0.2
Leadville	M	9,313	17.1	10.1	--	0.69	1.0	63.0	5.2	1.2	1.1	0.2	0.3
Leadville	M	9,270	16.5	9.9	--	0.31	0.2	63.3	5.1	2.1	1.8	0.3	0.3
Leadville	M	6,150	69.2	18.3	0.1	0.90	--	4.5	0.6	4.8	0.1	0.3	0.3
Leadville	M	7,980	93.6	4.8	--	0.20	--	0.4	0.2	--	0.2	--	0.1
--	--	--	69.9	23.0	0.2	0.15	--	0.6	0.2	0.7	0.1	0.1	0.2
Leadville	M	7,034	88.6	4.9	0.1	0.40	--	5.2	0.4	0.3	--	--	0.1

1978). The gas is relatively wet (C_{2+} values of as much as 46 percent) and contains significant amounts of carbon dioxide (as much as 35 percent) and nitrogen (as much as 21 percent) (Moore and Sigler, 1987b). In addition, as much as 1.7 percent H_2S and as much as 1 percent He are present in the gas. Methane $\delta^{13}C$ values measured during this sampling program range from –42.3 to –42.1‰, and carbon dioxide $\delta^{13}C$ values range from –11.9 to –9.5‰.

The gas produced from the McElmo field is composed of dominantly carbon dioxide and minor amounts of nitrogen (<3.5 percent) and methane (<1 percent) (Krivanek, 1978; Gerling, 1983). Carbon dioxide $\delta^{13}C$ values range from –11.8 to –4.2‰.

Gases from these fields are interpreted to have multiple origins. In the Lisbon field, the combination of methane $\delta^{13}C$ and gas wetness (C_{2+}) values, Rock Eval data (V. Nuccio, oral commun., 1992), and the association of gas with oil indicates that the hydrocarbon gases are thermogenic in origin and were generated at intermediate levels of catagenesis (in the oil window; vitrinite reflectance values about 0.8–1.0 percent). Organic-rich shale intervals in the Leadville Limestone having total organic carbon values of more than

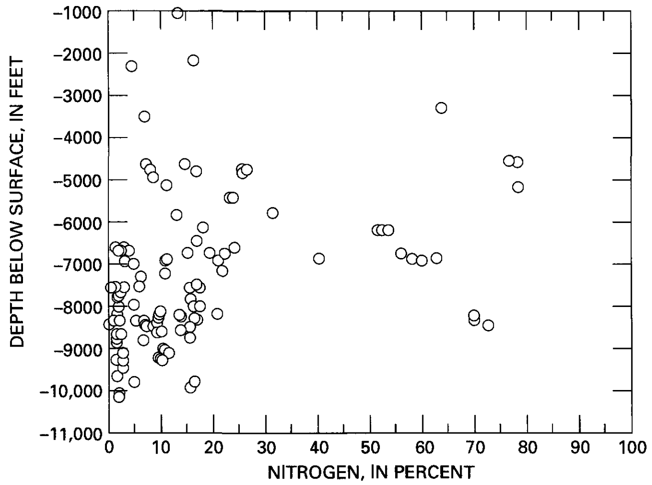

Figure 2. Nitrogen versus depth in all gas samples.

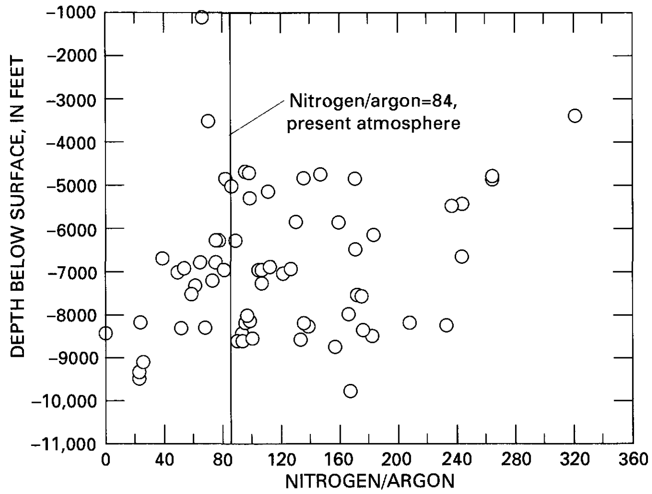

Figure 3. Ratio of nitrogen to argon versus depth in all gas samples.

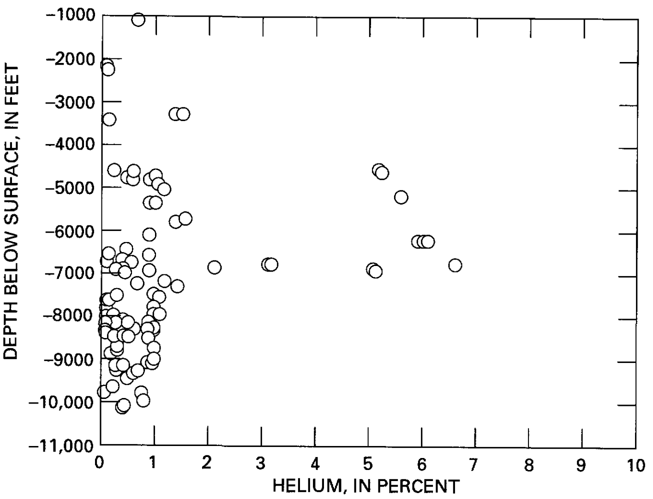

Figure 4. Helium versus depth in all gas samples.

Table 2. CO₂ production from the McElmo field, 1970–1992.
[From records of Colorado State Oil and Gas Conservation Commission]

Year	Number of producing wells	Production (thousand cubic feet)
1970	1	82,273
1971	1	132,458
1972	1	159,447
1973	1	142,813
1974	1	123,016
1975	1	229,382
1976	1	317,720
1977	1	574,087
1978	1	542,779
1979	2	678,101
1980	2	634,514
1981	2	727,930
1982	2	842,144
1983	2	575,002
1984	3	49,260,031
1985	23	134,772,282
1986	21	189,198,089
1987	23	173,560,252
1988	23	179,303,144
1989	23	198,204,816
1990	23	205,028,642
1991	37	207,522,248
1992	37	213,028,144

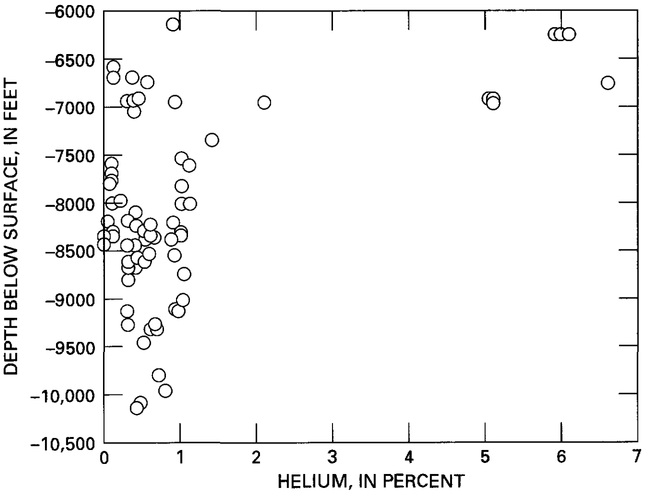

Figure 5. Helium versus depth in gas samples from rocks of Mississippian age.

Table 3. Carbon isotope analyses of gas samples from the Leadville Limestone, Paradox Basin, Colorado and Utah.

[Analyses conducted at the U.S. Geological Survey, Denver, Colorado. Abbreviations: C_1, methane; C_2, ethane; C_3, propane; iC_4, iso-butane; nC_4, normal butane; iC_5, iso-pentane; nC_5, normal pentane]

Sample	Well	Location	Volume percent									$\delta^{13}C$ (‰)	
			CO_2	N_2	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	CO_2	C_1
McElmore field, Montezuma County, Colorado													
MCAC–D51	Dudley No. 5	Sec. 13, T. 36 N., R. 18 W.	77.50[1]	22.49	--	--	--	--	--	--	--	-11.80	--
MCAC–S21	Schmidt No. 2	Sec. 24, T. 36 N., R. 18 W..	92.02[1]	7.97	--	--	--	--	--	--	--	-3.77	--
MCS–YA1	YA–1	Sec. 13, T. 37 N., R. 18 W.	92.38[1]	6.82	0.79	--	--	--	--	--	--	-4.43	--
MCS–YA2	YA–2	Sec. 13, T. 37 N., R. 18 W.	93.87[1]	6.12	--	--	--	--	--	--	--	-4.15	--
Lisbon field, San Juan County, Utah													
LF–A715	A–715	Sec. 15, T. 30 S., R. 24 E.	23.19	24.80	28.11	14.23	5.48	1.08	2.42	0.31	0.15	-11.09	-42.28
LF–D89	D–89	Sec. 9, T. 30 S., R. 24 E..	16.76	28.81	38.81	13.29	2.55	0.40	0.76	0.15	0.15	-9.50	-42.09

[1] Analyses in U.S. Bureau of Mines Information Circulars (Moore and Sigler, 1987a, b, 1988; Hamack and Sigler, 1989, 1990, 1991) and Shell Western E&P's current analytical database indicate that CO_2 contents of gases in McElmo field are on the order of 97–98 percent. Sampling during the program described herein was aimed at gaining information on the carbon isotope ratios, and the sampling method may have caused some influx of atmospheric nitrogen, thereby decreasing CO_2 values.

1 percent (V. Nuccio, oral commun., 1992) probably were source rocks for the oil and associated hydrocarbon gases.

Major quantities of carbon dioxide are generated from the thermocatalytic decomposition of oxygen-bearing functional groups in kerogen (Hunt, 1979; Tissot and Welte, 1984). The carbon dioxide has $\delta^{13}C$ values similar to the kerogen from which it was generated (–30 to –20‰); however, carbon dioxide is highly soluble in water and very reactive, and most of this early formed carbon dioxide is probably not preserved (Hunt, 1979). Significant amounts of carbon dioxide in present-day reservoirs, such as the Lisbon and McElmo fields, probably have an origin other than early-stage thermal decomposition of kerogen. Possible sources of carbon dioxide are (1) thermal destruction of carbonates by contact metamorphic processes (Lang, 1959; Picard, 1962; Hunt, 1979; Clayton and others, 1990; James, 1990), (2) carbonate dissolution linked to silicate hydrolysis (Smith and Ehrenberg, 1989), (3) bacterial degradation of organic matter (Carothers and Kharaka, 1980; Whiticar and Faber, 1986), (4) bacterial hydrocarbon oxidation (James and Burns, 1984), (5) migration directly from Laramide and younger intrusive rocks (Picard, 1962), and (6) migration of juvenile carbon dioxide from the mantle and crust (Smith and others, 1985; Kotarba, 1990).

In the Lisbon and McElmo fields, the large amounts of carbon dioxide are in carbonate reservoirs that experienced higher than normal geothermal gradients during early to mid-Tertiary time because of nearby igneous activity. The McElmo field is less than 5 mi north of the Laramide calcalkaline Ute Mountain laccolith, whereas the Lisbon field is about 15 mi south of the mid-Tertiary La Sal Mountains, an alkalic laccolith (Mutschler and others, 1987).

A comprehensive study of the geochemistry of carbon isotopes (Craig, 1953) demonstrates that calcite in normal marine limestone ranging from Cambrian to Pleistocene in age has $\delta^{13}C$ values of from +2.4 to –3.3‰ and an average value of –0.2‰. Carbon from normal sedimentary rocks has $\delta^{13}C$ values of from –14.0 to –30.0‰ (Craig, 1953). $\delta^{13}C$ values for the calcite in the two drill-core samples of the Leadville Limestone (table 4) are close to zero, well within the range of calcite from normal marine limestones, and one analysis of organic carbon from the Lisbon field has a $\delta^{13}C$ value of –27.06‰, typical of organic carbon from sedimentary rocks (Craig, 1953). The produced carbon dioxide gas at the McElmo field has a $\delta^{13}C$ value of about –4‰, and $\delta^{13}C$ values for the gas at the Lisbon field average about –10‰ (table 3). On the basis of both the proximity of the Lisbon and McElmo fields to Tertiary intrusive complexes and the $\delta^{13}C$ values of carbon dioxide, rock calcite, and organic carbon, the carbon dioxide is interpreted to be the result of high-temperature thermal decomposition of carbonate in the Leadville Limestone. Late-stage fractionation or some input from organic carbon may have produced the $\delta^{13}C$ values of

Table 4. Carbon isotope analyses of drill-core samples from the Leadville Limestone, Paradox Basin, Colorado and Utah.
[Analyses conducted at the U.S. Geological Survey, Denver, Colorado. Leaders (--) indicate not detected]

Sample	Field	Well	Location	County	State	Depth (feet)	$\delta^{13}C$ (‰)	
							Calcite	Organic C
MCS–HB2r	McElmo	Shell HB-2	Sec. 31, T. 38 N., R. 18 W.	Montezuma	Colo.	8,172	–0.64	--
LFU–BS4r	Lisbon	Pure B816	Sec. 16, T. 30 S., R. 24 E.	San Juan	Utah	8,481	0.34	-27.06

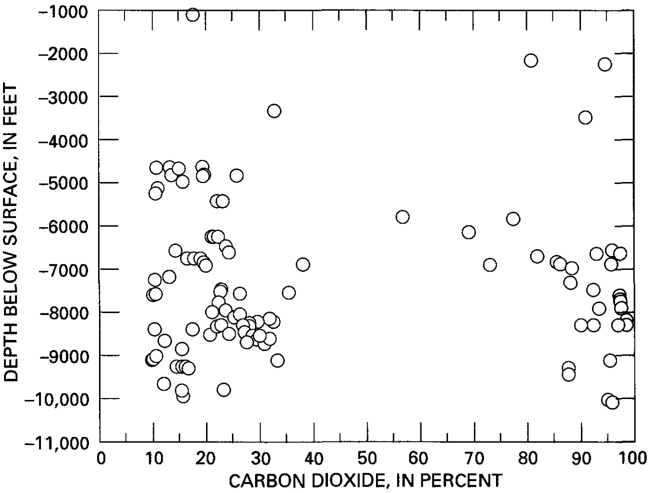

Figure 6. Carbon dioxide versus depth in all gas samples.

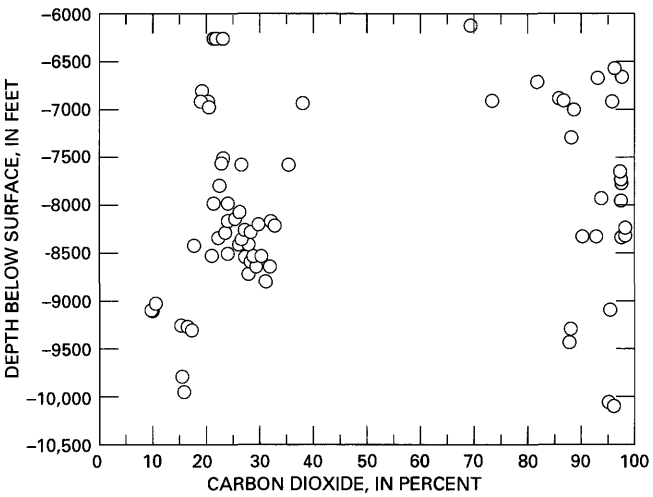

Figure 7. Carbon dioxide versus depth in gas samples from rocks of Mississippian age.

from –9 to –11‰ for the carbon dioxide from both samples taken from the Lisbon field and from sample MCAC–D51 from the McElmo field.

Some of the carbon dioxide may be juvenile and may have migrated from the crust and mantle; however, graphs of all carbon dioxide values versus depth (fig. 6) and only Mississippian carbon dioxide values versus depth (fig. 7) show no correlation between carbon dioxide and depth. In addition, the almost complete absence of carbon dioxide in good reservoir rocks in the underlying Devonian and Cambrian strata does not support a crustal or mantle source for the carbon dioxide (or nitrogen and helium). A source of carbon dioxide from direct migration from Laramide or younger intrusive rocks is a distinct possibility. In the Paradox Basin the high percentage of carbon dioxide associated with carbonate reservoirs indicates that carbonate in the reservoir rock is the critical factor; however, the high percentage of carbon dioxide, 19.6–26.1 percent (table 1), in siliciclastic reservoirs just outside the limits of the Paradox Basin, such as the Middle Jurassic Entrada Sandstone at the San Arroyo field in Grand County, Utah, indicates that other factors may be equally important. The striking coincidence of Laramide or younger igneous rocks and siliciclastic carbon dioxide reservoirs at the Sheep Mountain field, Huerfano County, Colorado, gives credence to the hypothesis that the carbon dioxide is related to direct migration from igneous rocks (Roth, 1983).

Nitrogen, hydrogen sulfide, and helium are also significant components of the gases, particularly at the Lisbon field. The hydrogen sulfide probably resulted from thermochemical sulfate reduction at high temperatures; the source of the sulfate was evaporites such as anhydrite (Orr, 1977). The helium may have had a radiogenic origin because uranium and thorium are present in anomalously high amounts in the surrounding sedimentary and Laramide igneous rocks. Some of the helium may have migrated from the deep crust and mantle along major faults, such as the Lisbon fault at the Lisbon field.

In conclusion, gases containing large amounts of carbon dioxide in the Lisbon and McElmo fields are both organic and inorganic in origin. These gases of different origins are present in significant quantities because of trapping and sealing conditions. The hydrocarbon gases were generated from adjacent organic-rich shale by thermochemical processes at intermediate stages of thermal maturity, whereas the carbon dioxide and hydrogen sulfide resulted from high-temperature thermal processes affecting adjacent carbonates and sulfates, respectively. The helium probably was derived from surrounding uraniferous rocks. The source of the nitrogen remains conjectural; however, it probably did not come from the underlying crust and mantle.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication December 7, 1994
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APPENDIX—EXAMPLES OF POROSITY AND PERMEABILITY EVALUATIONS FROM SONIC, NEUTRON, AND MICRORESISTIVITY LOGS

Four wells (fig. 1) were selected to demonstrate, in a qualitative manner, the determination of porous and permeable zones in the Mississippian Leadville Limestone in the Paradox Basin of the Four Corners region of Colorado, Utah, New Mexico, and Arizona.

SONIC LOG

The Risley Canyon Unit No. 2 well is in the McElmo field, Montezuma County, Colorado. The sonic log (appendix fig.1) of the Leadville Limestone shows a zone of porosity in carbonate rocks from a depth of 7,055 to 7,210 ft. The estimated porosity in this zone is 5 percent, and in one part of the zone is as high as 9 percent. This porous zone was perforated and had an initial production of 115,000 MCFG/D.

NEUTRON LOG

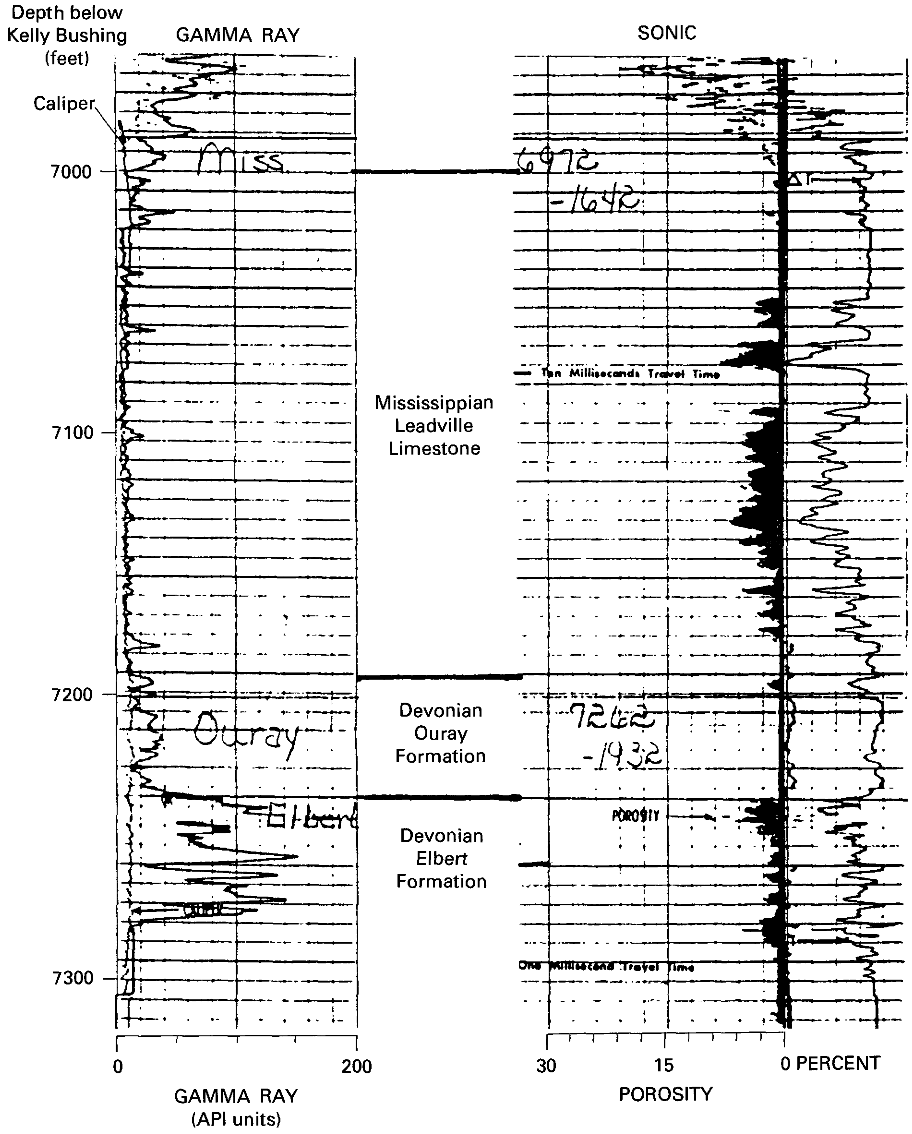
The Navajo Tract 138 No. 1 well is in Apache County, Arizona. The neutron log (appendix fig. 2) of this well shows a zone of porosity from 5,570 to 5,700 ft. A drill-stem test of the upper zone recovered 1,200 ft of heavily gas- and mud-cut oil. Drill-stem test recoveries from lower in the Leadville Limestone are indicative of wet and tighter zones of porosity. The well was perforated from 5,566 to 5,589 ft and had an initial production of 240 BO/D and 43 MCFG/D.

MICROLATEROLOG

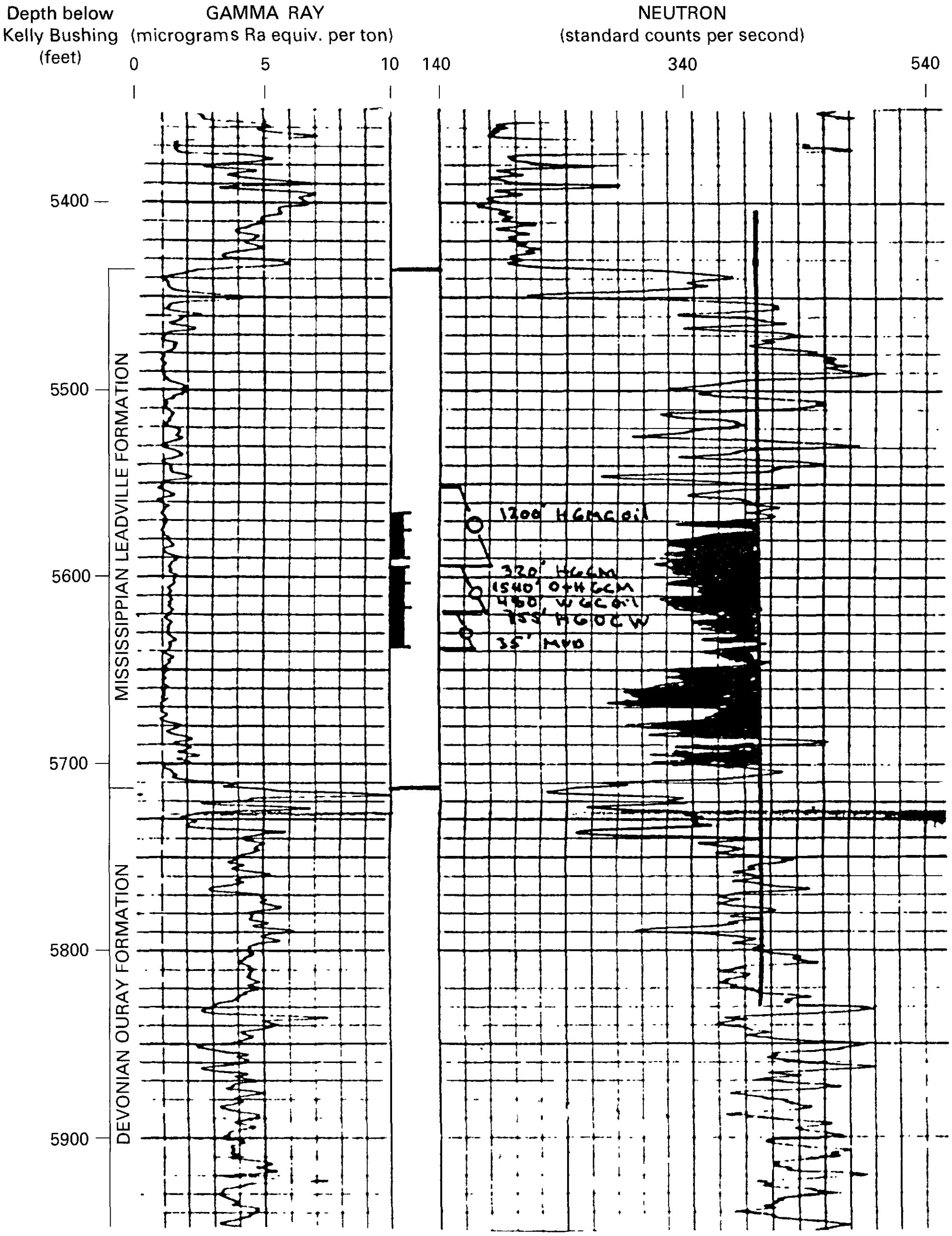
The Kikel 55–17 well in La Plata County, Colorado, was plugged and abandoned in April 1959. The neutron log (appendix fig. 3) defines well-developed zones of porosity from 9,908 to 9,921 ft and from 9,926 to 9,956 ft. The Microlaterolog shows two zones of permeability from 9,908 to 9,920 ft and from 9,932 to 9,953 ft. A drill-stem test from 9,903 to 10,031 ft recovered 275 ft of very gas cut mud with a flow pressure of 70–91 pounds per square inch. The neutron and Microlaterolog logs indicate a more porous and permeable zone than do the drill-stem results.

COMPOSITE DUAL LATEROLOG, MICRO-SFL, DUAL INDUCTION-SFL

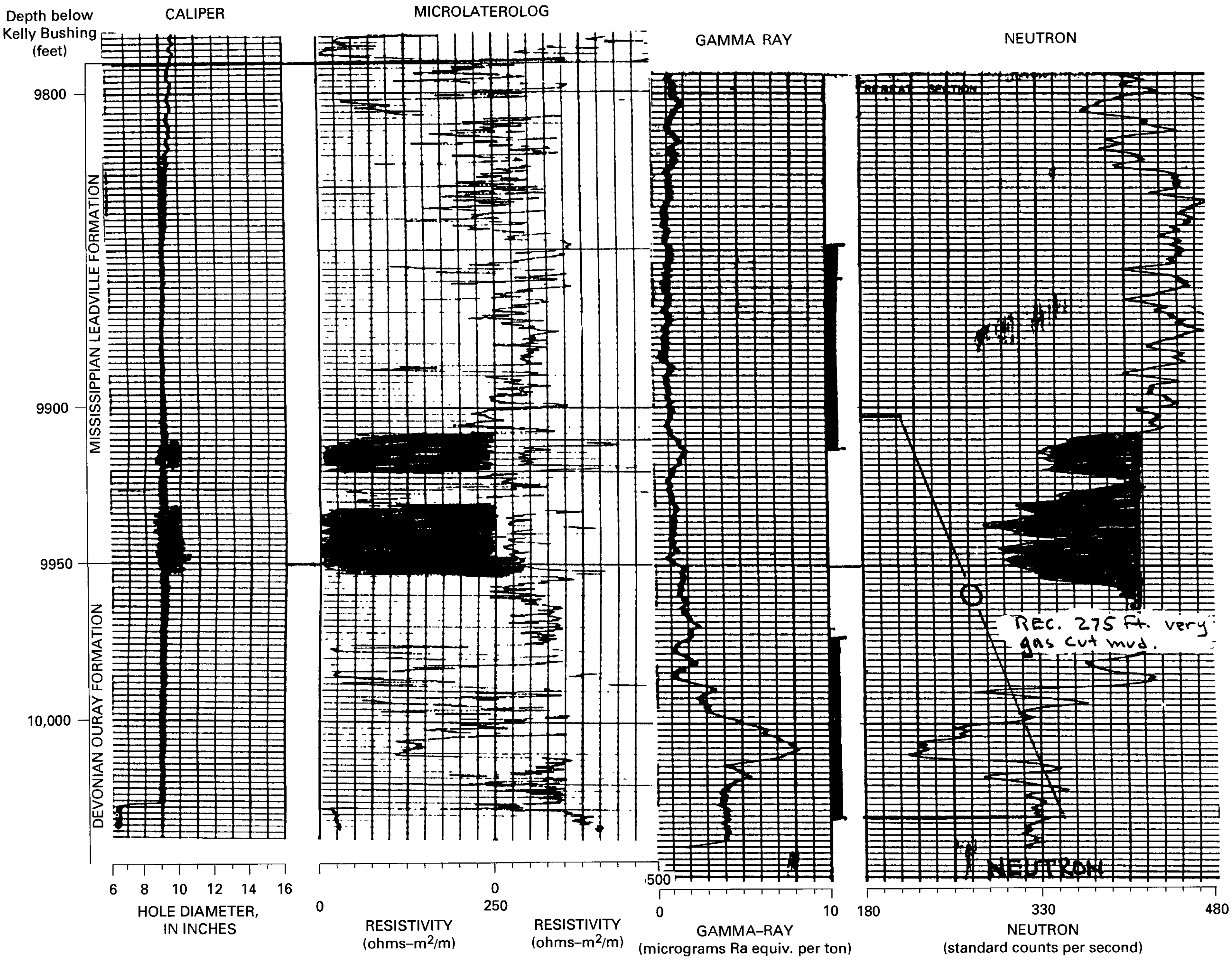
The McElmo Dome Unit HC No. 2 is in the McElmo field in Montezuma County, Colorado. A zone of enhanced permeability is shown on the composite log from 8,224 to 8,238 ft (appendix fig. 4). Initial open-flow production was 323 MMCF/D CO_2 from the Leadville Limestone. The well was perforated from 8,110 to 8,297 ft.



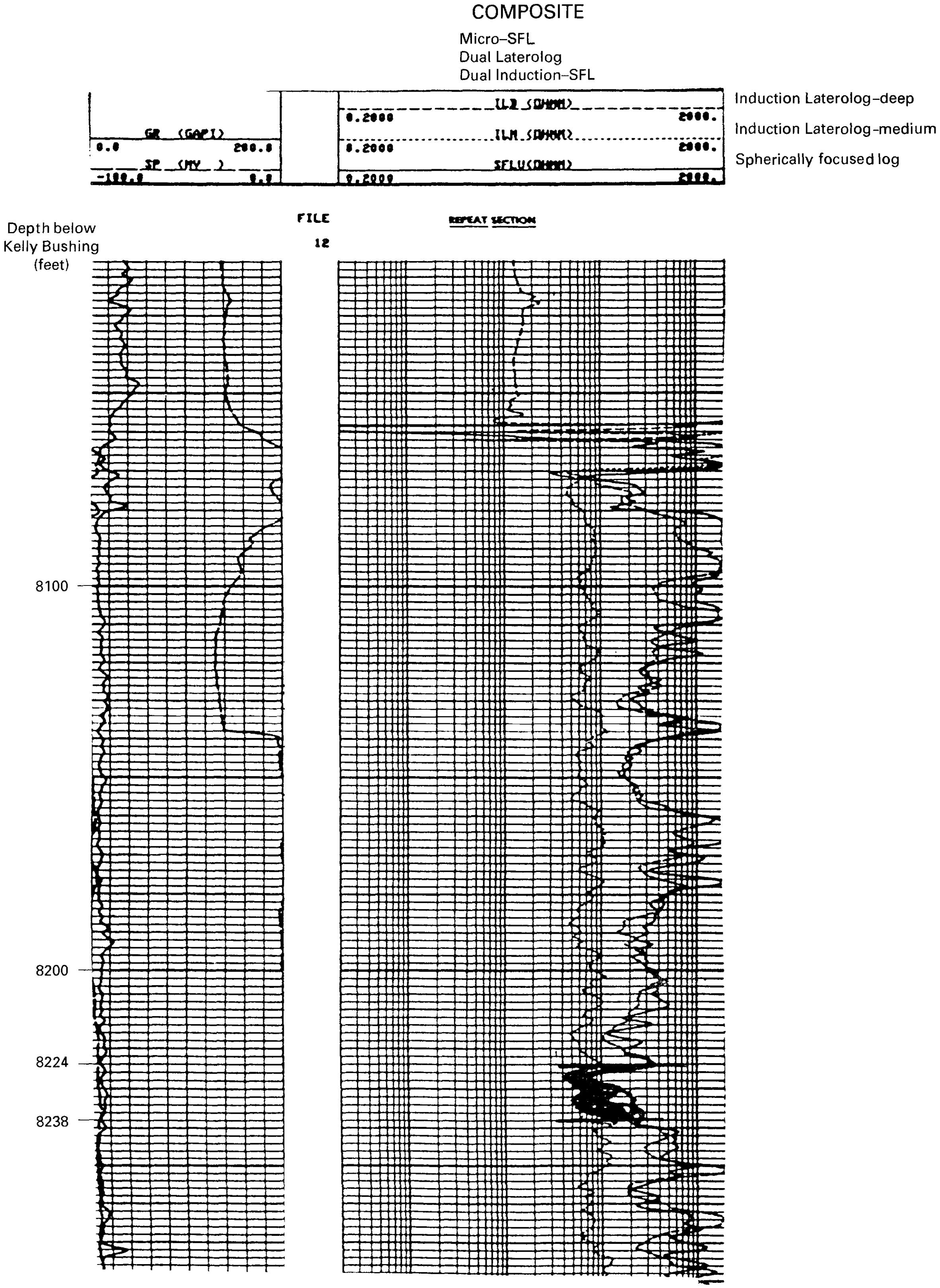
Appendix figure 1. Gamma-ray and sonic logs, API 05–083–06200, Mobil Oil Corp., Risley Canyon Unit No. 2. Sec. 2, T. 36 N., R. 18 W., Montezuma Co., Colo. Completed gas well, March 19, 1978. Initial production 115 MMCFG/D; production zone 7,056–7,208 ft; perforations 7,376–7,392 ft, 7,204–7,208 ft, and 7,056–7,194 ft.



Appendix figure 2. Gamma-ray and neutron logs, API 02–001–90031, Texas Pacific Coal O&G, Navajo Tract 138 No. 1. Sec. 11, T. 40 N., R. 28 E., Apache Co., Ariz. Completed oil well, July 28, 1959. Initial production 240 BO/D, 43 MCFG/D; perforation 5,566–5,589 ft Mississippian.



Appendix figure 3. Gamma-ray, neutron, caliper, and Microlaterolog resistivity logs, API 05–067–05544, General Operating Co., Kikel 55–17. Sec. 17, T. 34 N., R. 11 W., La Plata Co., Colo. Plugged and abandoned April 13, 1959.



Appendix figure 4. Gamma ray, spontaneous potential, dual-laterolog, micro-sfl, and dual-induction-sfl logs, API 05-083-06290, Shell Western E&P, McElmo Dome Unit HC No. 2. Sec. 12, T. 37 N., R. 19 W., Montezuma Co., Colo. Completed CO_2 well, June 16, 1984. Initial open flow production 323 MMCF/D CO_2 243 BW/D.

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