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Carbon Dioxide in the Subsurface of Northeastern New Mexico

Ronald F. Broadhead

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CARBON DIOXIDE IN THE SUBSURFACE OF NORTHEASTERN NEW MEXICO

RONALD F. BROADHEAD

New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro NM, 87801, ron.broadhead@nmt.edu

ABSTRACT — Two naturally occurring subsurface accumulations of carbon dioxide (CO₂) gas, the Bravo Dome field and the Des Moines field, have been discovered in northeastern New Mexico. The Bravo Dome field is located on Bravo Dome, a southeast-plunging extension of the Sierra Grande Uplift. The field is formed by a combination of structural and stratigraphic elements with the Tubb Sandstone (Permian) as the main reservoir. Cumulative production is 3.3 trillion ft³ (TCF) CO₂, which is used almost entirely for enhanced oil recovery in the Permian Basin. Isotopic studies by several workers indicate the CO₂ originated in the mantle. Age dates of extrusive basalts in the Bravo Dome area appear to bracket the timing of basaltic magmatism and major CO₂ emplacement to between 1.46 and 5.29 Ma. The Des Moines field is located near the axial crest of the Sierra Grande Uplift. It is a small accumulation that produced CO₂ from Abo (Permian) sandstones and was abandoned circa 1966. Exploratory wells drilled elsewhere on the Sierra Grande Uplift have encountered shows of CO₂ and indicate the uplift is a CO₂ province and not a hydrocarbon province. The wide distribution of CO₂ and presence of CO₂ updip of confining seals in the Bravo Dome field require either multiple migration pathways from the mantle or widespread seepage from deep magmatic sources. Gases in adjacent basins are dominantly hydrocarbon except where reservoirs are associated with Tertiary-age intrusives or are not stratigraphically associated with petroleum source rocks.

INTRODUCTION

Naturally occurring carbon dioxide (CO₂) gas has been produced from two fields in northeastern New Mexico: the Bravo Dome field and the Des Moines field (Fig. 1). The Des Moines field is located near the axis of the Sierra Grande Uplift. The Bravo Dome field is located on the Bravo Dome, a southeast-plunging extension of the Sierra Grande Uplift. The Bravo Dome field was discovered in 1917 but remained unproduced until 1935. It is a major accumulation of CO, with up to 10 trillion ft³ (TCF) recoverable CO₂. Production has continued through the present. Since inception of production, 3.3 TCF CO, have been produced from Bravo Dome. The Des Moines field was discovered in 1935 and produced from 1952 until about 1966. Cumulative production is unknown but minor compared to Bravo Dome. Other noncommercial shows of CO, have been encountered by exploratory wells drilled on the Sierra Grande Uplift and in the Bravo Dome area. Gases in adjacent basins are dominantly hydrocarbons except for CO₂-rich gases in the Las Vegas Basin that are associated with laccolithic intrusion and in the Raton Basin where CO2-rich gases are associated with stratigraphic intervals devoid of petroleum source rocks. Historically CO, was produced for conversion into dry ice and bottled, liquid CO, but modern use is almost entirely for enhanced oil recovery in older oil fields.

This paper summarizes the geology of the Bravo Dome and Des Moines fields as well as other noncommercial occurrences of CO₂ in northeastern New Mexico. It also summarizes work done by multiple investigators determining the origin of CO₂ gases in northeastern New Mexico. In conjunction with the geology and trapping mechanisms of the CO₂ occurrences as well as published age determinations of volcanic rocks in the Bravo Dome area, insights are provided into timing and

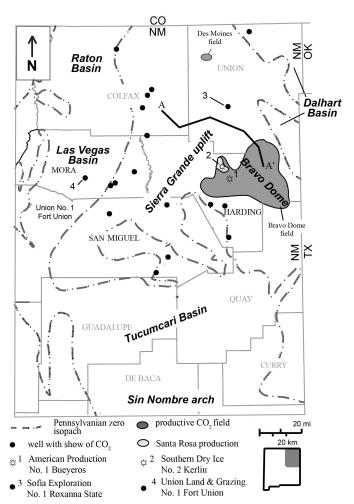


FIGURE 1. Map showing locations of major tectonic elements in northeastern New Mexico. Also shown are historically productive CO₂ fields and exploratory wells with shows of CO₂. The track for cross section A-A' (Fig. 4) is also indicated

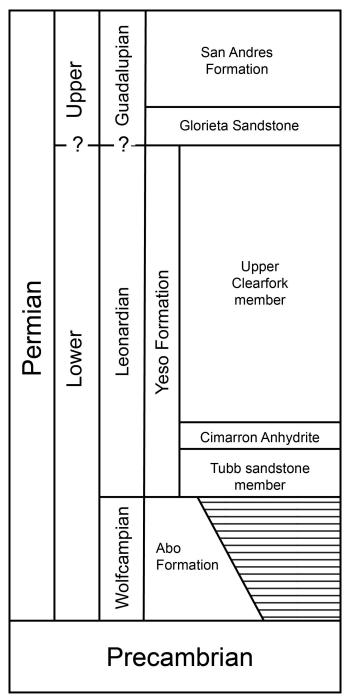


FIGURE 2. Stratigraphic column showing Lower Permian strata at the Bravo Dome CO₂ field. See Figure 4 for all strata from the surface to Precambrian basement.

pathways of CO₂ migration. Possibilities for future, untapped resources are also examined.

GEOLOGIC SETTING

The Sierra Grande Uplift and its southeastern extension, the Bravo Dome (Fig. 1), are Ancestral Rocky Mountain uplifts. They formed during the Pennsylvanian Period. Uplift along bounding faults exposed the cores of these tectonic elements.

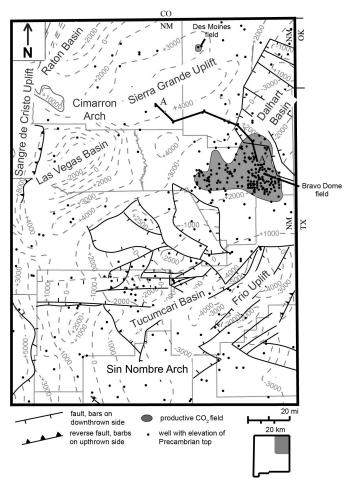


FIGURE 3. Map showing structural elements in northeastern New Mexico and structure contours of the top of Precambrian basement. Structure on top of Precambrian basement is simplified from Broadhead (2009). Also indicated is the location of cross section A-A' (Fig. 4).

Higher parts of the uplifts were eroded to the Precambrian basement (Baltz, 1965; Broadhead and King, 1988; Broadhead, 1990; Baltz and Myers, 1999). Eroded sediment was deposited in the adjacent basins during Late Pennsylvanian and Early Permian time. As a result, Lower Permian strata rest on Precambrian basement on top of the Sierra Grande Uplift and Bravo Dome but older strata are present in the adjacent basins (Figs. 2, 3, 4). On the lower parts of the uplifted areas, fluviatile red beds of the Abo Formation (Lower Permian: Wolfcampian) rest unconformably on Precambrian rocks. On higher parts of the uplifts, continental orange siltstones and fine-grained sandstones of the Yeso Formation (Lower Permian: Leonardian) overstep Abo strata and rest on the Precambrian.

CO₂ FIELDS AND OCCURRENCES Bravo Dome CO₂ Field

The Bravo Dome field was discovered in 1917 by the American Production Co. No. 1 Bueyeros well (Fig. 1). The well was drilled as an oil exploration well that did not find oil but instead encountered CO_2 gas in the Tubb Sandstone Member of the Yeso Formation at a depth of 2000 ft. The well reportedly

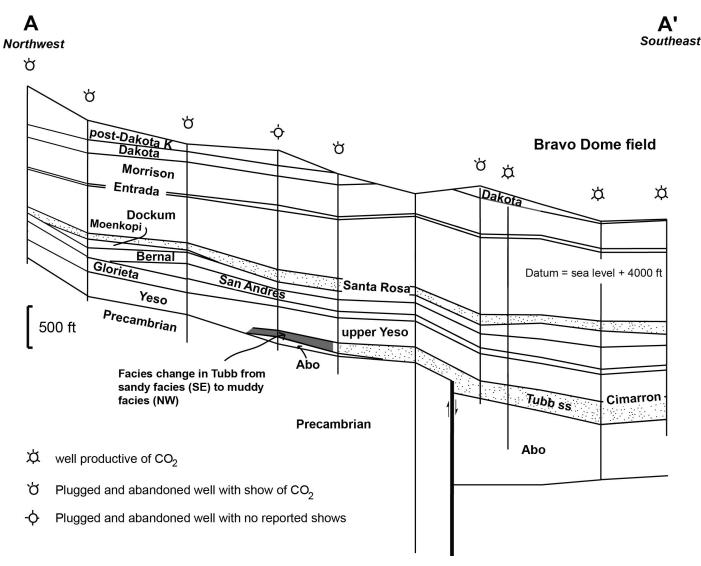


FIGURE 4. A-A' northwest-southeast structural cross section through the Bravo Dome CO₂ field showing stratigraphy, Tubb and Santa Rosa Sandstone CO₂ reservoirs, and updip trap-forming lithofacies transition within the Tubb Sandstone. See Figures 1 and 3 for location of cross section (adapted from Broadhead, 2017).

flowed CO₂ gas at a rate of 25 million ft³ gas per day. The well was plugged because there was no market for the gas (Anderson, 1959). The field lay dormant and undeveloped until 1931 when additional wells were drilled, establishing production from the Santa Rosa Sandstone (Triassic) as well as from the Tubb. Production was at minimal levels from 1931 through 1982 (Fig. 5). During this period, 19 productive wells had been drilled and the field was named after the nearby town of Bueyeros. The CO₂ was compressed into dry ice that was used for refrigeration and into liquid that was used for the carbonation of beverages (Anderson, 1959).

In the early 1980s a new use for CO_2 emerged, enhanced oil recovery. When injected into an oil reservoir at a mature stage of production, CO_2 mixes with the remaining oil and makes it more mobile. Oil that cannot be produced through primary production or waterflooding can often be produced through CO_2 injection. As a result, a major market for Bravo Dome CO_2 was established and pipelines for transport of CO_2 were built to the

Permian Basin in west Texas and southeastern New Mexico. Exploration for and development of CO₂ at Bravo Dome ensued and more than 270 wells were drilled into the Tubb Sandstone on 640-acre spacing (1 well per mi²). At this time the field's name was changed to Bravo Dome (from Bueyeros). As a result of the extensive drilling, CO₂ production increased markedly (Fig. 5). The produced CO₂ is compressed into a liquid and shipped via underground pipeline to the Permian Basin. More than 3.3 trillion ft³ CO₂ have been produced from the Bravo Dome field with 89 billion ft³ CO₂ worth \$97 million produced during 2018. Estimates of recoverable CO₂ range from 5.3 to 10 trillion ft³ (Johnson, 1983; Cassidy et al., 2007). The Bravo Dome CO₂ field exerts a major impact on the economy of northeastern New Mexico as well as the state in general.

The main reservoir, the Tubb Sandstone, is draped onto the margins of the Bravo Dome structure. Continental red beds of the Abo Formation, which underlie the Tubb, are thicker in down faulted areas (Fig. 4; Broadhead, 1990). On uplifted

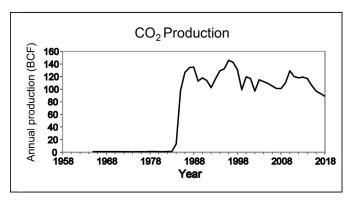


FIGURE 5. Diagram showing historical CO₂ production from the Bravo Dome field (based on data published on the website of the New Mexico Oil Conservation Division).

blocks, the Abo is either absent or present as a thin sedimentary unit that rests on Precambrian basement in paleotopographic lows. The Tubb is 0 to 400 ft thick and consists of orange, fine- to medium-grained sandstones and siltstones with siltstones dominating in many areas of the reservoir (Broadhead, 1990). Sandstones are fluvial and the siltstones are loess deposits (Kessler et al., 2001). Net pay averages 120 ft. Tubb sandstones and siltstones have an average porosity of 20% and an average permeability of 42 millidarcies (Johnson, 1983). The Tubb thins to less than 100 ft to the northwest and is absent over buried erosional knobs on the upper surface of the Precambrian basement (Broadhead, 1990). Thinning is accompanied by a facies change to muddy sediments (Fig. 4; Broadhead, 1993). The Tubb thickens to the southeast where it transitions into a shallow-marine facies with interbedded mudstones, anhydrites and dolostones. The Tubb is overlain by the Cimarron Anhydrite. The Cimarron Anhydrite is 10 to 20 ft thick over most of the Bravo Dome field but pinches out to the northwest on higher parts of the Bravo Dome, updip of the northwest limits of gas accumulation. It thickens to more than 50 ft to the south and east where these anhydrites are interbedded with thin sandstones on the flanks of Bravo Dome.

The Bravo Dome field is formed by a combination of structural and stratigraphic elements (Broadhead, 1990, 1993). Structure controls the downdip limit of the field on the northeast, southeast and southwest sides (Fig. 3). In these areas, the top of the Tubb passes under the downdip gas-water contact (Cassidy et al., 2013). However, there is no structural closure on the updip, northwest flank. The updip limit of the field on the northwest is formed by the facies change within the Tubb to impermeable muddy sediments (Fig. 4). The accompanying regional thinning of the Tubb results in progressively decreased reservoir capability in the updip direction with the vertical seal provided by the Cimarron Anhydrite (Fig. 2). The ductile nature of the anhydrite provides an effective seal for high-angle faults present in the Bravo Dome field. Depth to production in the Tubb reservoir is 1900 ft at the northwestern updip limit of the CO, accumulation and 2,950 ft at the southeastern, downdip limit of the field.

The fluviatile Santa Rosa Sandstone is a minor secondary reservoir in the Bravo Dome field (Broadhead, 1990). Al-

though the Cimarron Anhydrite is an effective seal for the Tubb reservoir, it is possible that there has been some leakage through at least some of the faults. If this is the case, then the faults would have provided a potential migration pathway for the CO₂ trapped in the Santa Rosa Sandstone. Overlying ductile shales within the Dockum Group provide the vertical seal for the Santa Rosa. The discovery well for the Santa Rosa Sandstone was the Southern Dry Ice No. 2 Kerlin (Fig. 1). The well was drilled in 1931 and established the first production from the Bueyeros (now Bravo Dome) field. The reservoir was encountered at a depth of 960 ft and flowed CO₂ at a reported rate of 3.7 million ft³ gas per day.

Gas at Bravo Dome consists of 98 to 99% CO₂ (Johnson, 1983; Broadhead et al., 2009 for gas analyses of individual wells). The non-CO₂ component consists of trace amounts of noble gases, nitrogen and helium. Hydrocarbons are present in trace amounts in some areas but are absent from most wells.

The CO, at Bravo Dome is juvenile. Isotopic analyses of the CO, and associated noble gases indicate that the gas has a mantle rather than a crustal origin (Phinney et al., 1978; Staudacher, 1987; Gilfillan et al., 2008; Cassidy et al., 2013). Presumably Tertiary-age magmas that formed basalts in the region carried the gas in solution from the mantle. As the magmas rose and confining pressure decreased, the gas exsolved and formed a separate phase. For magmas extruded as basalt flows at the surface, a large portion of the gas escaped into the atmosphere and was lost. However, for magmas that intruded crustal rocks and formed laccoliths, sills, dikes, and other hypabyssal bodies, the exsolved gas would have migrated under pressure into porous sedimentary reservoirs. If the intrusive body was located below the top of Precambrian basement, the gas may have migrated upward through fractures and faults into overlying sedimentary reservoirs.

A specific source of the CO_2 has not been identified. Brennan (2017) studied isotopes of CO_2 and associated noble gases across the Tubb accumulation. Based on areal trends in ratios of these isotopes, Brennan inferred a source for the CO_2 in the northwestern part of the Bravo Dome field near its updip limit (Fig. 6). In this general area, age dates of extrusive basalts are 1.46 to 5.29 Ma, which may bracket the timing of most CO_2 migration into the reservoir.

Analysis of bottom-hole reservoir pressures indicates that the Tubb reservoir at Bravo Dome is divided into seven compartments with static pressure gradients (Fig. 6; Broadhead, 1993). Boundaries between the seven compartments appear to be coincident with faults mapped in the subsurface using well-log data or where faults are inferred to be present by locations of streams at the ground surface (unpublished map by Broadhead; Cassidy et al., 2013). Compartment A has the highest pressures. Compared to a calculated static water pressure gradient (Fig. 7), compartment A is underpressured relative to a hydrostatic system with connection to the outcrop. Eastward from A, there is a large decrease in pressure to compartments B, C and G, which border A to the east and northeast. Compartments B through F exhibit an eastward, stepwise decrease in pressures. Compartment G, which is characterized by the lowest pressures, abuts compartments A through

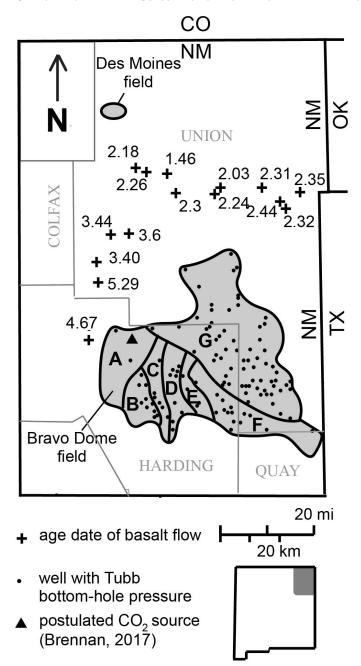


FIGURE 6. Map showing the seven static pressure compartments (A through G) in the Tubb Sandstone reservoir of the Bravo Dome CO₂ field (Broadhead, 1993) and age dates of extrusive basalts in the region (Stroud, 1997 and Nereson et al., 2013). Also shown is the postulated location of the CO₂ source (Brennan, 2017).

F. The boundary between compartment G and compartments A through F is formed by a major northwest-southeast trending fault that can be clearly mapped in the subsurface using well data. At the surface where Mesozoic and Tertiary strata crop out, a northwest-southeast trending drainage divide is coincident with this boundary, suggesting that the fault may be a compressive structure. If so, then it may be Laramide in age. Alternatively it may be an older Ancestral Rocky Mountains fault that was reactivated during Laramide compression. Some of the pressure compartment boundaries in the western part of

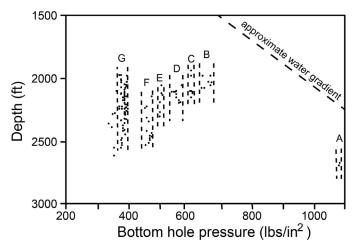


FIGURE 7. Diagram showing depth vs. bottom-hole pressure (BHP) in the Tubb sandstone reservoir of the Bravo Dome field. The diagram segregates pressures into seven static pressure compartments (Broadhead, 1993; see Fig. 6 for a map of the pressure compartments). Pressures were obtained from data submitted by Amoco Production Company to the New Mexico Oil Conservation Division. Also shown is the calculated hydrostatic water gradient for a hypothetical system where the fluid system of the Tubb is in pressure communication with the outcrop.

the field may be formed by lateral discontinuities in sandstone and siltstone reservoirs (Akhbari and Hesse, 2017). If true, it may be that the extent of the reservoir facies is controlled by pre-existing faults or deposition of the Tubb Sandstone over erosional topography at the unconformity on top of the Precambrian basement. The relatively wide scatter of data in compartments B and D (Fig. 7) may in turn be caused by internal stratigraphic heterogeneity of the Tubb but further investigations are required to verify this.

Brennan's (2017) postulated migration pathway for the CO₂ is situated at the northern end of compartment A (Fig. 6). If this source was the only migration path for CO₂ that migrated upward from igneous bodies within the Precambrian, it would explain the distribution of pressures across the compartments. It may be that the boundaries between the compartments act as baffles rather than complete barriers to fluid flow over geologic time. The result would be that CO, gas that entered the Tubb Sandstone from this postulated source would have filled compartment A and slowly dissipated into the other compartments through the baffles. However, Cassidy et al. (2013) and Akhbari and Hesse (2017) conclude that the low pressures in the compartments were at least partially caused by solution of CO₂ into the regional aquifer at the downdip, gas-water contacts in each of the compartments. It may also be that Brennan's postulated source reflects only one migration path from the mantle and that CO, actually migrated upward from a deeper magmatic source over a wider area. Baker and others (1995) identified continent-wide seepage of CO, from deep magmatic sources in eastern Australia. A widely spread source or multiple local sources are necessary to account for CO2 occurrences at locations over the Sierra Grande Uplift that are updip (northwest) of the permeability boundary that forms the northwestern side of the Bravo Dome, Tubb sandstone accumulation.

Des Moines CO₂ field

The Des Moines CO₂ field (Fig. 1) was discovered in 1935 by the Sierra Grande Oil Co. No. 1 Rogers well. The well was drilled for oil exploration but discovered CO₂. Reservoirs are lenticular fluvial sandstones and conglomerates in the Abo Formation (Permian: Wolfcampian) and were encountered at depths ranging from 2300 ft to 2600 ft. An estimated 6 million ft³ day of gas flowed from these reservoirs. The well was plugged and abandoned without establishing production.

The Des Moines field lay dormant until 1951 when the Nelson-Moore No. 1 Fee well was drilled to a total depth 2685 ft. The well was completed in 1952. Production was established from depths of 2020 to 2600 ft. Three additional wells were drilled between 1953 and 1955. The main reservoirs are sandstones in the Abo Formation but a secondary ultra-low pressure reservoir (5 psi) was encountered in a dolomite within the Bernal Formation (Upper Permian) at depths of 1100 to 1200 ft. Foster and Jensen (1972) correlated this secondary reservoir with the Alibates Dolomite (Upper Permian) of the Texas panhandle. Composition of the Abo gas is 98.6% CO, with the remainder being nitrogen and hydrocarbons (Anderson, 1959). The composition of the gas from the Bernal Formation remains unknown. A small plant was erected that processed the CO₂. Initially liquid CO₂ was produced but by 1966 dry ice was produced (Anderson, 1959; Foster and Jensen, 1972). The processing plant was subsequently abandoned along with the gas field, most likely during the late 1960s. The non-CO₃ components of the gas apparently caused significant problems with gas processing (Anderson, 1959).

The Des Moines field is located near the crest of the Sierra Grande Uplift (Fig. 3). The areal and vertical extents of the field have not been defined by drilling and remain unknown. Records of annual and cumulative production have apparently not been preserved. Therefore, it is not possible to estimate the volume of CO₂ that has been produced or the CO₂ that may remain

CO₂ on other parts of Sierra Grande Uplift and Bravo Dome and in adjacent basins

CO₂-rich gas is widespread in Paleozoic and Mesozoic strata of northeastern New Mexico (Talmage and Andreas, 1942; Anderson, 1959; Foster and Jensen, 1972; Broadhead et al., 2009). Apart from the Bravo Dome and Des Moines fields, CO, has been encountered in numerous wells drilled on the Sierra Grande Uplift and also on the Bravo Dome southwest of the Bravo Dome field (Fig. 1; Broadhead et al., 2009). Reservoirs with CO₂ shows in wells include the Abo and Yeso Formations (Lower Permian), the Glorieta Sandstone and San Andres Formation (Lower Permian), and Triassic sandstones. Where compositional analyses are available, the gases in these areas consist of more than 90% CO₂ (Broadhead et al., 2009). Nitrogen-rich gases are present locally in sandstone reservoirs of the Dockum Group (Triassic). Wells drilled on the Sierra Grande Uplift and Bravo Dome have not encountered appreciable amounts of hydrocarbons. This is probably due to the absence

of petroleum source-rock facies in strata present on top of these uplifts. The Sofia Exploration No. 1 Roxanna State was drilled as a CO₂ test in 1986 along the axis of the Sierra Grande Uplift (Fig. 1). The well targeted a seismically defined anticlinal structure (Oil and Gas Journal, 1986). It is notable because it was drilled to a total depth of 3763 ft and encountered the top of Precambrian basement at 2184 ft. As a result, 1579 ft of Precambrian basement were drilled. Yeso sandstones rest on Precambrian basement. Examination of thin sections of well cuttings (Broadhead, unpublished) revealed that the Precambrian consists of metamorphic quartzites, metamorphosed subarkosic arenites, and metamorphosed arkosic wackes that have been intruded by monzonites. Authigenic replacive calcite is ubiquitous. The well encountered small methane and ethane gas shows in Triassic and Yeso sandstones and sporadic shows of CO, throughout the Precambrian. The presence of CO, within the Precambrian basement supports the possibility of widespread seepage of CO₂ through the crust. Encounters with CO₂ by exploratory wells and the general lack of indications of hydrocarbons suggest that this region should be considered a CO, and not a hydrocarbon province.

Kodiak Petroleum drilled three CO₂ exploration wells within three miles of the Sofia Roxanna well in 2008. In all three wells, casing was perforated in the Santa Rosa Sandstone (Triassic) at depths ranging from 1048 to 1466 ft, the Glorieta Sandstone (Lower Permian) at depths ranging from 1600 to 1970 ft, and the Yeso Formation (Lower Permian) at depths ranging from 1740 to 2132 ft. All three wells were plugged and abandoned without establishing production. Completion forms indicate that all three wells flowed gas. Neither flow rate nor composition of the gas were reported. However, well records indicate that the gas was vented to the surface, suggesting that it consisted of noncombustible components and not hydrocarbons. It is thus likely that reservoir pressures were insufficient to establish commercial production of CO₂.

Pennsylvanian strata are not present on the Sierra Grande Uplift or on the Bravo Dome, but are present in adjacent basins (e.g., Tucumcari Basin to the south, Dalhart Basin to the east, Las Vegas and Raton Basins to the west and northwest; Fig. 1). Gases in Pennsylvanian reservoirs in the adjacent basins generally contain low concentrations of CO, and consist mostly of hydrocarbons because the Pennsylvanian section in these basins contain thick sections of generative source rocks that contain hydrocarbon gases (Broadhead et al., 2002; Broadhead, 2001, 2008, 2015, 2017). In the Raton Basin, pre-Cretaceous reservoirs that are stratigraphically associated with petroleum source rocks contain hydrocarbon gases and reservoirs that have no stratigraphic association with petroleum source rocks harbor CO₂-rich gases (Broadhead, 2012). In the Las Vegas Basin an exploratory well drilled on the flanks of the Turkey Mountains uplift, the Union Land and Grazing No. 1 Fort Union (Fig. 1), encountered gas with a 97% CO, content in Sangre de Cristo Formation (Pennsylvanian-Lower Permian) sandstones (Broadhead, 2008, 2015). The Tertiary-age igneous intrusive that forms the core of the uplift was the source of the CO₂ and also formed a structural trap with four-way closure that resulted in accumulation of the CO₂.

THOUGHTS ON FUTURE RESOURCES

The current drilling and production boom in the Permian Basin has resulted in markedly increased oil production within New Mexico and west Texas (Broadhead, 2017). The stark majority of reservoirs presently and recently developed are very fine-grained clastics. As a consequence of the fine-grain size, pore spaces within the reservoirs are small and may not respond to waterflooding but may respond to CO₂ flooding. Therefore, optimum development of these new oil resources may depend on the availability of new CO₂ resources coming into play. Given that oil production in the southeastern part of the state has increased approximately four-fold from 61 million bbls/year to almost 250 million bbls/year as a result of drilling these fine-grained clastics, it seems obvious that future CO₂ demand will greatly exceed existing supplies, which are currently in decline.

At this time it is unknown if the Sierra Grande Uplift, Las Vegas Basin, and Raton Basin harbor undiscovered CO₂ resources of sufficient size and purity to render them of economic value. On the Sierra Grande Uplift, fluvial and alluvial sandstones in the Abo Formation may be too lenticular and laterally limited to provide a sizeable resource. From the sparse available data, CO₂ in shallower strata appears to have insufficient reservoir pressures to provide a major and producible resource. In addition, many of the gases in the supra-Abo section appear to be N₂ rich. However, Bravo Dome indicates that pressures may vary substantially among different gas compartments so that higher pressure areas may exist that have not yet been drilled. In contrast, low-pressure areas may result from widespread seepage from the mantle and higher-pressure areas may result from the infusion of additional CO₃ from volcanic intrusions.

The Turkey Mountains Uplift in the Las Vegas Basin may contain substantial CO₂ resources. However, Pennsylvanian sandstone reservoirs within the Las Vegas Basin have limited porosity and permeability compared to the Tubb Sandstone reservoir at Bravo Dome. In addition, kerogen-rich Pennsylvanian shales in the Las Vegas Basin are petroleum source rocks (Broadhead, 2008, 2015) and will likely have introduced hydrocarbon gases into the system. The result may be that different sandstone reservoirs will contain differing percentages of CO₂ and hydrocarbons, which will complicate gas processing.

Pre-Cretaceous reservoirs that are not stratigraphically associated with petroleum source rocks in the Raton Basin are characterized by CO₂-rich gases (Broadhead, 2012). Therefore, these reservoirs may have potential for CO₂. The Entrada Sandstone (Jurassic) crops out along the western margin of the basin and in drainages east of the basin. While the Entrada is characterized by CO₂-bearing gases, there are limited possibilities for traps in this widespread eolian sandstone. It is likely that CO₂ gas encountered by wells drilled through the Entrada was introduced into the reservoir from the structurally deeper parts of the basin and migrated updip towards the outcrop. Perhaps the best opportunities for undiscovered CO₂ resources may lay in Permian strata that onlap the northwestern flank of the Sierra Grande Uplift. The Glorieta Sandstone and sandstones of the Yeso Formation are permeable reservoirs of wide-

spread lateral continuity. However, widespread evaporates that form the vertical seal at Bravo Dome are not present in the Raton Basin (Broadhead, 2008). The presence of a widespread vertical seal in the Permian that could contain migrating ${\rm CO_2}$ as well as act to form a trap has not been established. Without a widespread seal, migrating ${\rm CO_2}$ will likely have been disseminated throughout shallower strata.

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