PROVEN AND HYPOTHETICAL HELIUM RESOURCES IN UTAH

by Tyler J. Wiseman and Marc T. Eckels

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by Tyler J. Wiseman [1] and Marc T. Eckels [2]

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***Cover photo:** Lisbon gas processing facility in San Juan County, Utah. This plant recently re-started processing helium.*

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ABSTRACT

For nearly 100 years the naturally occurring noble gas, helium, has been documented in the gas stream of natural gas wells in eastern Utah. Global demand for helium is outstripping production as proven helium-rich gas fields continue to decline and the U.S. government moves to exit from atop its dominant position in the global helium industry. This transition creates opportunity for focused exploration and production of helium in eastern Utah and the Four Corners region of the Colorado Plateau.

Helium occurrences in eastern Utah have been influenced by a combination of mantle and crustal processes. Like a petroleum system, an effective helium system is governed by predictable processes that control generation, migration, and entrapment. Helium migration initiates with the alpha decay of uranium and thorium from mineral grains. Recrystallization and diffusion concentrate helium into pore water and groundwater over tens to hundreds of million years. Migrating volcanogenic and thermogenic gases sweep helium and nitrogen from old pore water. Recrystallization of acidic gases into solid minerals over long migration distances helps to concentrate helium and nitrogen in the gas phase. Thus, the longer the migration duration, the more nitrogen- and helium-rich the gas. Helium-rich gas migrates through carrier beds and can become trapped beneath impermeable seals like other natural gases.

Helium-rich gas in Utah is not limited to areas of proven oil and gas production or reservoir rock of a particular age or type. Due to significant helium dilution by methane generation, helium is not typically found in basin centers where most hydrocarbons are produced. In general, Paleozoic rocks typically have had more time to generate and collect more helium than younger rocks, but this relationship is based on the older (Paleozoic) helium- and nitrogen-rich groundwater that fills the pore spaces rather than the age of the rock itself. Thus, understanding the hydrodynamics of a prospective helium play is critical.

In east-central Utah, significantly high helium gas concentrations have been found in Triassic-Jurassic reservoirs along hydrodynamically complex basin-uplift transition areas and on the margins of proven petroleum fields. Helium-rich gas streams in southeastern Utah have been documented in Devonian-Mississippian reservoirs below thick cycles of hydrocarbon-rich shale, salt, and anhydrite of the Pennsylvanian Paradox Formation. In some cases, helium-rich gas has been documented in the gas cap of prolific Paleozoic petroleum systems.

Over 400 wells drilled in Utah have been tested and analyzed for helium with ranges from trace amounts up to 7.31%, with the highest helium concentrations in Jurassic sandstone reservoirs on the crest of the Harley Dome structure in east-central Utah. Although Utah helium prospects have been documented since the early 20th century, recent renewed interest of several upstream helium exploration and production companies has brought attention back to the helium potential of eastern Utah. With several high-helium gas plays and natural gas wells with associated helium concentrations above the historical 0.30% economic threshold, Utah deserves the consideration of those interested in exploring for and producing helium.

INTRODUCTION

Helium (He) is a colorless, odorless, chemically inert element of the noble gas family with two stable isotopes: the lighter, rarer primordial helium-3 (^{3}He) and the heavier, more common radiogenic helium-4 (^{4}He) that has historically been a byproduct of natural gas production (figure 1) (Anderson, 1998; Gilfillan and others, 2008). The unique properties of helium (e.g., inert, non-toxic, lighter-than-air, ultra-cool liquid temperature, and small molecular size) make it an element that can be used in a variety of high-tech commercial, industrial, medical, defense, and research applications as both a liquid and a gas (National Research Council, 2010). Demand for helium is outstripping production (figure 2) and helium prices will likely be high and demand strong for the foreseeable future. A sequence of global helium shortages over the past decade has occurred as the manager of the single most important depository of crude helium in the world, the U.S. government (Pacheco and Ali, 2008), exits the helium business. Shortages are also due to fragile overseas supply lines and known depletion of U.S. helium-bearing natural gas fields (Bahl, 2019; Brown, 2019), which have prompted exploration companies to explore for helium-rich gas outside of proven natural gas productive areas (plate 1). Such supply and demand driven exploration activities, coupled with continuous declines in natural gas prices, challenge the notion that production of helium is only driven by the demand for natural gas (National Research Council, 2000, 2010).

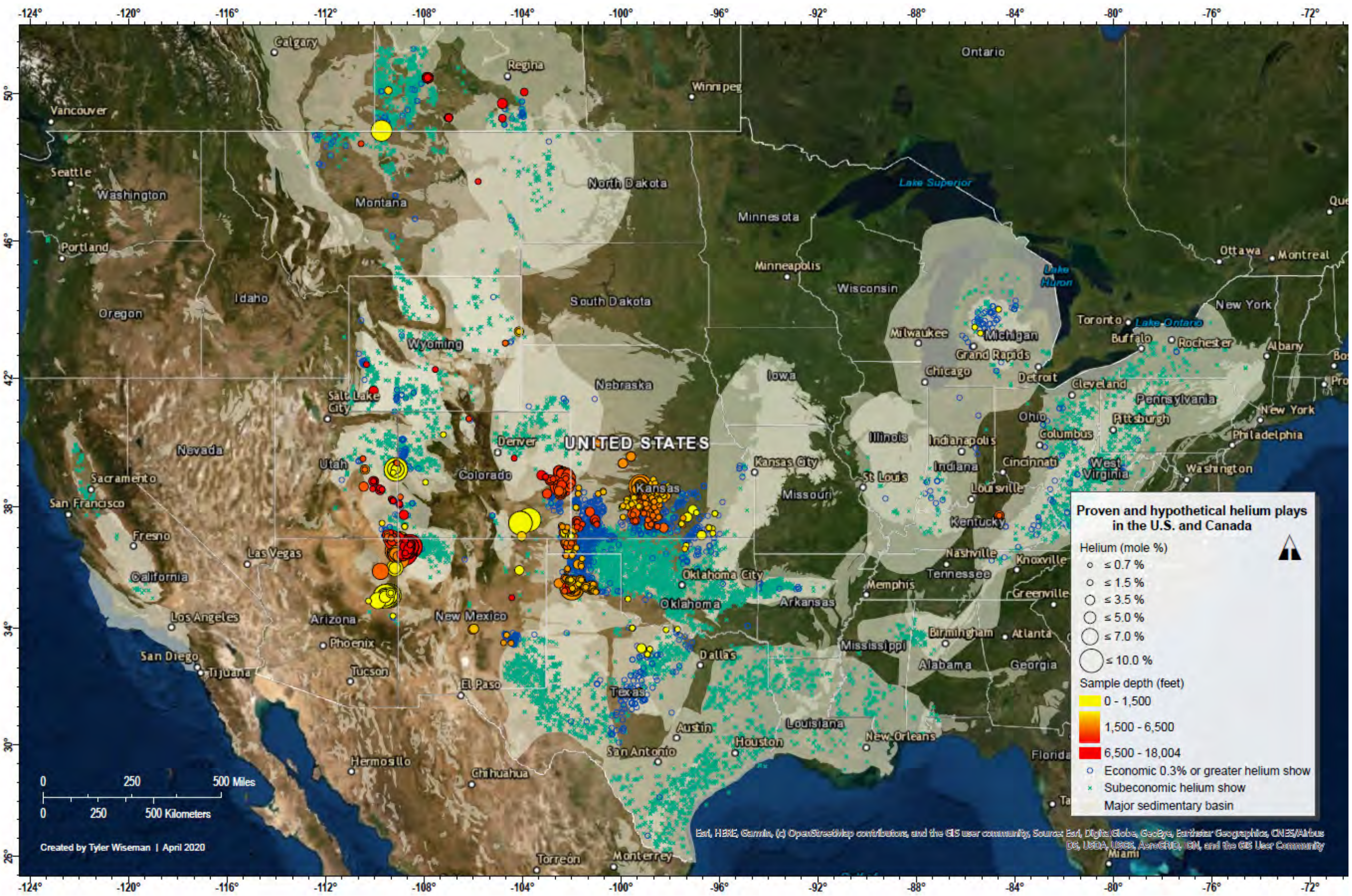

Figure 1. Helium trends and basin distribution in the contiguous United States and Canada. Graduated symbol map illustrating documented helium-rich natural gas concentrations vs. sample depth.

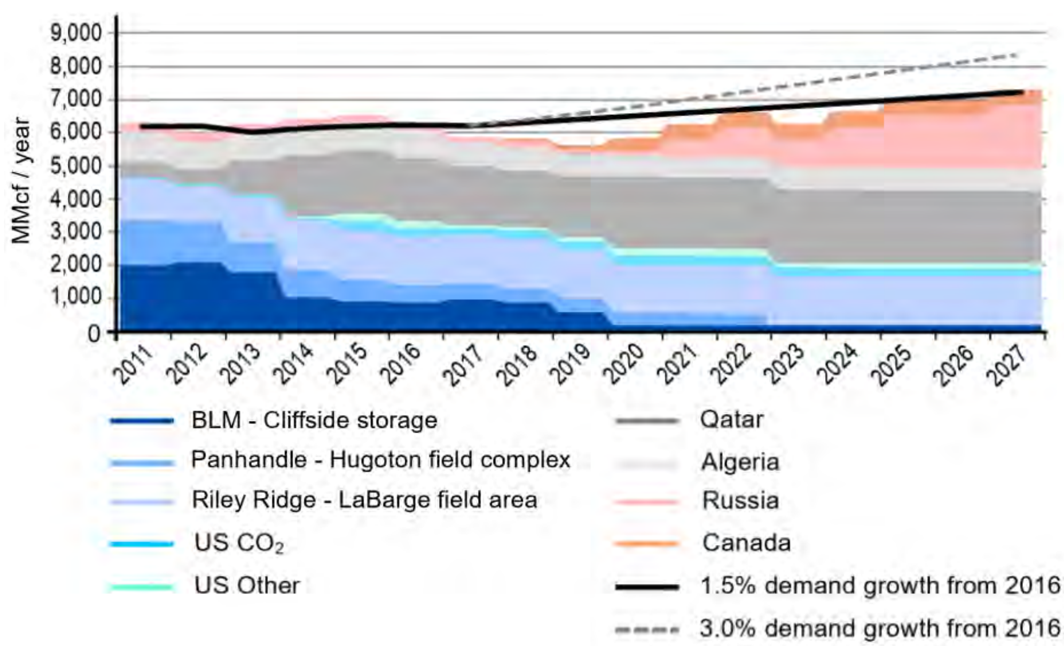

Figure 2. Estimated global helium supply vs. demand forecast modified from Bahl (2019). Currently operated by the BLM, the Federal Helium Reserve was commissioned at the Bush Dome near Amarillo, Texas in 1967 following the 1960 amendments to the Helium Conservation Act of 1925. The Act enabled the U.S. government to monopolize the helium industry by controlling production, refining, and storage of the gas. The 3.0% increase in demand from 2016 correlates with the depletion of stored helium in the Federal Helium Reserve, depletion of domestic helium-rich natural gas fields, subeconomic natural gas prices, and fragile overseas supply lines. According to Bahl (2019) the less dramatic 1.5% demand growth from 2016 is more likely as new, but limited, sources of supply from Eastern Europe ramp up helium production.

With low natural gas prices continuing for the foreseeable future, the high value of helium ($210 average per Mcf for grade-A gaseous helium as of federal fiscal year 2018) found in the gas stream may offset the economic impact of low natural gas prices and high operational cost (U.S. Geological Survey, 2019, 2020). Therefore, the helium content of a gas stream can be significant. Historically, a volume concentration of helium found in a gas stream in excess of 0.30 mol% (hereafter referred to as %) has been considered a potential helium resource (figure 1). Recent work by Grynia and Griffin (2016) suggests that a gas stream helium concentration greater than 0.50% is necessary for economic production outside of federal helium pipeline access. Concentrations in excess of 7.0% He are significantly rare yet have been discovered and documented in the gas stream of wells drilled on the northwestern flank of the Uncompahgre uplift on the Harley Dome structure located in east-central Utah (plate 1).

Since 1917, gas samples from oil and gas wells and natural gas pipelines throughout the United States have been collected for the Federal Helium Program by the U.S. Bureau of Mines (USBM; now U.S. Bureau of Land Management [BLM]) in a continuing search for helium occurrences. This responsibility was charged to the USBM for ensuring a continued supply of helium to meet essential government needs and future demands (Rogers, 1921). In the 1930s, the federal government monopolized the production of helium after securing production facilities in eastern Colorado, Kansas, and Texas. Since 1962, the BLM has maintained the only significant long-term, large-scale storage facility and pipeline for crude helium in the world within the Panhandle-Hugoton gas field complex spanning southwest Kansas, northwest Oklahoma, and the panhandle of Texas (figures 3 and 4) (National Research Council, 2000, 2010; Anderson, 2017).

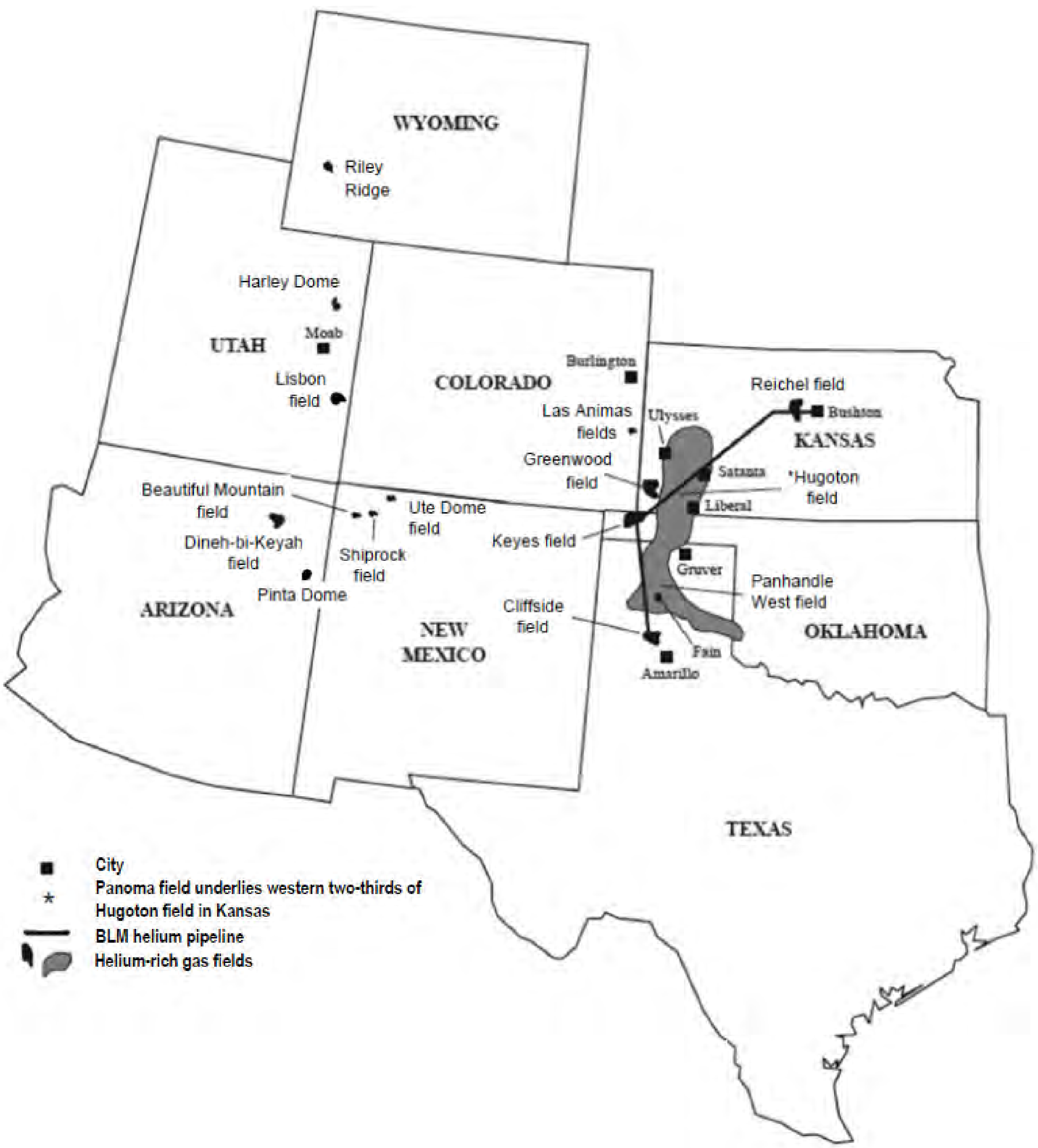

Figure 3. *Major helium-bearing natural gas fields in the United States. Modified from Grynia and Griffin (2016).*

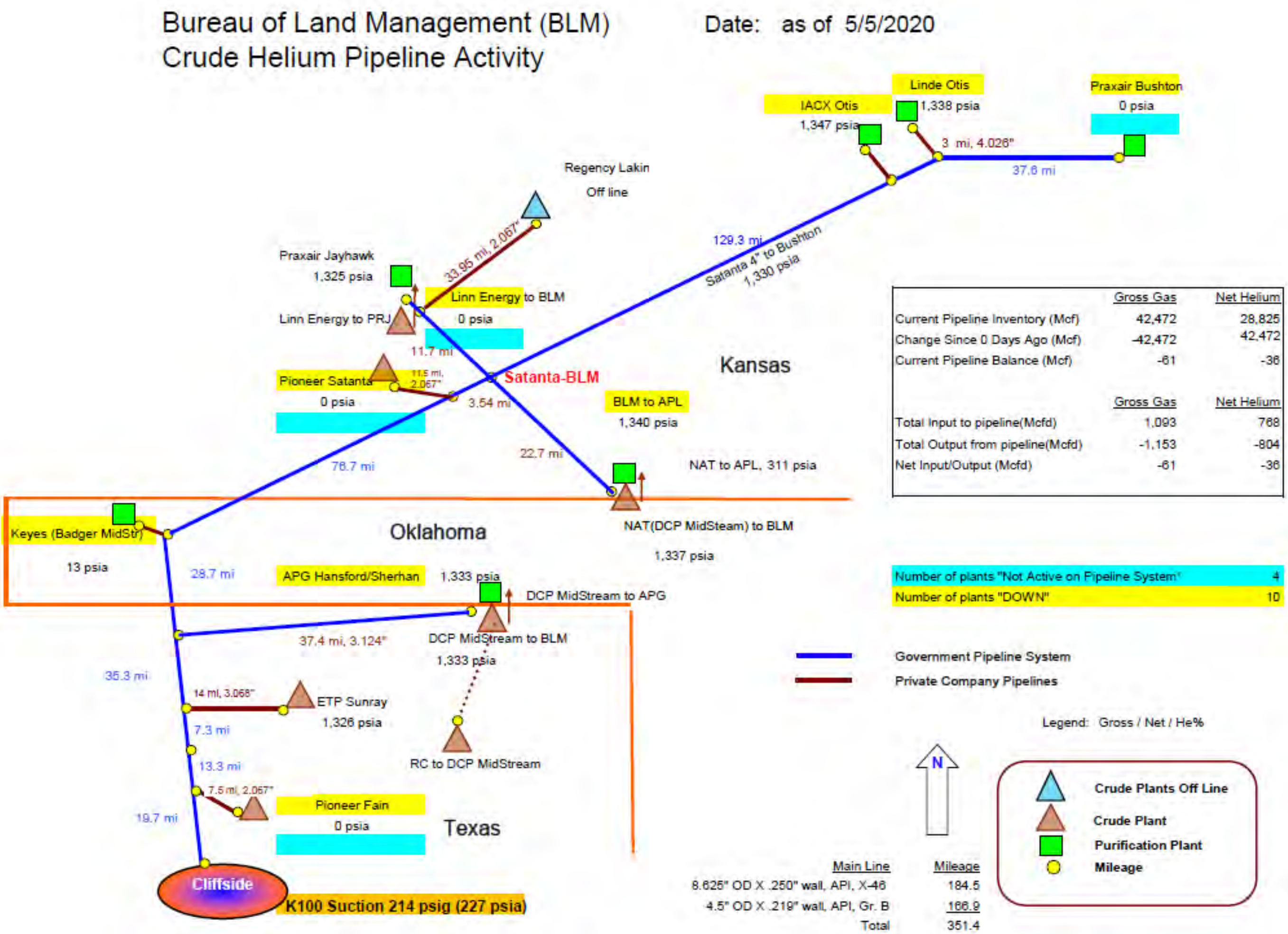

Figure 4. *Area reference map for the Panhandle-Hugoton gas field complex, which spans the Texas and Oklahoma panhandle and stretches into central Kansas. Emphasis is on infrastructure associated with the BLM's Federal Helium Program as of May 5, 2020. At the time of this report, the Cliffside (Bush Dome) depleted gas reservoir is the only long-term and large-scale crude helium storage facility in the world. Modified from the BLM's Federal Helium Program website: https://www.blm.gov/programs/energy-and-minerals/helium/federal-helium-operations.*

Helium Migration

Although helium is the second-most abundant element in the universe, it is extremely rare on Earth. Our atmosphere contains ~5 ppm (Prinzhofer, 2013), and even though helium is present in most natural gas reservoirs, most hydrocarbon gases (natural gases) have low helium concentrations (Yurkowski, 2016). Some natural gases have high helium concentrations, and these are potential economic resources (figure 1).

Like a petroleum system, helium occurrence in natural gas is governed by predictable processes of generation, migration, and entrapment. The helium system differs from the petroleum system in terms of source rock, and hydrodynamics are of much greater importance (figures 5 and 6) (Brown, 2010; Prinzhofer, 2013). Helium is generated from all rocks at a slow rate (Keevil, 1940, 1943), and generation of economic quantities of helium typically requires tens to hundreds of million years (figure 7) (Brown, 2010). Helium is roughly half the size of a methane molecule and the lightest rare gas, which means it can diffuse and move more easily than other natural gases (Sugisaki, 1987). This requires a more effective seal to trap helium in a reservoir than is required for hydrocarbons (Yurkowski, 2016). The Colorado Plateau is favorable for occurrence of high-helium gas due to the old age of the rocks, active hydrodynamics to help helium migrate to gas, recent tectonic reactivation that may aid helium release by mineral recrystallization and faster diffusion, thick deposits of salt and bedded anhydrite, and a large number of potential migration pathways and trapping geometries (figures 8 and 9) (Rogers, 1921; Casey, 1983; Anderson, 2007; Brown, 2010, 2019). In certain areas near the Four Corners of the Colorado Plateau mantle degassing may concentrate high helium gas (Brown, 2010).

Most helium on Earth is radiogenic (Zartman and others, 1961), although a small fraction may be of primordial origin (Ballentine and Burnard, 2002). Most of Earth's helium-3 (^{3}He) is primordial, and it comes from the mantle (Anderson, 1998, 2007). Gases with unusually high ^{3}He/^{4}He ratios typi-

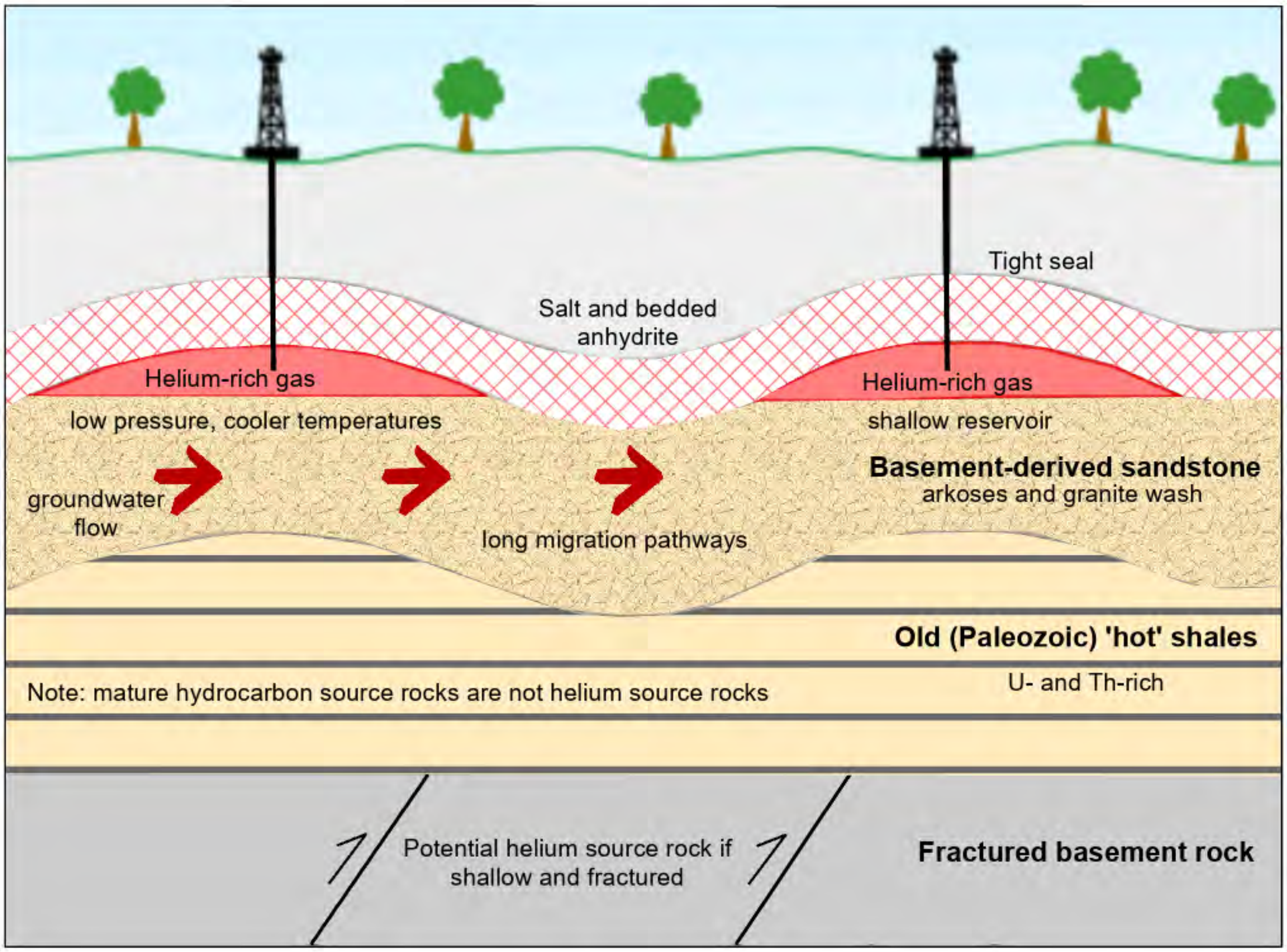

Figure 5. *Diagrammatic cross section of a generalized helium system highlighting potential source rocks, modes of migration, and an effective conventional trap. In general, helium will have had more time to accumulate economic concentrations in older rocks, however, the age of the rock itself is trivial compared to the age of the pore water. Typical generation rates are low for all rocks, especially in higher porosity sandstones. Old (Paleozoic-age) shales have the highest potential to be helium source rocks, followed by granitic basement rock. Their higher than average uranium and thorium content and low porosity favor a higher rate of helium generation. Regardless of source rock, large rock volumes, favorable hydrodynamics, and long geological time is required to generate economic amounts of helium. Helium fractionates into the gas phase easier in shallow, cooler, and underpressured reservoirs with higher salinity formation water.*

cally have a lower total helium concentration below that which is considered economic. Thus, most helium-3 is produced along with helium-4 (^{4}He) (Ballentine and Burnard, 2002).

Helium exploration means exploring for economic concentrations of radiogenic helium in natural gas. Generation of radiogenic helium-4 occurs in the subsurface over significant geological time as the alpha decay product of uranium (U) and thorium (Th). Typical rocks enriched in uranium and thorium include granites; other alkaline crystalline basement rocks; mudrocks, specifically black shales with a predominant humic component; arkoses; and granite wash (Rogers, 1921; Bell and others, 1940; Keevil, 1943; Swanson, 1960; Zartman and others, 1961; Brown, 2010; Craddock and others, 2017). The source rocks with the largest potential for helium generation are crystalline basement rocks, including granites, and old (Paleozoic) mudrocks, and granite washes (figure 5). Impurities from radioactive mineral grains in dirty carbonates and sandstones can promote significant helium generation, but clean limestones, dolomites, and sandstones are typically low in radioactive material (Bell and others, 1940; Swanson, 1960), and are consequently low helium generators (figure 7). As U and Th decay to lead (Pb), each alpha particle produced becomes a stable helium atom (Keevil, 1943; Ward and Pierce, 1973; Ballentine and Burnard, 2002):

$$^{238}U \rightarrow (8)^4He + {}^{206}Pb$$

$$^{235}U \rightarrow (7)^4He + {}^{207}Pb$$

$$^{232}Th \rightarrow (6)^4He + {}^{208}Pb$$

Long helium generation duration and large rock volumes are necessary to generate potentially economic quantities of helium, regardless of the type of helium source rock. Typically, Paleozoic rocks are more likely to generate and accumulate economic amounts of helium compared to younger rocks because of the long generation rates for helium (figure 7). Porosity and

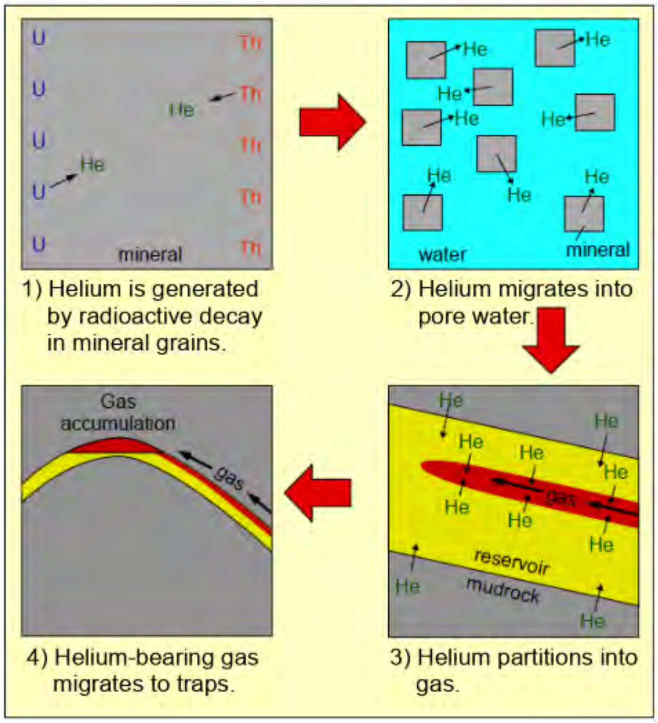

Figure 6. *Generalized helium system modified from Brown (2010). Radiogenic helium-4 (^{4}He) is generated in solid mineral grains enriched in uranium (U) and thorium (Th) and released through alpha decay. Mineral recrystallization and diffusion transfers helium into pore water where it concentrates given sufficient time and a large source rock volume. Helium will partition from water to a gas at initial contact. This could include migrating gas that sweeps helium from old pore water, or helium-rich water migrating via advection that contacts trapped gas. Once incorporated into the gas phase, helium will migrate updip through carrier beds and accumulate beneath effective trapping mechanisms the same way as conventional natural gas.*

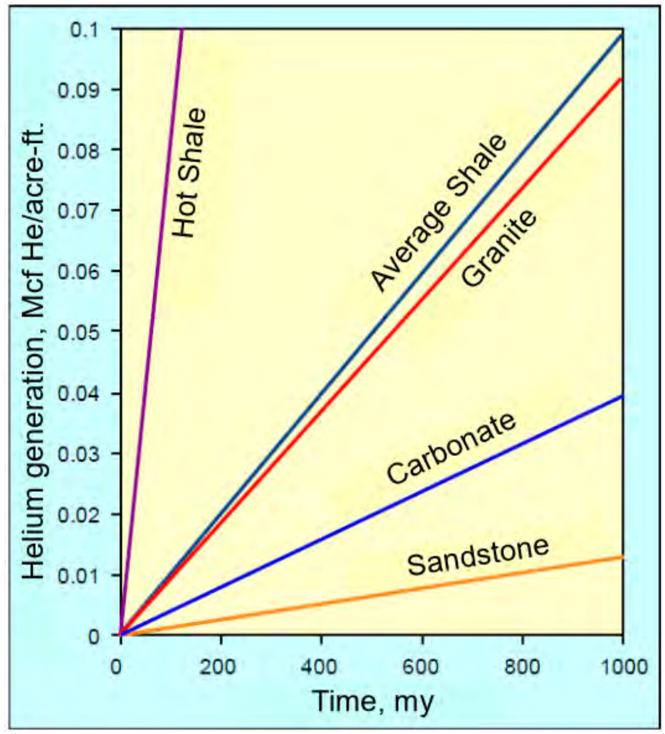

Figure 7. *Typical generation rates for helium in average rocks modified from Brown (2010). Black "hot" shales can contain significantly higher concentrations of uranium than other typical rock types (~8x higher than average shale), which can make them potential helium source rocks given a large rock volume and significant geological time. Average shales and granites have a nearly linear generation rate vs. time, whereas average carbonates and sandstones require significantly more time to generate the same amount of helium in the subsurface. This graph from Brown (2010) does not imply that unconventional shale plays should target or expect helium to be a major component of the gas stream because the hydrocarbon gases dilute helium to subeconomic levels. Similarly, many of the shale plays in the United States are too young to have generated significant concentrations of helium. Under the right conditions, some sedimentary and basement rocks may have a similar helium source potential.*

water saturation controls on helium concentration may also favor older source rocks because helium concentrates more effectively in less water where total porosity is low (Brown, 2010). For accumulation of economic amounts of helium, the age of the host rock is less important than the complex accumulation history and age of the old (Paleozoic), helium-charged water interacting with a gas phase (Zartman and others, 1961; Brown, 2010). More helium will partition to gas in shallow, underpressured reservoirs rather than deep reservoirs (Brown, 2010, 2019). Higher salinity and cooler temperatures also promote helium gas phase partitioning (Sugisaki, 1987, Brown, 2010; Yurkowski, 2016). Thus, younger (Mesozoic) reservoirs may also accumulate economic amounts of helium through gas migration given a favorable hydrodynamic system and effective shallow trapping mechanism.

Distribution of helium-rich gas accumulations is the result of a four-step process as described by Brown (2010). (1) Through the alpha decay of uranium and thorium, helium is initially released from the mineral grains within which it was generated (figure 6). (2) Following initial creation, helium transfers to and accumulates within pore water by mineral recrystallization and diffusion or becomes entrained within migrating groundwater via advection. Given sufficient time and large enough source rock volumes helium can become concentrated in the water (figure 10, A). (3) As soon as the helium-enriched water encounters a gas, either through migrating gas and stagnant helium-rich pore water or migrating helium-rich groundwater and trapped gas (figure 10, B), helium will partition out of the liquid and into the gas. (4) Like conventional natural gas, the helium-bearing gas migrates through carrier beds and permeable pathways until trapped by conventional mechanisms (Ballentine and Burnard, 2002; Brown, 2010; Ellis, 2019).

Helium on the Colorado Plateau

Non-hydrocarbon gases on the Colorado Plateau have been extensively researched (e.g., Dane, 1935; Zartman and others, 1961; Picard and Holland, 1962; Cappa and Rice, 1995; Allis and others, 2001, 2003; Rauzi, 2003; Broadhead, 2005;

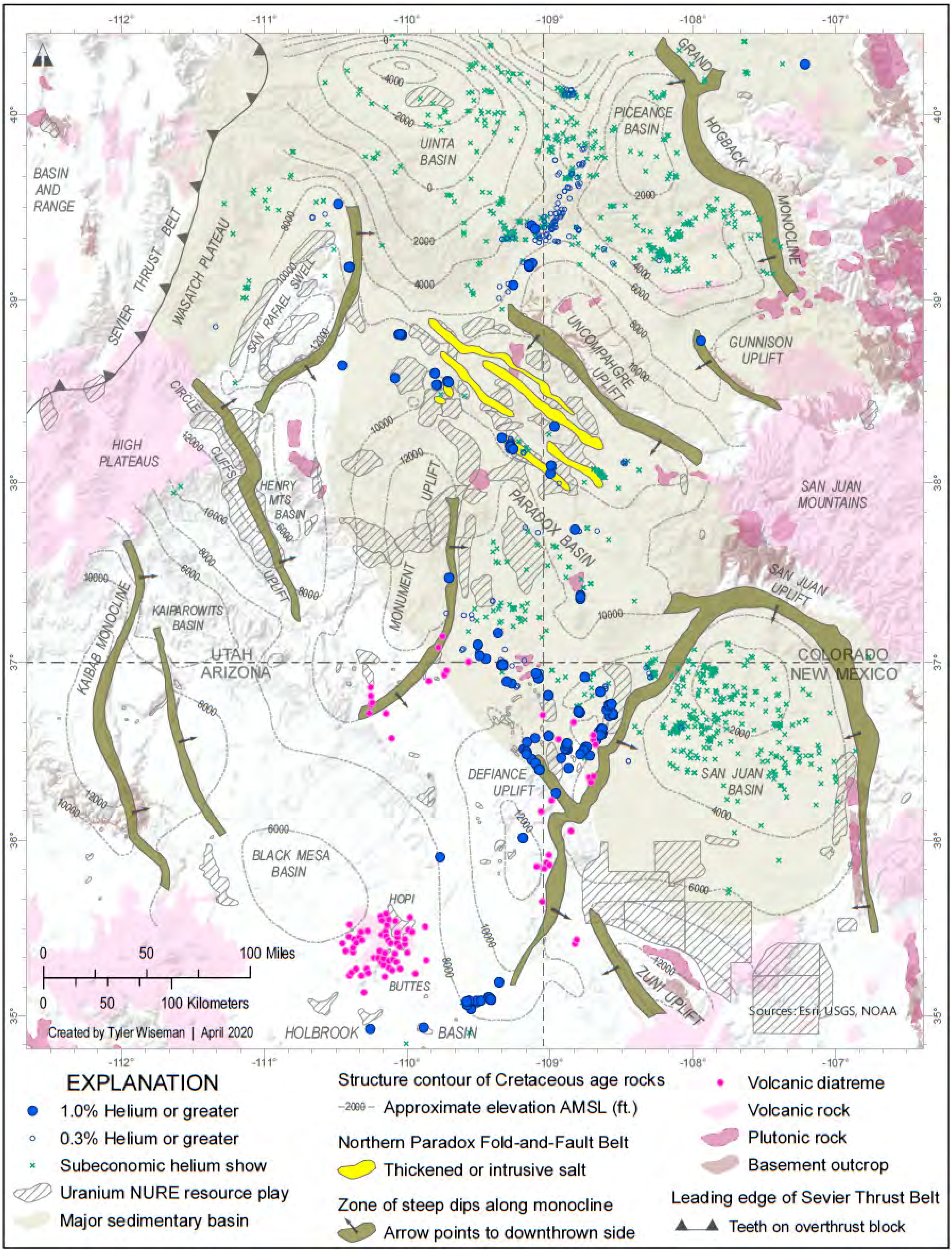

Figure 8. *General area and structural contour map of Cretaceous age rocks on the Colorado Plateau. Modeled after Shoemaker (1955).*

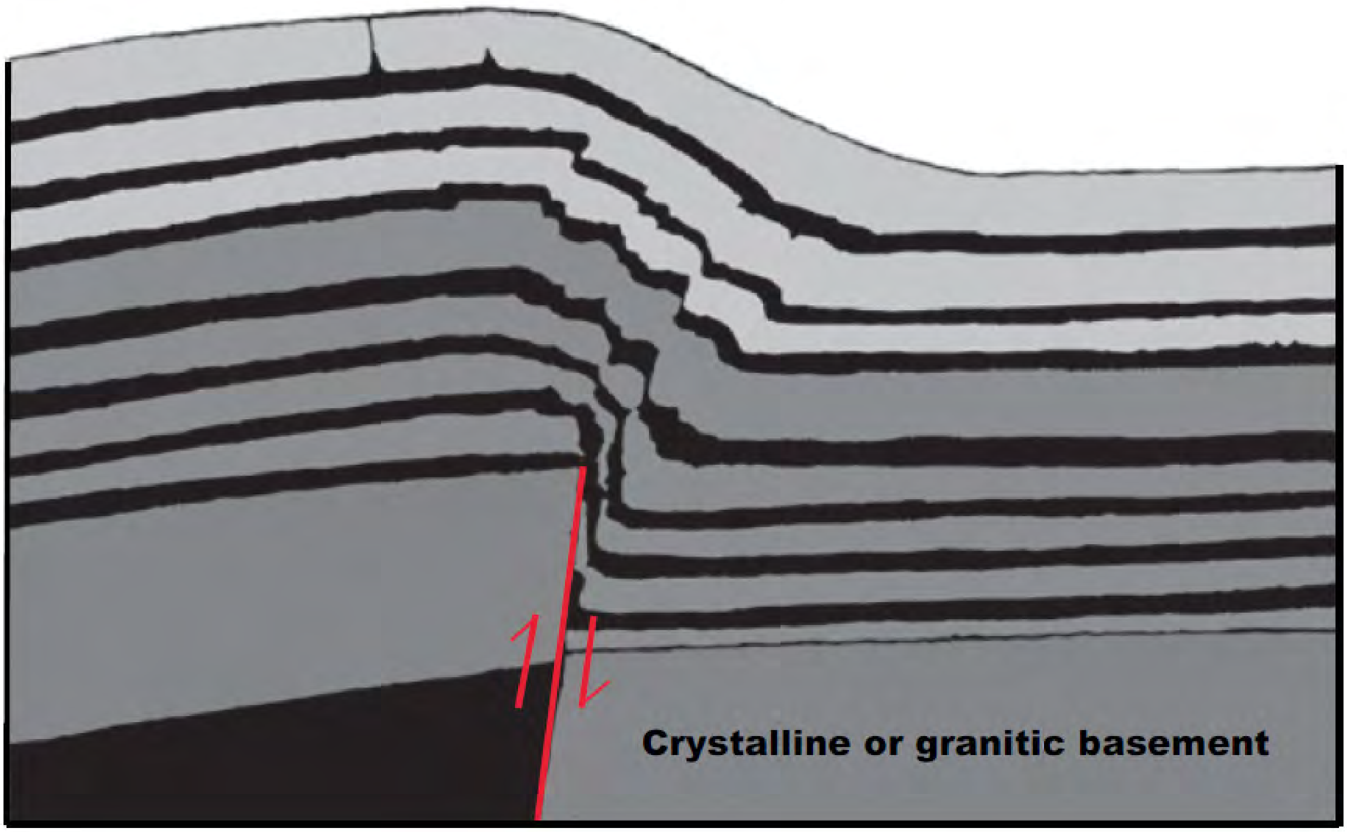

Figure 9. *Experimental simulation of the relationship of monoclines to faulted basement rock produced by compressional end-loading. Modified from Davis and Bump (2009). Typical Laramide-style tectonics on the Colorado Plateau produced steep-sided fault-propagation folds which resulted in multiple "uplifts" with a relatively gentle slope on one limb while the other limb underwent severe deformation in both the basement and the sedimentary layers above.*

Gilfillan, 2006; Gilfillan and others, 2008; Pacheco and Ali, 2008; Heath and others, 2009; Brown, 2010; Craddock and others, 2017; Halford, 2018). Many authors note a strong helium to nitrogen (N_2) correlation. Compared to helium, nitrogen may have many additional organic and inorganic contributing sources including: the atmosphere, meteoric water, ammonium released from clays by cation exchange with formation water, terrestrial coal, organic marine, and metasedimentary settings, as well as from nitrogen found in weathered igneous rock (Chamberlin, 1908; Zartman and others, 1961; Holloway and Dahlgren, 2002; Brown, 2017, 2019). Some nitrogen-rich gases may have a deep-crustal, igneous and/or metasedimentary origin (Jenden and Kaplan, 1989). In contrast, Holloway and Dahlgren (2002) discuss a significant increase in nitrogen concentration from granites to sedimentary rocks, fundamentally due to large accumulations of hydrocarbons.

The abundant carbon dioxide (CO_2) gas found on and around the Colorado Plateau (figure 11) and Rocky Mountain regions (Allis and others, 2001, 2003; Gilfillan, 2006; Gilfillan and others, 2008; Heath and others, 2009; Toner and others, 2019), specifically within Paleozoic reservoirs (Picard and Holland, 1962; Cappa and Rice, 1995), may originate from multiple sources including: Precambrian basement, inorganic Laramide-induced magmatism (e.g., mantle degassing, diagenesis, and thermal decomposition of carbonate rock by contact and regional metamorphism), and/or the product of organic processes, such as hydrocarbon maturation or biodegradation of organic matter, associated with the depositional environment (Chamberlin, 1908; Picard and Holland, 1962; Cappa and Rice, 1995; Jenden and Kaplan, 1989; Gilfillan and others 2008; Heath and others, 2009; Brown, 2010 ; Ellis, 2019). Acidic gases found at depth within the central Colorado Plateau have been largely generated by bacterial and thermal sulfate reduction (TSR) associated with maximum burial during the Late Cretaceous and early Tertiary in the Paradox Basin (Nuccio and Condon, 1996; Seneshen and others, 2010). TSR can effectively destroy or significantly decrease hydrocarbon concentrations through chemical reaction (Ellis, 2019). The high concentrations of CO_2 in the gas stream of wells drilled into the Mississippian Leadville Limestone reservoir near more recent volcanic intrusions may favor a volcanic origin by thermal decomposition of carbonate rock rather than a primary mantle source (Brown, 2010), although mantle degassing may be equally significant in certain areas around the Four Corners (Gilfillan, 2006; Craddock and others, 2017).

Laramide-age upwarps, basement-involved monoclines, and laccolithic intrusions are defining characteristics of southeast-

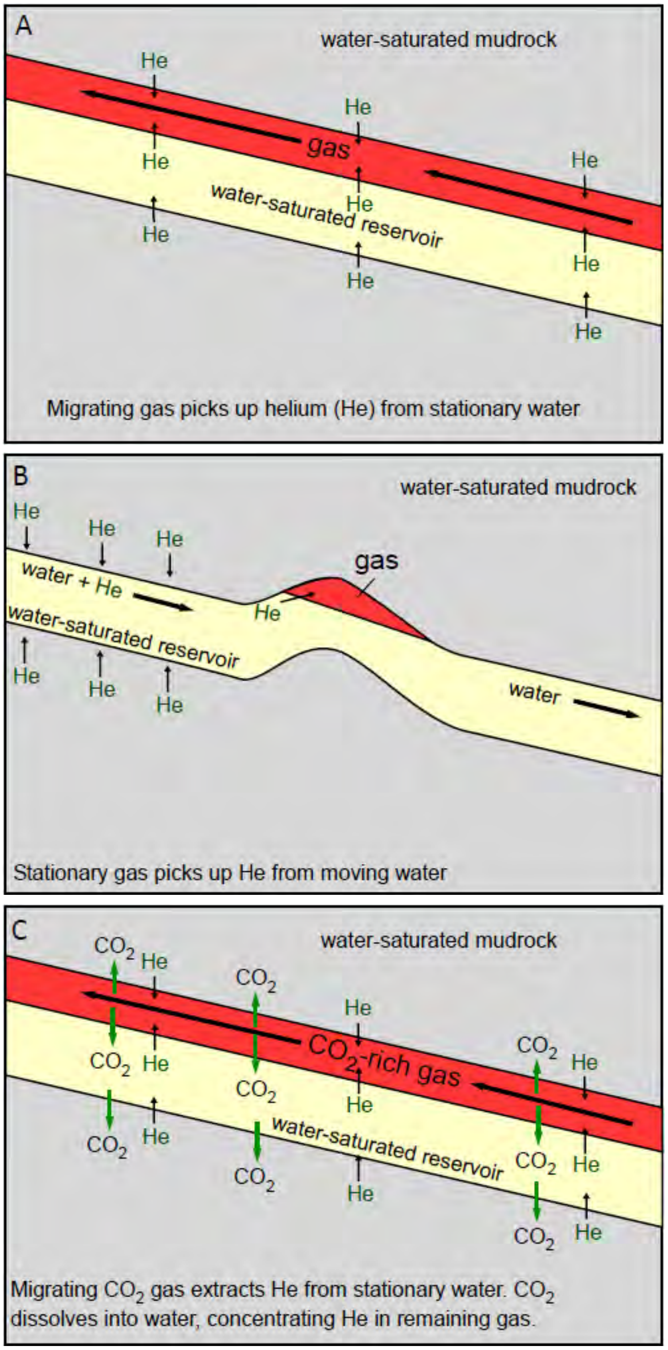

Figure 10. *Typical helium migration models from Brown (2010). Model* ***(A)*** *illustrates that as gas migrates through a water-saturated reservoir that has accumulated high helium concentrations from the surrounding rocks it strips the helium from the immobile water. This type of model has been suggested to account for the high-helium gas found in Central Kansas. Alternatively, model* ***(B)*** *shows how a stationary gas accumulation can gain helium by interacting with moving water with a high dissolved helium content. The helium-rich gas found in the Panhandle-Hugoton gas complex of Texas, Oklahoma, and Kansas demonstrates this type of modeling. Model* ***(C)*** *demonstrates how a carbon dioxide-rich gas strips helium and other gases dissolved in pore water as it migrates. As migration continues, the total gas volume decreases as carbon dioxide dissolves into pore water and reacts with minerals, leaving a gas rich in inert gases, and trace hydrocarbons. This model best represents the occurrence of high-helium gas found throughout the Colorado Plateau.*

ern Utah and much of the Colorado Plateau (figure 8) (Conley and Giardina, 1979; Baars and Stevenson, 1981; Karlstrom and Humphreys, 1998; Davis and Bump, 2009). The relationship of Laramide-style monoclines to faulted basement rock (figure 9) not only created multiple avenues for helium to migrate along fracture planes, but also deformed the upper section of basement so severely that the helium retained in the mineral grains (Keevil, 1941; Zartman and others, 1961) was likely expelled. Rejuvenations of tectonic activity along major structures (figure 12) influenced local and regional episodes of rapid uplift and erosion (Baars, 1966; Condon, 1995, 1997), which caused changes in reservoir pressure. As pressure dropped, gas expanded. Helium-rich gas on the Colorado Plateau reaches its peak concentration at a depth of ~1500 feet and decreases with increasing depth (Brown, 2010). Rather than suggesting that high-helium gas is correlated with age of the reservoir rock, Brown (2010) suggests that the observed age effect is related to the age of the pore water at the time of gas expansion and migration.

Short- and long-distance migration of both thermogenic and volcanogenic gases on the Colorado Plateau has charged many hydrocarbon reservoirs of different ages. Spillage from conventional traps likely further enabled the migration, commingling, and dilution of gases from distant source areas (Jenden and Kaplan, 1989; Chidsey, 2016a). Thermogenic gases migrating from source areas updip from adjacent hydrocarbon productive basins likely swept helium-bearing formations on their way to structural traps in Devonian-Jurassic reservoirs located along basin-uplift transition areas of eastern and southeastern Utah, respectively (plate 1). Although sampling bias may be significant, the predominant factor for negligible concentrations of helium found in Cretaceous-Eocene hydrocarbon productive basin centers throughout eastern Utah and the Colorado Plateau region is not the young age of the reservoir, but dilution of helium by methane generation in nearby hydrocarbon source rocks (figure 13) (Prinzhofer and Battani, 2003; Whidden and others, 2014).

According to Brown (2010), the most likely scenario for non-flammable, helium-rich gas in southeastern Utah and the Four Corners region of the Colorado Plateau is an original carbon dioxide gas that was dominated by nitrogen and helium. Generated either from degassing of the mantle or decarbonation from local hydrocarbon and carbonate source rocks (Zartman and others, 1961), CO_2-rich gas migrated updip and through migration pathways just like other natural gases. As CO_2-rich gas migrates it picks up dissolved helium (figure 10, C), nitrogen, and methane in pore water, while fractions of the CO_2 simultaneously dissolve into the water where they chemically react and are incorporated into solid minerals such as carbonates and sulfides (Brown, 2010). The farther CO_2 gas migrates from its source, or the greater the volume of the carrier bed, the less CO_2 is retained in the gas phase. This can result in a predominantly nitrogen-rich gas with a significant helium component, and only minor concentrations of hydrocarbon and acidic gases remain after long-distance migration (Cappa and Rice, 1995; Brown, 2010).

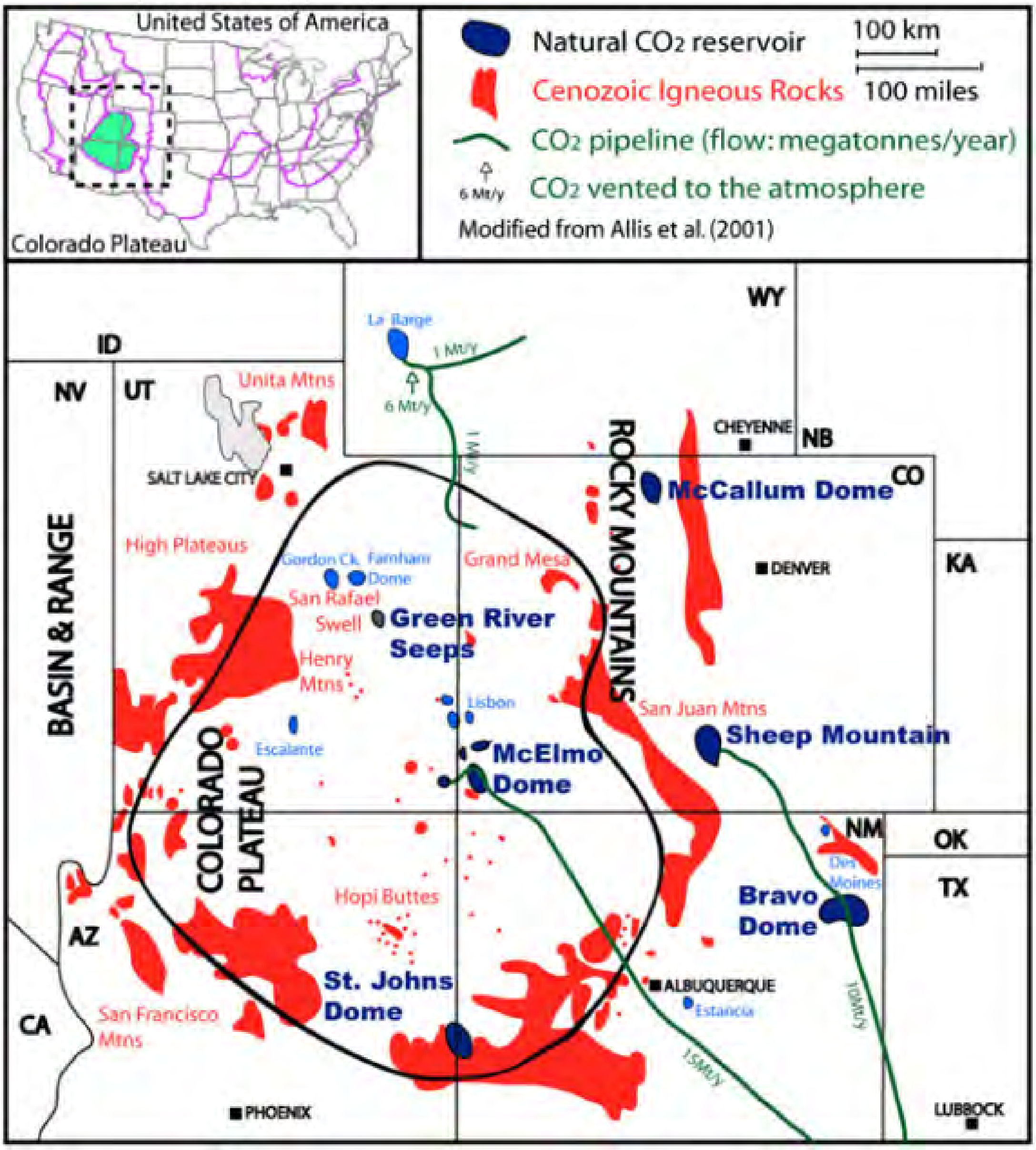

Figure 11. *Map showing natural carbon dioxide gas reservoirs and associated infrastructure from the Colorado Plateau and Rocky Mountain provinces, USA. From Gilfillan and others (2008).*

Helium Extraction and Production

At the time of this publication, only two gas processing plants have transported economic amounts of helium in Utah: (1) the 60 MMcfd Lisbon gas plant in San Juan County, and (2) the 30 MMcfd Harley Dome plant in Grand County (plate 1). Helium recovery from a natural gas stream typically involves a combination of acid gas removal, dehydration, methane liquefaction, and nitrogen rejection (figure 14) (Parker and others, 2011; Grynia and Griffin, 2016). Large-scale helium extraction and grade-A purification units (figure 15, top) are capital-intensive and require sufficiently large volumes of helium to remain economic (Anderson, 2017). Small-scale, non-cryogenic helium recovery operations employ pressure swing adsorption (PSA) units to economically extract up to 12 MMcfd of pure 99.995% He from natural gas (Grynia and Griffin, 2016). PSA units utilize high pressures and ambient temperatures, rather than low temperatures, to separate the helium from the gas stream; this allows helium exploration and production companies to pursue smaller, overlooked or bypassed helium-rich gas fields where cryogenic processing is uneconomic and pipeline access is restricted or non-existent. For this type of helium recovery unit, gas stream helium concentrations of 0.50% or more are generally required to be economic (Grynia and Griffin, 2016). The recovery and sale of helium gas at the Harley Dome plant from 2013 to 2018 by IACX Energy was made possible by the installation of a helium PSA on the southern edge of the field (figure 15, bottom).

Initially operated by Union Oil/UNOCAL and now Paradox Upstream, LLC., the Lisbon Plant (figure 16) came on-line in 1967 with substantial gas processing improvements, includ-

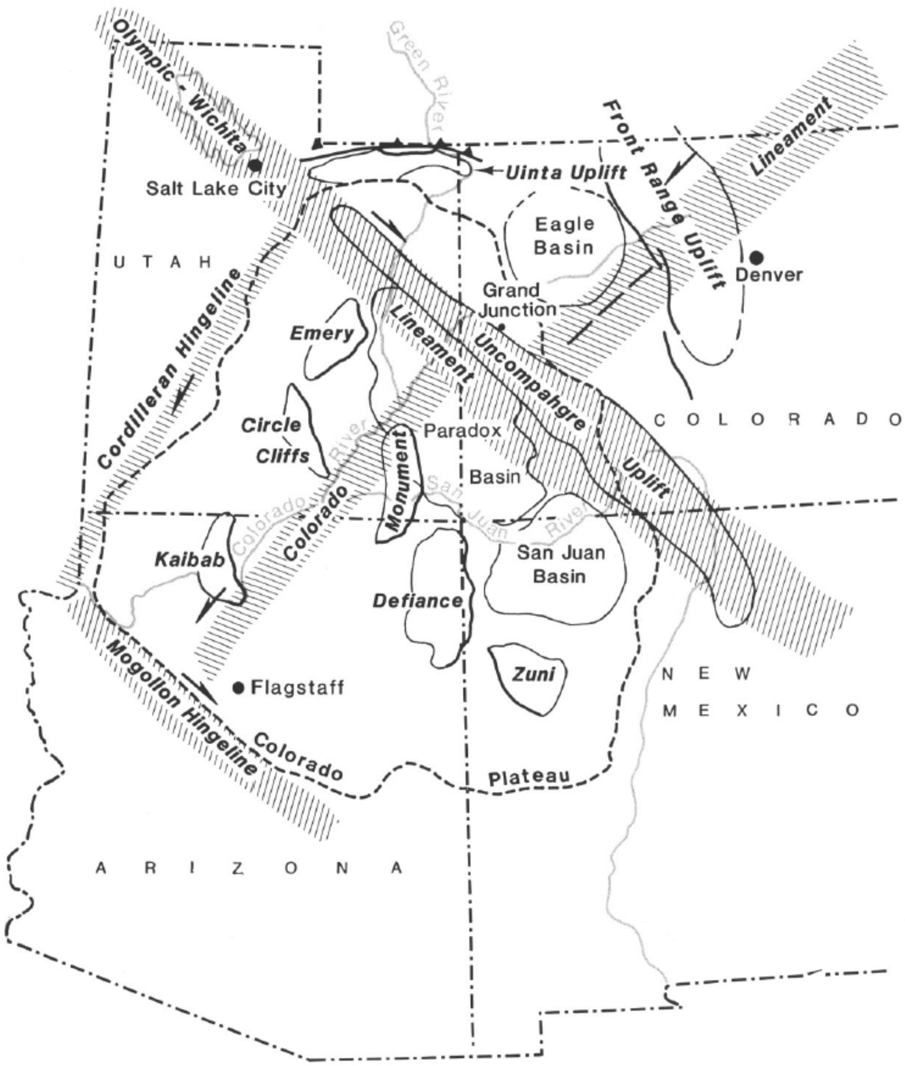

Figure 12. General location of the Colorado Plateau with emphasis on the relationship to major orthogonal set of basement lineaments and structural geometries from Baars and Stevenson (1981). Northwest-southeast lineaments are right-lateral, northeast-southwest lineaments are left-lateral.

ing the addition of a cryogenic plant and helium-recovery unit (HRU), in 1993 following a helium contract with the USBM and amendments to the unit agreement to include helium as a producible gas component (Utah Trust Lands Administration, 2019). The Lisbon plant processed, sold, and transported helium extracted from surrounding oil and gas fields by truck consistently from April 1994 to February 2011 when helium extraction was no longer economic, and the HRU was shut down. During those 17 years, the Lisbon gas plant produced 15,263,477 lbs. of helium as well as sulfur, propane, butane, ethane, and gasoline in varying amounts (Utah Division of Oil, Gas and Mining, 2020). Early 2020 press releases from Paradox Resources, LLC indicate that the Lisbon plant, and its associated HRU, is back online and selling purified helium to market.

High helium market prices coupled with advances in helium-rich natural gas extraction and purification technology will likely promote an increase in exploration of proven and hypothetical helium plays throughout the United States, primarily in the helium play fairways of the Colorado Plateau and Rocky Mountain region (U.S. Geological Survey, 2020). With the development of portable, small-scale, non-cryogenic PSA helium recovery equipment, exploitation of helium by both large and small helium producers is now possible in areas that would have otherwise been condemned. Processing of helium can be done on location and is typically transported to market as a liquid using multilayer insulated bulk liquid tankers or by tube trailers in its gaseous state (figure 15, bottom) (Reisch, 2017).

Historical Account of the Federal Helium Program

For strategic purposes, the Mineral Leasing Act of 1920 reserved all helium contained in natural gas fields on federal lands to the U.S. government (Moore, 1976). The Helium Act, also known as the Helium Conservation Act (HCA), of 1925 transferred all government-related helium activities to the USBM, enabling the federal government to dominate the helium market by controlling the production and refining of

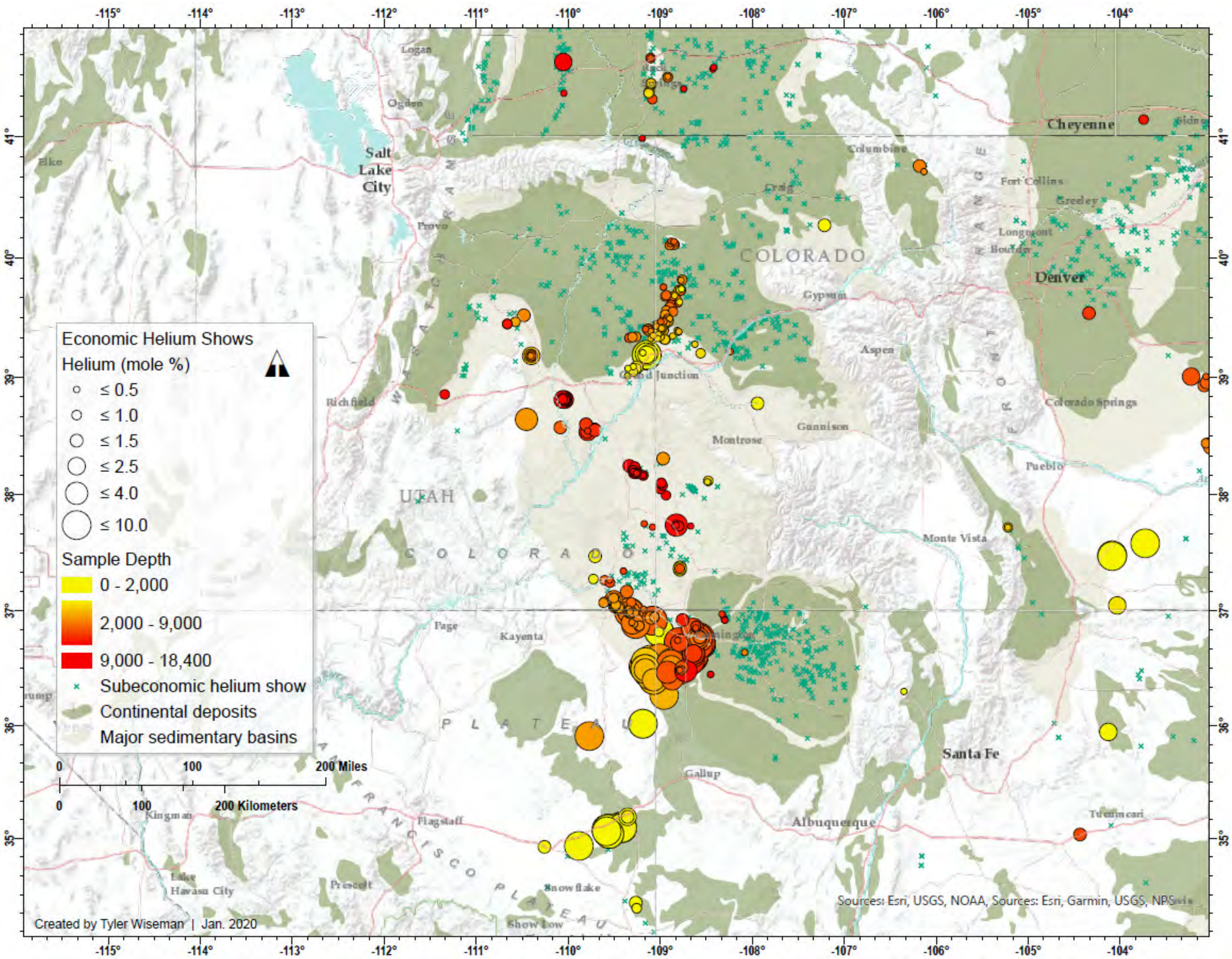

__Figure 13.__ Graduated symbol map illustrating documented high-helium gas accumulations vs. sample depth throughout the Colorado Plateau and Rocky Mountain regions. The larger the diameter of the circle, the higher helium concentration found in the sample. Warm colors represent deeper sample depths. Note that on the Colorado Plateau helium gas tends to accumulate near the margins of major petroleum systems. Significantly high helium gas seems to be found in shallow (< 2000 ft.) structural traps along basin-uplift transitional areas. Most of the helium sampled on the Colorado Plateau has been from Devonian and Mississippian reservoirs.

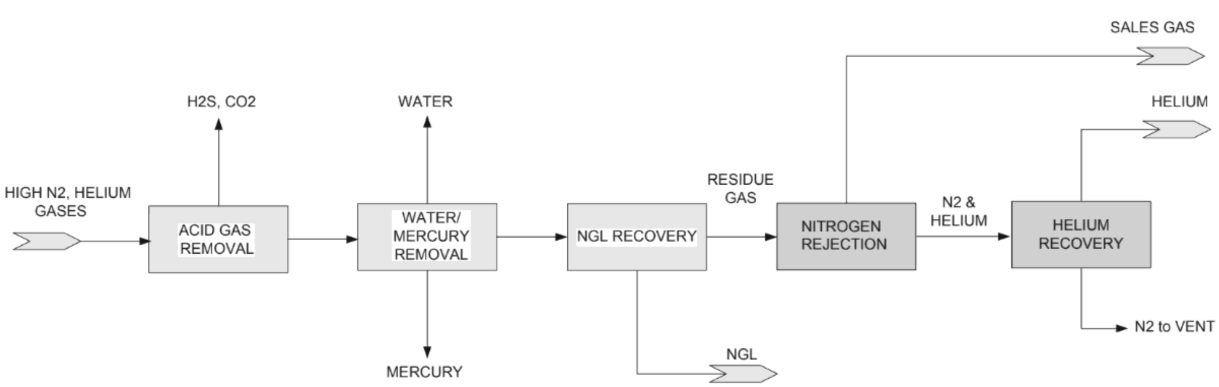

__Figure 14.__ Typical block diagram for nitrogen rejection and helium recovery from Mokhatab and others (2019). For most medium- to large-scale midstream helium operations a cryogenic plant is complimentary to the larger gas processing plant. Feed gas to the nitrogen-rejection unit (NRU) is the residue gas from the methane liquefaction (NGL) recovery unit and will typically contain ~25% N_2 and 0.5%−1.0% He, depending on the original gas stream concentration. The NRU operates at -245°F and 350 psig. The crude helium and nitrogen gas mixture is then chilled to -315°F, which effectively liquefies the nitrogen and produces a helium-rich gas stream with ~90% purity and a recovery level of 99%. Further helium purification units comprised of membrane and adsorption-based processes can significantly upgrade the helium to grade-A purity (grade 5, "five-nines," or 99.999% purity).

http://deq.wyoming.gov/isd/application-permits/resources/labarge-carbon-capture-project/

https://www.iacx.com/helium-projects/

Figure 15. *(Top) Image from Wyoming Department of Environmental Quality shows an aerial view of ExxonMobil's Shute Creek gas plant in the Riley Ridge area of southwestern Wyoming. At a depth of over 15,000 feet and with average gas compositions of 66% CO_2, 21% CH_4, 7.0% N_2, 5.0% H_2S, and 0.6% He, the LaBarge gas field project primarily captures carbon dioxide for enhanced oil recovery, but also separates methane and refines helium for sale. (Bottom) Image showing IACX's Harley Dome field helium plant in Grand County, Utah, during operations from 2013 to 2018. IACX utilized a proprietary, non-cryogenic helium recovery unit to economically extract and purify helium from the helium-rich (over 7.0% He) natural gas stream, sourced from the Jurassic Entrada Sandstone at less than 1000 feet, to over 99% purity and with minimal helium loss.*

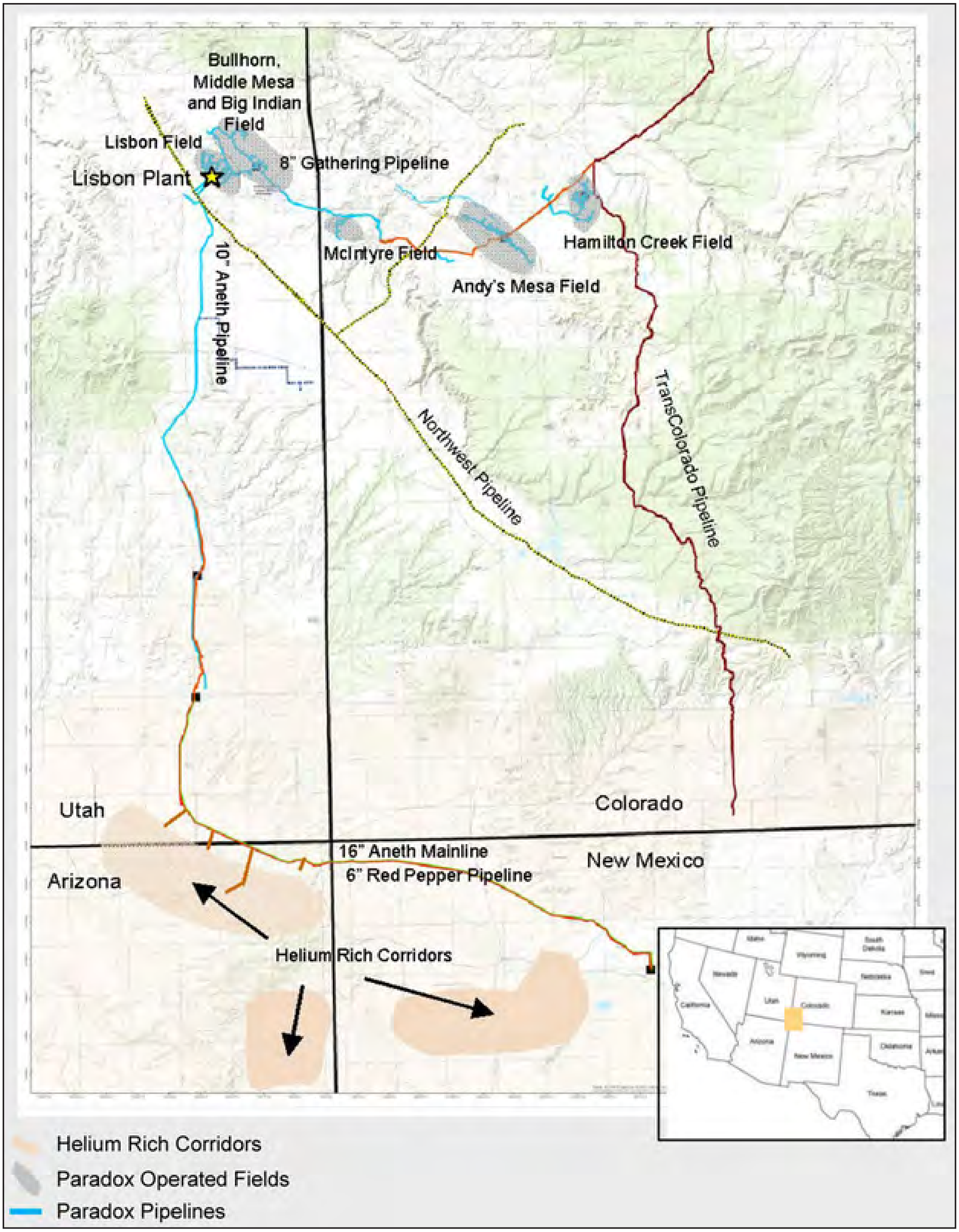

Figure 16. *The Lisbon gas plant processes pure helium from over 150 wells over ~98,000 net acres in the Paradox Basin. The gas processing plant is made up of a 60 MMcfd treating plant with a 45 MMcfd cryogenic plant and a 7500 bpd fractionation train. The helium recovery unit (HRU) is capable of 500 Mcfd at 90% recovery and purification of "five-nines" (99.999% He). The Lisbon plant is the only plant in the region capable of processing high nitrogen and carbon dioxide gas with helium purification and liquefaction capabilities. Map from Paradox Resources company website.*

the gas. Following a significant loan from the U.S. Treasury in 1960, amendments to the 1925 HCA enabled the federal government to develop Federal Helium Reserve (FHR) storage capabilities and a nearly 450-mile helium pipeline connecting central Kansas and Panhandle-Hugoton gas fields with the Cliffside (Bush Dome) depleted natural gas reservoir near Amarillo, Texas (figures 3 and 4) (National Research Council, 2000). About 1975, the federal government ended its stockpiling of helium, terminated their existing purchase agreements, and opened the Bush Dome storage reservoir for private helium storage (Massol and Rifaat, 2018).

Amid a large $1.4 billion and growing debt to the U.S. Treasury, the Helium Privatization Act of 1996 ordered the BLM to cease upgrading, refining, and marketing helium, as well as to liquidate all but 0.6 Bcf of the FHR by January 1, 2015 (National Research Council, 2000; Hamak, 2017; Massol and Rifaat, 2018). In 2013, the Federal Helium Program made a final recompense to the U.S. Treasury. To mitigate a helium shortage and industry monopolization, the Helium Stewardship Act (HSA) of 2013 mandated the federal helium stored in the Bush Dome reservoir at Cliffside to be incrementally sold at public auction until 3.0 Bcf remained in storage. The HSA also extended commercial operations of the FHR until September 30, 2021 (Anderson, 2017; Hamak, 2017). In August of 2018, the BLM conducted its fifth and final auction of the FHR (U.S. Geological Survey, 2019). In May 2018, the U.S. Geological Survey (USGS) included helium in a published report documenting the 35 most critical minerals to the nation's security and economic prosperity (Office of the Federal Register, 2018; U.S. Geological Survey, 2019, 2020). In August 2019, NAH Utah LLC, an affiliate of Canadian firm North American Helium, submitted applications to the BLM for permits to drill four remote helium test wells in Devonian and Mississippian reservoirs below the San Rafael Desert area in Emery County, Utah (plate 1) (Rocky Mountain Oil Journal, 2019).

Helium Leasing and Regulations in Utah

State of Utah oil and gas leases have always included helium gas among the leased substances. Historically, federal oil and gas leases have not. Helium produced from federal acreage is reserved for the federal government and requires a helium lease, which can be obtained through the BLM field office in Amarillo, Texas. Currently, the BLM requires 10% lessor royalty for gross sales of liquid helium and 12.5% royalty for gross sales of crude to gaseous helium with no post-production expenses.

The Helium Extraction Act of 2017 amended the Mineral Leasing Act of 1920 to include helium in a federal oil and gas lease (H.R. 3279 – Helium Extraction Act of 2017). The purpose of the bill was to ensure that extraction of helium from gas produced under a federal mineral lease would also maintain the lease as if the helium were oil or gas (Anderson, 2017; Reisch, 2017). Although privately-owned minerals do not need a helium contract with the BLM, private or fee lands commensurate with federal mineral acreage when in production, meaning that a percentage of all helium produced is considered federal helium (BLM – Federal Leased Lands Program). State-owned minerals were never subject to a federal helium sales contract. As the landowner of over 4.3 million mineral acres in Utah, the Utah School and Institutional Trust Lands Administration (SITLA) includes helium in its current oil and gas lease agreement and maintains the right to enter "other business arrangements" (OBAs) with potential lessees.

Except for the 6,038.76-acre Lisbon (Mississippian) federal unit in San Juan County, currently operated by Paradox Upstream, LLC. (figure 16), helium does not appear to be considered a "unitized substance" under the current BLM unit lease agreement. Special provisions and amendments to the federal unit agreement require BLM approval and can be obtained similar to a federal helium lease.

Although helium is an inert gas that is largely found within a nitrogen-rich, non-flammable gas stream, minor amounts of acidic gas and hydrocarbons are commingled within the gas. Methane in small concentrations ($< 15\%$ CH_4) may provide an upside in helium exploration and production because it can be used on location for power generation. A higher methane concentration would require pipelines, rights-of-way, and connections to market the excess methane gas. Carbon dioxide and hydrogen sulfide are common but minor components to a helium-rich gas stream and, following acid gas removal, are typically reinjected down the well annulus.

A few of the helium plays in Utah are within or near environmentally sensitive areas and may have little to no road access. Explorationists must be aware that obtaining BLM or private right-of-way access to certain helium prospects may be difficult.

Helium Trends in Utah and Vicinity

The evolution of the western Cordillera in eastern Utah produced a thick, stable (Davis and Bump, 2009), relatively undeformed environment with enough of the necessary ingredients to generate and accumulate economic concentrations of helium in the subsurface (figure 13). Complex hydrodynamic (figure 17), thermogenic, and volcanogenic processes and structural geometries (figure 18) within Paleozoic and Mesozoic formations at depth contribute greatly to the distribution and accumulation of helium in the subsurface (Zartman and others, 1961; Brown, 2010). Well-documented regional zones of weakness extending deep into fractured basement rock (figure 9) may provide pathways for helium microseepage to the surface (Seneshen and others, 2010; Craddock and others, 2017; Seneshen, 2018). Given tens to hundreds of million years, a source charge, old sediment with old pore water, long migration distance, an effective seal, and trap integrity, economic amounts of helium can be captured in reservoir rocks sealed by impermeable salt layers or in relatively shallow structural traps (figure 5).

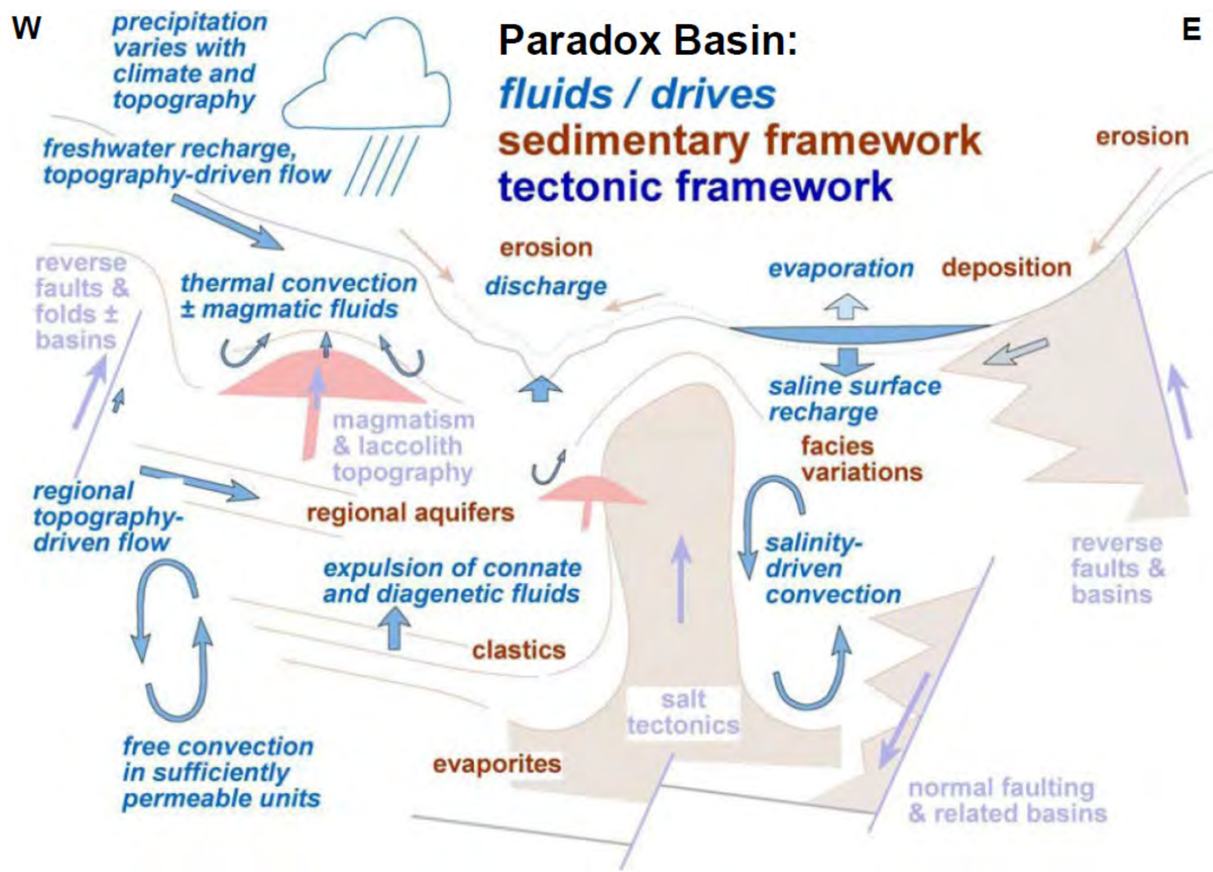

Figure 17. *Generalized cross section of fluid sources and drives for paleofluid flow in the Paradox Basin. Modified from Barton and others (2018).*

Helium-rich gas is not limited to areas of proven oil and gas production (figure 19) or reservoir rocks of a particular type or age (see appendix). In eastern Utah, helium has been predominantly documented within the northwest-trending Paradox Basin or along its margins (figure 13). Helium-bearing geologic units (figure 20) within the basin consist of Devonian through Permian calcareous sandstones, shales, and sandy carbonates below multiple layers of salt and anhydrite of the Pennsylvanian Paradox Formation (figure 18). High-helium gas is well documented in east-central Utah along the northeast margin of the Paradox Basin from shallow structural traps in underpressured Jurassic reservoirs (figure 21). Shallow traps are important in helium exploration because helium partitions into gas more efficiently at cooler temperatures found at shallow depths. Brines or higher salinity pore and groundwater may also aid in helium partitioning into a gas via groundwater migration (figure 17) (Brown, 2010).

Non-flammable, helium-rich gas concentrations have been documented in the San Rafael Desert, on the eastern flank of the basement-involved San Rafael Swell in central Utah (figure 8), in shaly dolomite beds of the Upper Devonian Elbert Formation (figure 20). High-helium gas has also been found in the overlying carbonate rock of the Mississippian Leadville Limestone. Combination trapping geometries, formed by pre-Laramide intermittent episodes of uplift with differential episodes of folding in Pennsylvanian time (Bartsch-Winkler and others, 1990), help to capture the migrating gas. Cycles of Pennsylvanian Paradox Formation salt and bedded anhydrite create an effective seal (figure 18).

In far southeastern Utah, the Boundary Butte field area on the Four Corners Platform has significant helium shows from samples taken within low-pressure, hydrodynamically complex Pennsylvanian clastic reservoirs trapped between layers of Paradox salt. In east-central Utah and western Colorado, interfingering arkosic sandstone and shale beds of the Permian Cutler Group and stratigraphically higher Mesozoic reservoirs along the western and southwestern flank of the Uncompahgre uplift have recorded similar helium concentrations, including the significant helium shows at Harley Dome (plate 1).

Helium has not been found west of the Wasatch Plateau in central Utah (figure 8), which locally recorded the eastern extent of the Sevier thrust belt and the more recent eastern margin of the Basin and Range (Wood and Chidsey, 2015). Due largely to dilution from methane generation, helium concentrations are negligible within young hydrocarbon productive basins such as the Paleogene Uinta and Piceance Basins of northeastern Utah and northwestern Colorado, respectively (figure 8). Trace amounts of helium are common in natural gas wells penetrat-

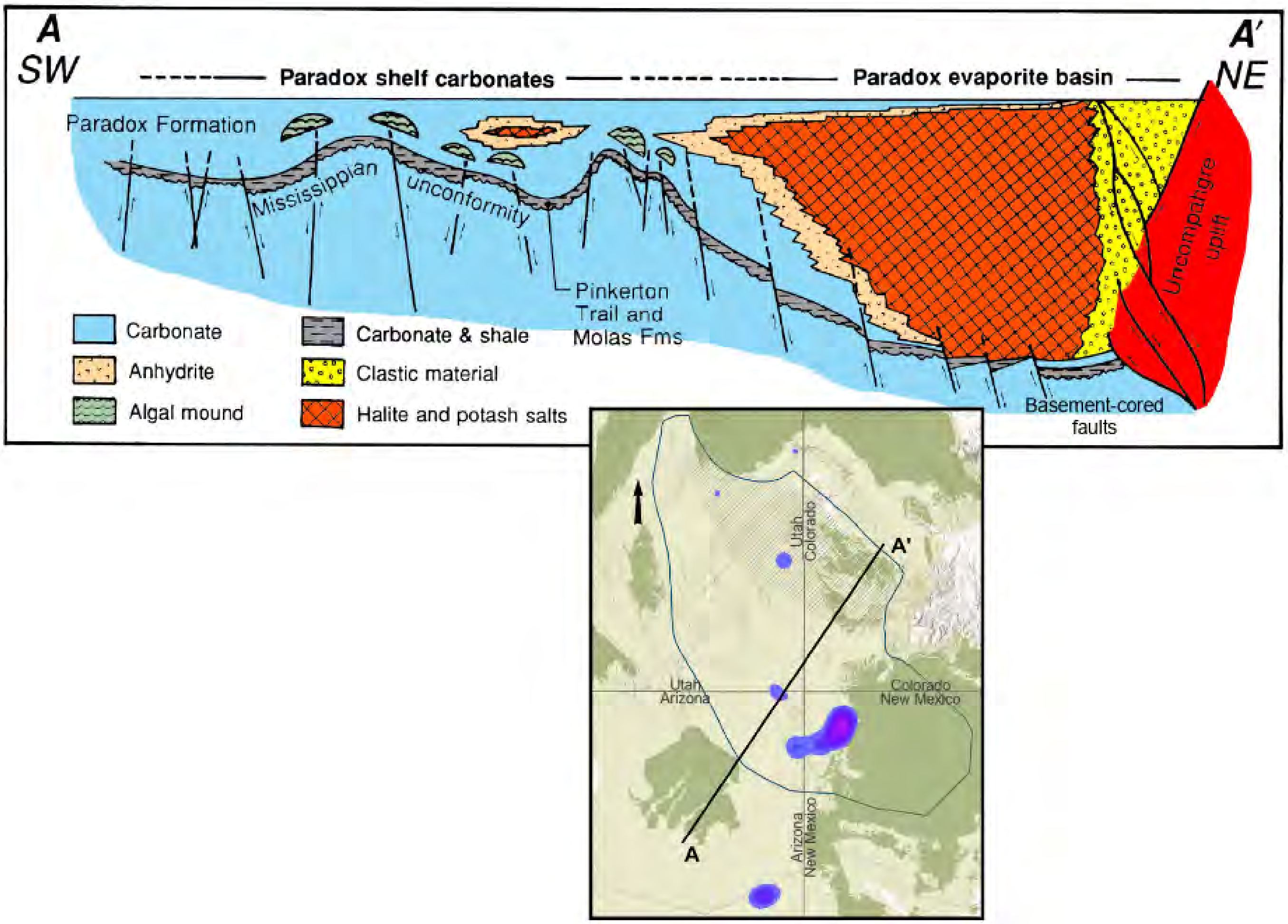

Figure 18. Southwest-to-northeast cross section of the Pennsylvanian lithofacies of the Paradox Basin modified from Chidsey (2016b) after Baars and Stevenson (1981). The structurally complex evaporative basin consists of a series of depositional cycles of siliciclastic mudstones and evaporites. Economic occurrences of helium have been recorded in proximal basin fill composed of arkosic sandstone and gravel of the Permian Cutler Formation sourced from granite wash along the flanks of the Uncompahgre uplift, where the Cutler interfingers with salt and anhydrite of the Pennsylvanian Paradox Formation. Significant helium shows are common in deeper calcareous shales, sandstones, and carbonate reservoirs of the Devonian Elbert Formation and Mississippian Leadville Limestone as well as within clastic zones of the Pennsylvanian Paradox Formation.

ing Paleozoic reservoirs with a higher Btu (British thermal unit) content. This relationship is likely associated with helium dilution from methane generation within hydrocarbon-rich zones of nearby petroleum source rocks (figure 13). Excessively higher percentage helium-rich gas (0.5%–7.0% He) is typically found in association with wells in which nitrogen and carbon dioxide are the dominant gas constituents and are separated from oil- and natural gas-producing formations by impermeable boundaries. Nitrogen-rich gases with a significant helium concentration are typically located at the margins of proven petroleum fields, whereas carbon dioxide-rich gases are commonly found near mid-Cenozoic volcanic intrusions (figure 8) at depths below hydrocarbon-rich source rocks. Both nitrogen- and carbon dioxide-rich gas streams seem to cluster near basement-cored faults and on basin-uplift transitional areas.

Helium shows in Utah range from negligible trace amounts up to 7.31% He (figure 22), with the highest concentrations on the crest of the Harley Dome structure from Jurassic reservoirs at depths around 1000 feet. Other significant helium shows (see appendix) have come from the relatively unexplored nitrogen-rich gases of Devonian-Mississippian carbonate and sandstone reservoirs primarily from the northern Paradox Basin and on the northern edge of the Four Corners platform in far southeastern Utah (plate 1). Acidic and hydrocarbon-rich gases are commingled with high-helium gas in the Lisbon area near the center of the Paradox Basin. Since typical natural gas sampling techniques do not measure for helium in the analysis, most wells that have been drilled in prospective helium play fairways were never tested specifically for helium (Grynia and Griffin, 2016). Although some of these resources have been documented since the early 20th century, recently renewed economic interest on the part of several helium exploration and production companies has brought attention back to Utah's helium potential.

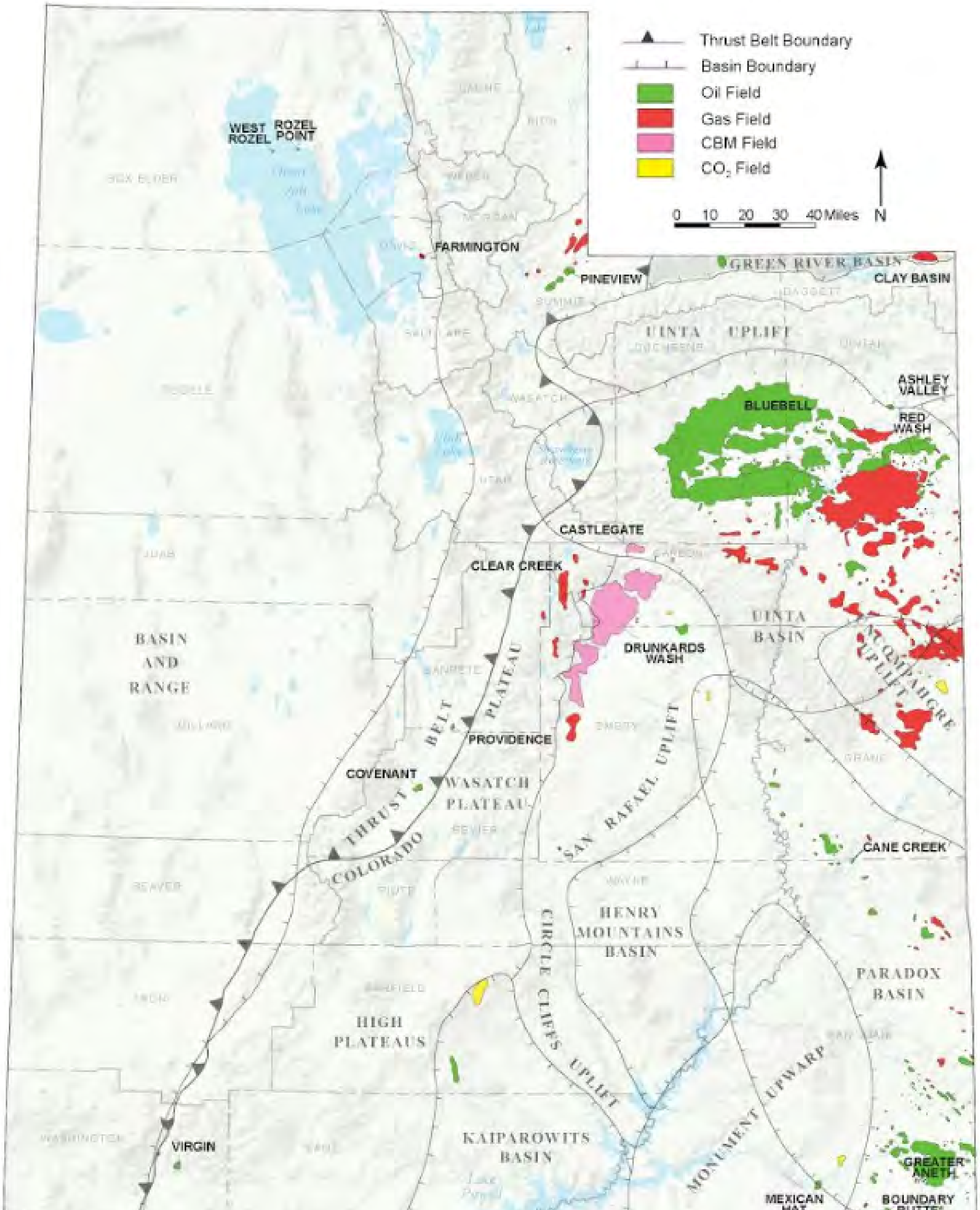

Figure 19. *Reference map illustrates the distribution of oil and gas fields and dominant structural elements specific to Utah. Modified from Wood and Chidsey (2015). Note that this map depicts the Harley Dome gas field in far east-central Utah as a carbon dioxide (CO_2) field. Gas compositions indicate that CO_2 found at Harley Dome is comparatively minor but increases to the north-northeast within the Bar X and San Arroyo gas fields that trend into Colorado.*

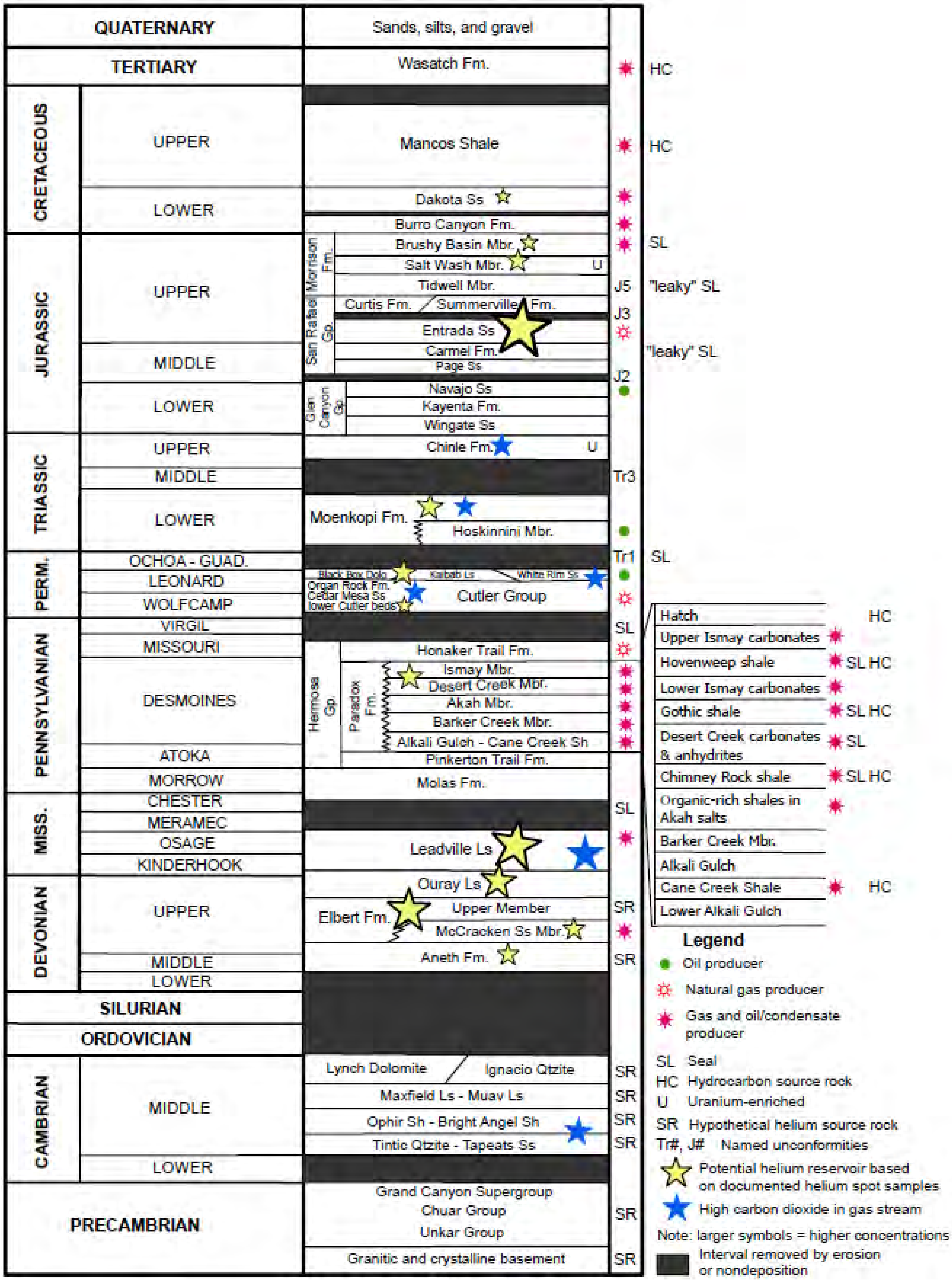

Figure 20. *Generalized stratigraphic column for eastern Utah and the central Colorado Plateau showing evidence for an effective helium system in both Mesozoic and Paleozoic strata. Helium source rocks are thought to be predominantly Paleozoic sedimentary rocks (e.g., Cambrian-Devonian dirty sandstones and shales) and the Precambrian basement with additional input from younger U- and Th-rich sediments. Degassing from the mantle may not play as large of a role here as in other areas of the Colorado Plateau (e.g., northeastern Arizona). Carbon dioxide may act as a carrier gas for helium in the subsurface. Modified from Whidden and others (2014) after Conley and Giardina (1979).*

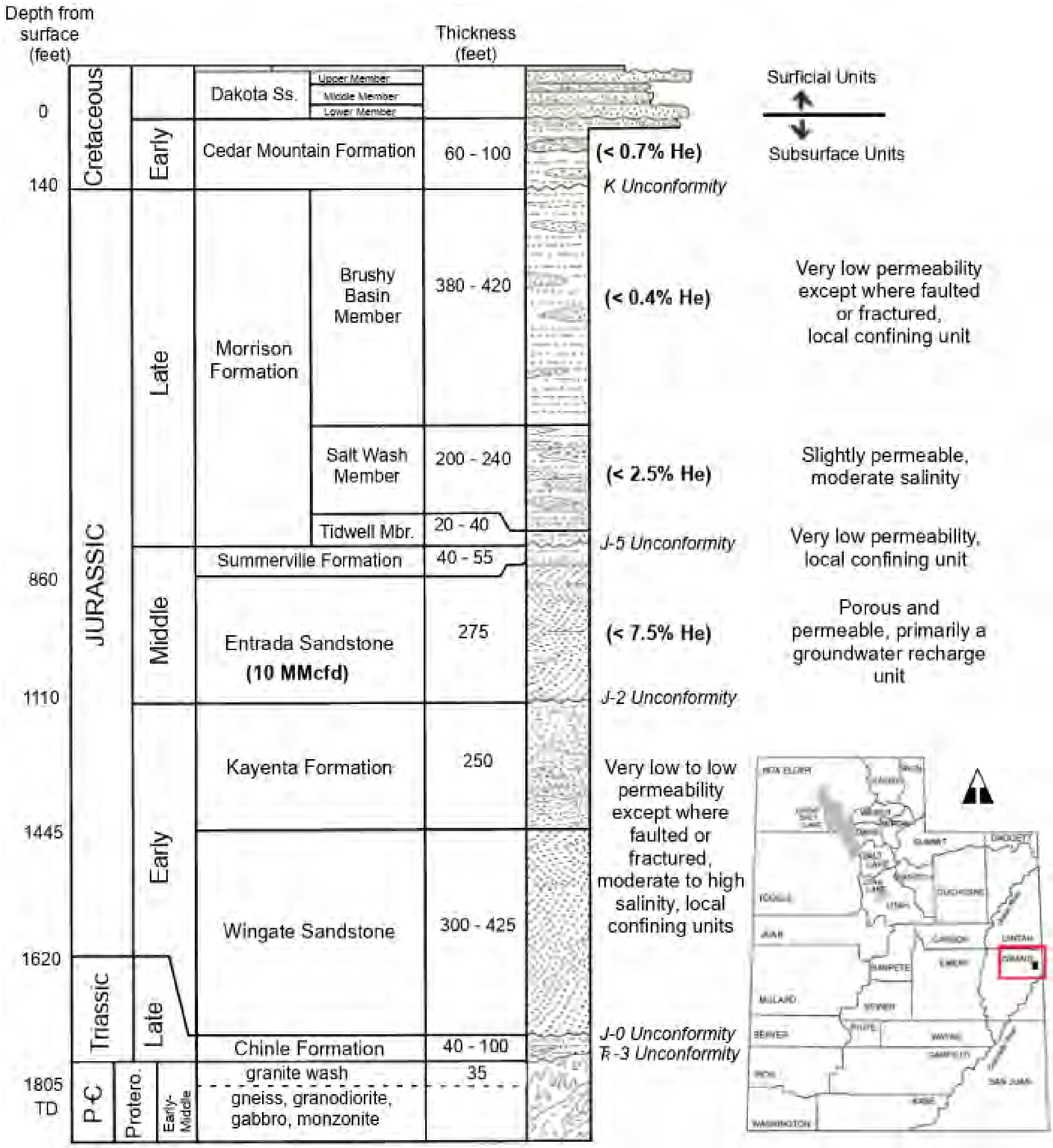

Figure 21. Northeastern Grand County, Utah, stratigraphic column modified from Willis (1994). Formation thickness from Willis (1994) is averaged over the area, whereas depth from surface was taken from the UDOGM well file drilling report from Daymon D. Gililland's Lansdale Govt 13 well (API 43-019-30008), SENE section 4, T. 19 S., R. 25 E. (SLB&M), in Grand County, Utah. Note that the Jurassic Entrada Sandstone is generally clean sand and a good carrier bed for fluids. Where present, the overlying dense shale beds of the Summerville Formation and Tidwell Member of the Morrison Formation provide an effective seal to helium-rich gases at Harley Dome. The uranium-bearing Salt Wash Member of the Morrison contains more channel sandstones with interbedded shales that act as leaky seals to migrating fluids.

CHEMICAL & GEOLOGICAL LABORATORIES
P. O. Box 279
Casper, Wyoming

GAS ANALYSIS REPORT

Company: A. Lansdale — Date: March 21, 1968 — Lab. No. 24162
Well No.: Unit No. 4 — Location: Section 3-19S-25E
Field: Harley Dome — Formation: Entrada
County: Grand — Depth:
State: Utah — Sampling point: ☐ Wellhead, ☐ Separator, ☐ Treater
Line pressure, ____ psig; Sample pressure 80 psig, Temperature ____ F
Remarks:

Component	Mole % or Volume %	Gallons per MCF
Oxygen	0	
Nitrogen	86.10	
Carbon dioxide	0.91	
Hydrogen sulfide	0	
Helium	7.31 ✓	
Methane	5.56	
Ethane	0.11	
Propane	0.01	0.003
Iso-butane & higher	Trace	-
N-butane		
Iso-pentane		
N-pentane		
Hexanes		
Total	100.00	0.003

Gross btu/cu. ft. @60°F & 14.7 psia (dry basis): 58
Specific gravity (caluculated from analysis): 0.889
Specific gravity (measured): 0.892
GPM of pentanes & higher fraction: -

Figure 22. *Gas analysis report from the Jurassic Entrada Sandstone reservoir penetrated by the Lansdale Govt 4 well (API 43-019-30003) located atop the Harley Dome structure in Grand County, Utah. This 1968 gas analysis was taken from the public well file report from the Utah Division of Oil, Gas and Mining (UDOGM).*

PROSPECTIVE HELIUM PLAYS

The following sections describe potential helium plays in Utah. Results are based on the compilation of a verifiable database of economic helium analyses from 93 wells with helium concentrations at or above 0.30% located throughout 12 proven and developed natural gas field areas and five helium-prospective play areas (see appendix). Ten-digit API numbers were used in this report for wells with ambiguous well names.

Like a petroleum system, the terms “play” and “play fairway” used throughout this report represent a geographic area defined during the exploration phase that has the combined source, seal, and reservoir components necessary for helium to accumulate in the subsurface. The play fairway typically consists of a group of geologically related prospects defined by a general area. A play can be proven or hypothetical, but the prospect is defined independently by an effective reservoir, source charge, and trap integrity evaluated by drilling a well (Otis and Schneidermann, 1997).

The U.S. Energy Information Administration (EIA) defines Mcf as the volume of one thousand standard cubic feet of gas. Utah Administrative Code R746-320-1 4.c defines a legal standard foot of gas as the volume of gas that occupies one cubic foot at a temperature of 60 degrees Fahrenheit and at absolute pressure. The Federal Helium Program (FHP) defines a standard cubic foot (scf) as the volume of gaseous helium occupying one cubic foot at a pressure of 14.65 pounds per square inch absolute (psia) and a temperature of 60 degrees Fahrenheit (BLM – Federal Helium Operations). Other volumetric measurements used in the following sections include: MMcf (one million cubic feet of gas), MMcfd (one million cubic feet of gas per day), Bcf (one billion cubic feet of gas), bpd (barrels of oil equivalent per day), and MMbbls (one million barrels of oil). Traditionally, 42 U.S. gallons equal one barrel of oil. Pressure measurements for this paper have been reported in psi (pounds of force per square inch of area). The FHP has historically used psia (pressure measured relative to a full vacuum) when referring to laboratory measurements and psig (gauge pressure) at the wellhead in relation to atmospheric pressure. Very dilute concentrations of substances use the abbreviation ppm (parts per million), meaning "out of a million."

"Helium-rich" gas is used throughout this report to represent a helium concentration of 0.50% or more contained in the gas stream. Similarly, the terms "carbon dioxide- and nitrogen-rich" gas have been used to denote concentrations higher than 30% of the combined gas stream. Acidic gas refers to a gas with significant concentrations of carbon dioxide (CO_2) and hydrogen sulfide (H_2S); whereas sour gas refers to H_2S specifically. Craddock and others (2017) express gas analyses as molar percentages (mol %), while the FHP has historically used volume concentration (vol %). This report follows the ideal gas assumption that equates mol % to vol % at standard temperature and pressure.

While the study objective has been to highlight Utah's documented helium potential resource plays as a guide for explorationists, the field and well data in this report are by no means the only areas where helium may be prospective in Utah. Many wells were drilled in potential helium play fairways throughout Utah, but few were ever tested or completed in proven helium-bearing formations. Most wells completed in known helium gas reservoirs did not document a helium test specified as part of a gas analysis. Similarly, many prospective helium plays remain so sparsely drilled that there is potential for entire helium accumulations to be discovered between dry holes. Also, the USBM, BLM, and USGS helium data used in this report are based on analyses of spot samples obtained from wells, and as such they do not necessarily represent the concentration of helium in the reservoir. In some instances, the gas analysis may include commingled gas from two or more potential helium-bearing horizons within the same well (e.g., Jurassic Entrada Sandstone and Morrison Formation at Harley Dome).

Our search for possible helium plays in Utah began with a survey of all known gas producing areas with documented helium occurrences. Data presented in this report were compiled from several publications (e.g., Preston, 1961; Stowe, 1972; Campbell and Bacon, 1976; Moore, 1982; Moore and Sigler, 1987; Jenden and Kaplan, 1989; Hamak and Sigler, 1991; Hamak and Gage, 1992; Hill and Bereskin, 1993; Gage and Driskill, 1998, 2005; Driskill, 2008; Craddock and others, 2017), including supporting documentation found in individual public well files from the Utah Division of Oil, Gas and Mining (UDOGM). Each helium-prospective play area in this report was subjected to in-depth study and analysis to identify the most promising helium resources in Utah.

Application of Data

The most prolific aggregator of helium well data for this report has been the USBM, succeeded by the BLM, which since 1917 requested gas samples from production and wildcat wells drilled in helium-prospective play areas as part of the strategic Federal Helium Program (Rogers, 1921; Moore, 1976, 1982). In 2015, helium analyses obtained by the USBM were digitized and included in the publicly available USGS Energy Resources Program – energy geochemistry database (EGDB) (U.S. Geological Survey, 2015). In 2018, the USGS created a separate and condensed database specifically for and limited to helium analyses throughout the United States (Brennan and others, 2018).

Historically, spot samples of the gas stream were collected by the operator or USBM official at the wellhead using glass bottles at atmospheric pressure or in pressurized steel cylinders (Moore and Sigler, 1987). Using a variety of methods samples were analyzed, tabulated, and published as Information Circulars (figure 23) by the Section of Research and Analytical Services branch of the USBM Federal Helium Program out of Amarillo, Texas (Anderson and Hinson, 1951; Driskill, 2008; Craddock and others, 2017).

Early gas sample analytical work used rudimentary technology and has been considered "generally reliable" (Rogers, 1921; Anderson and Hinson, 1951), although the data may not be as precise as analyses using modern gas chromatographic techniques. In 1949, the more modern mass spectrometer gradually replaced older analytical methods (Anderson and Hinson, 1951; Craddock and others, 2017). In 1978, the helium gas chromatograph was introduced by the USBM and used in conjunction with the mass spectrometer and is still in use today (Moore, 1982; Driskill, 2008).

The USBM reported the composition of natural gas streams to the nearest 0.1%, except for helium, which was reported to the nearest 0.01% by total volume. The word "trace" has been used to represent helium quantities less than 0.005% and quantities of other gas constituents less than 0.05% (Moore, 1976; Driskill, 2008). Being highly soluble in water, hydrogen sulfide (H_2S) reported by the USBM prior to 1949 may not be entirely accurate due to the use of water during laboratory analysis (Anderson and Hinson, 1951; Moore and Sigler, 1987). A common indicator of sample contamination due to cleanliness and handling issues is excessive amounts of oxygen (O_2) (Anderson and Hinson, 1951). Although samples containing over 1.0% O_2 have not been omitted from this report, a note of caution is warranted for analyses containing oxygen levels above this threshold.

From its inception in 1917 to the most recent 2008 publication, the Federal Helium Program has analyzed, documented, and published 454 spot samples of helium occurrences in Utah (e.g., Moore and Sigler, 1987; Hamak and Sigler, 1990; Gage and Driskill, 1998, 2005; Driskill, 2008). Of these 454 samples, 94 have returned helium concentrations of 0.30% He or greater, with one helium occurrence sourced from a pipeline gas sample (see appendix).

	INDEX 190 SAMPLE 18837	INDEX 191 SAMPLE 18832	INDEX 192 SAMPLE 18833
STATE	UTAH	UTAH	UTAH
COUNTY	GRAND	GRAND	GRAND
FIELD	BITTER CREEK W	HARLEY DOME	HARLEY DOME
WELL NAME	LANSDALE GOVERNMENT NO. 15	LANSDALE GOVERNMENT NO. 1	LANSDALE GOVERNMENT NO. 4
API			
LOCATION	SEC. 15, T18S, R25E	SEC. 33, T18S, R25E	SEC. 3, T19S, R25E
OWNER	GILILLAND ENERGY CORP.	GILILLAND ENERGY CORP.	GILILLAND ENERGY CORP.
COMPLETED	68/09/00	67/06/00	68/04/00
SAMPLED	89/08/08	89/08/04	89/08/07
FORMATION	JURA-SALT WASH-MORRISON	JURA-MORRISON	JURA-ENTRADA
GEOLOGIC PROVINCE CODE	585	585	585
DEPTH, FEET	580	944	1054
WELLHEAD PRESSURE,PSIG	180	150	180
OPEN FLOW, MCFD	NOT GIVEN	189	470
COMPONENT, MOLE PCT			
METHANE	57.1	49.0	5.0
ETHANE	0.9	1.0	0.0
PROPANE	0.4	0.4	0.0
N-BUTANE	0.0	0.0	0.0
ISOBUTANE	0.1	0.1	0.0
N-PENTANE	0.0	0.0	0.0
ISOPENTANE	0.0	TRACE	0.0
CYCLOPENTANE	0.0	0.0	0.0
HEXANES PLUS	0.0	0.0	0.0
NITROGEN	38.7	46.5	86.5
OXYGEN	0.0	0.0	0.0
ARGON	0.1	0.2	0.5
HYDROGEN	0.3	0.3	0.0
HYDROGEN SULFIDE**	0.0	0.0	0.0
CARBON DIOXIDE	0.0	0.1	1.1
HELIUM	2.43	2.51	6.99
HEATING VALUE*	610	529	50
SPECIFIC GRAVITY	0.714	0.747	0.897

Figure 23. *Example of data gathered and published by the Section of Research and Analytical Services branch of the U.S. Bureau of Mines (USBM). The sample index 192 on the far right is the same 1968 Lansdale Govt 4 well as shown in figure 22. Note the difference in sample dates and helium concentration from 7.31% He in figure 22 to 6.99% He as reported by the USBM.*

For oil and gas wells drilled in eastern Utah, documented gas stream composition data is better preserved in the public well file for older wells (figures 22 and 24), particularly those drilled from the 1940s into the 1970s. This preservation may originate because drill stem tests (DSTs) were commonly used during the frontier exploration phase to obtain fluid and pressure data from a geological formation during the drilling of a well (figure 24) before more sophisticated wireline logging tools were developed. This results in fewer gas stream analyses in more recently drilled wells, especially within the intervals most prospective for helium. A note of caution is warranted here for documented gas analyses from a DST because of the increased potential for sample contamination by oxygenated mud filtrate (Selley and Sonnenberg, 2015).

Big Flat Area, Grand County

The Big Flat field area (figure 25), located primarily within T. 23 S., R. 17 E. (Salt Lake Baseline and Meridian [SLB&M]), is composed of multiple fields of variable size (Wood and Chidsey, 2015) and is geographically located on the northwestern flank of the Paradox Basin in the salt anticline area of Grand County, adjacent to Canyonlands National Park to the west and Arches National Park to the east (plate 1). Bounded by basement-involved northwest to southeast-oriented high-angle faults, these fields produce oil and associated gas primarily from the Cane Creek shale zone within the structurally complex, faulted anticlines and fractured reservoirs of the Pennsylvanian Paradox Formation (Hill and Bereskin, 1993). Other significant oil and gas shows in the area are from similar Paradox clastic zones as well as the deeper helium-bearing Mississippian Leadville Limestone (figure 20). Geophysical 3-D data are useful in locating the deeper structures.

The Big Flat, Long Canyon, and Bartlett Flat wells that comprise this play area were drilled in the 1950s and 1960s to depths ranging from 7441 to 7954 feet (Preston, 1961; Hill and Bereskin, 1993). The three helium-prospective wells drilled at Big Flat and the former Bartlett Flat field have been plugged and abandoned, but documented percentages for these wells range from 0.30% to 1.70% He and up to 86.0% N_2 (Stowe, 1972; Moore and Sigler, 1987). The Big Flat Unit 1 well recorded “non-flammable gas” with “black water” from Mississippian DSTs #4 and #5 from a depth interval of 7486 to 7637 feet (Utah Division of Oil, Gas and Mining, 2020). The UDOGM well file records a gas analysis in DST #4 showing 86.13% N_2, 5.77% CH_4, 1.76% CO_2, and 5.77% light hydrocarbons. Although there were minor shows farther up section in the Paradox Formation, the most promising helium shows in these wells were sourced from nitrogen-rich reservoirs of the Leadville Limestone below the salt of the Paradox Formation. Consistent with the methane dilution concept

GEOLOGICAL DATA AND DRILLING AND COMPLETION PROCEDURE

FORMATION OR DATE	TOP-DEPTH INTERVAL	REMARKS OR DESCRIPTION AND RESULTS OF WORK

D.S.T. No. 6 (4670 ft. - 4741 ft.)

Tool open five minutes, closed in 30 minutes for ICIP. Re-opened with very strong blow, spray of mud and water to surface in 45 minutes; strong steady blow throughout test. No combustible gas to surface. Tool open 155 minutes.

Recovered: 2.387 MMCFD inert gas, 220 feet muddy water
(NOTE: Gas analyzed 2.77% Helium, 97.23% Nitrogen)

IHMP 2144 psi
ICIP 1770 psi in 30 minutes
IFP 240-438 psi) 5 min. - 155 minutes
FFP 277-497 psi)
FCIP 1675 psi in 30 minutes
FHMP 2144 psi

D.S.T. No. 7 (4755 ft. - 4886 ft.)

Tool opened five minutes, closed in 30 minutes for ICIP. Re-opened tool with slight blow, continued throughout test. No gas to surface. Tool open 63 min.

Recovered: 15 ft. drilling mud. No oil or water.

IHMP 2234 psi
ICIP 310 psi in 30 minutes
IFP 28-37 psi) 5 minutes - 63 minutes
FFP 28-63 psi)
FCIP 727 psi in 30 minutes
FHMP 2227 psi

D.S.T. No. 8 (3916 ft. - 4010 ft.) (Straddle Test)

Tool opened five minutes, closed in 30 minutes for ICIP. Re-opened tool with weak blow, decreased to very weak blow throughout test. No gas to surface. Tool open 120 minutes.

Figure 24. *Daily drilling report from Texaco's 1960 Temple Springs Unit 1 well (API 43-015-11324), section 14, T. 25 S., R. 13 E. (SLB&M), Emery County, Utah, shows an inert gas stream was encountered during drill stem test #6 within a depth interval of 4670 to 4741 feet. The analyzed sample recorded 2.77% He and over 97% N_2 from the Devonian Elbert Formation beneath the San Rafael Desert in central Utah. This well penetrated Precambrian basement rock at a depth of 6260 feet. Sourced from the Utah Division of Oil, Gas and Mining public well file.*

for control on high-helium gas, the most significant helium concentrations were found below the hydrocarbon productive Cane Creek shale (figure 20).

Like the Big Flat field, the more southerly positioned Long Canyon field also has helium shows in the Leadville. Documented helium percentages for the two wells located in the Long Canyon area are 1.30% and 1.48% He with significantly high nitrogen concentrations of over 91% N_2 and exceptionally low methane and carbon dioxide (Moore and Sigler, 1987). Well reports from two Mississippian DSTs taken from a depth interval of 7606 to 7766 feet in the Long Canyon 1 well indicate that "5 MMcfd of inert gas" and "black sulfur water" was encountered while drilling with a "trace of oil" and orders were made to plug back and complete in the Paradox. The Long Canyon 2 well had mechanical issues downhole and was subsequently plugged and abandoned.

This area experienced drilling activity from the earliest days of oil exploration in Utah. More recently, Fidelity Exploration and Production Co. shot a 3-D seismic survey in this area from which they based a successful directional and horizontal drilling program in the Paradox Formation. In 2016, Fidelity sold their interests to Wesco Operating Inc., which has been actively drilling to further define the Paradox petroleum play. Helium testing of gas samples from these wells should be encouraged, especially wells that penetrate deeper Devonian-Mississippian reservoirs.

Boundary Butte Area, San Juan County – Navajo Nation

The Boundary Butte field area is located on the southern rim of the Paradox Basin (figure 19), near the southeastern flank of the Monument uplift, in the Four Corners region of Utah (plate

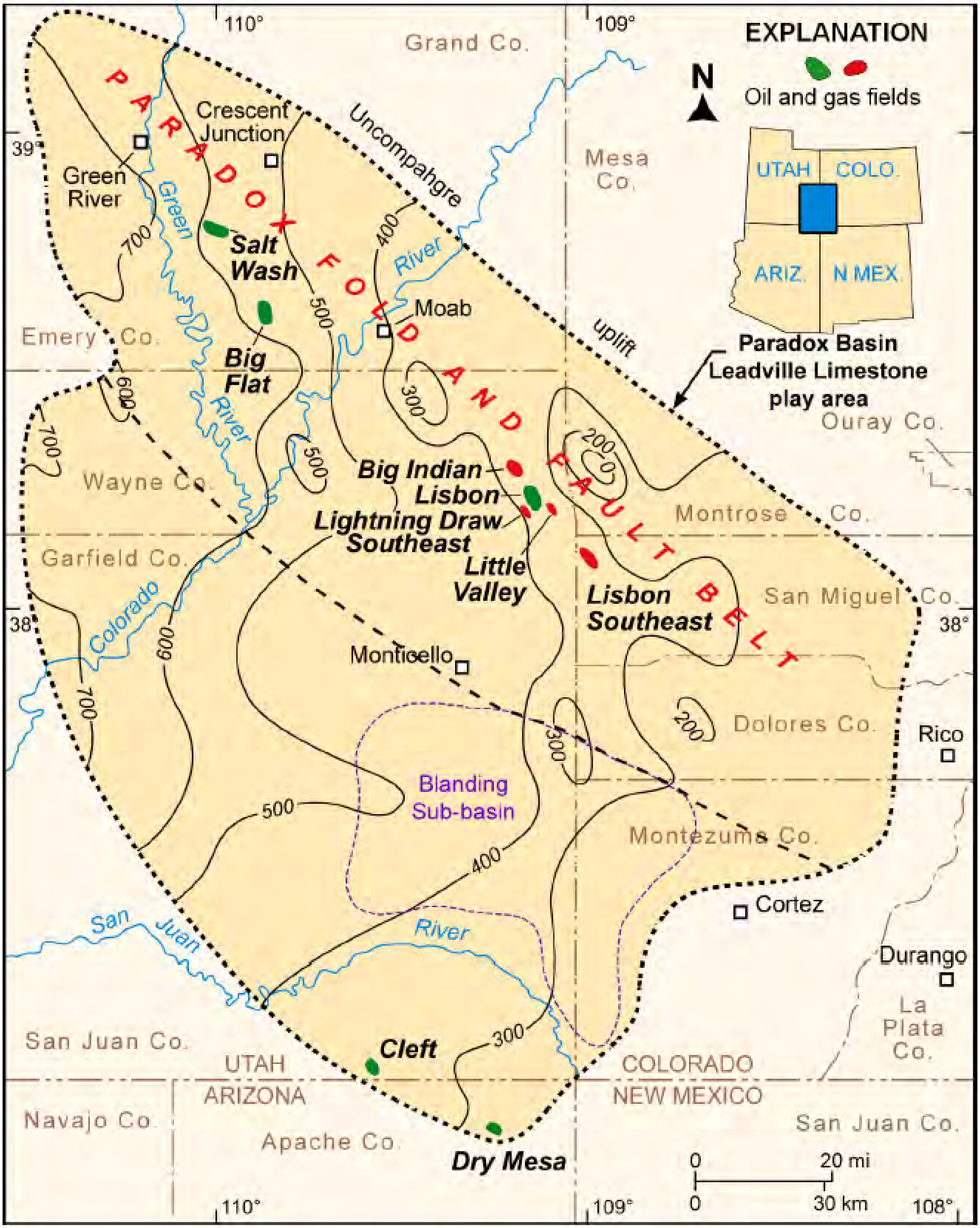

Figure 25. *Generalized isopach map for the Mississippian Leadville Limestone from Chidsey (2016 a). Map shows location of fields that produce from Mississippian reservoirs. Dotted region illustrates the extent of the Leadville Limestone play fairway in the Paradox Basin.*

1). Extending into northeastern Arizona (Conley and Giardina, 1979), the Boundary Butte area is composed of underpressured, hydrodynamically driven oil and gas fields with historic and current production primarily from structurally complex, faulted anticlines of the Middle Pennsylvanian Ismay Zone (figure 20) of the Paradox Formation (Preston, 1961; Stowe, 1972; Campbell and Bacon, 1976; Hill and Bereskin, 1993; Wood and Chidsey, 2015). Additional productive units include similar carbonate zones of the Middle Pennsylvanian Hermosa Group as well as the Mississippian Leadville Limestone and Devonian Ouray Limestone (Hill and Bereskin, 1993), all of which are prospective for helium. Likely sourced from metamorphism of marine carbonates and black shales by nearby igneous intrusive rocks from the southeast (figure 8), carbon dioxide gas is common in hydrocarbon productive Paleozoic reservoirs throughout the Four Corners region.

Thirteen gas wells reported economic amounts of helium in the Boundary Butte field area (Stowe, 1972; Moore, 1982; Moore and Sigler, 1987), located entirely on Navajo Tribal Lands in extreme southeastern San Juan County. Also included are analyses from wells in the Chinle Wash, Desert Creek, Gothic Mesa, and White Mesa fields, similarly located on Navajo land. The gas content of the Boundary Butte helium play fairway has two stratigraphically distinct reservoirs. Devonian reservoirs are carbon dioxide-rich (56%–78% CO_2) and have only minor amounts of methane, whereas shallower Pennsylvanian reservoirs show negligible carbon dioxide and increased methane content.

The Boundary Butte helium prospects tested from 0.44% to 1.58% He with the majority of sampled wells completed in the Pennsylvanian Paradox Formation without testing the deeper formations (Moore, 1982; Moore and Sigler, 1987). Although Campbell and Bacon (1976) note a maximum helium concentration of nearly 3.0% for the Desert Creek field, no specific gas analysis with this high helium concentration could be tied to a particular well in the USBM or UDOGM database. The most promising 1.58% He test was from the Devonian Ouray Limestone stratigraphically situated below the Paradox salt in section 2, T. 42 S., R 22 E. (SLB&M). Two wells in the Chinle Wash field tested 0.73% and 0.80% He from the Paradox. The single prospect at Desert Creek had a helium show of 1.37% from the Ouray Limestone. The White Mesa well tested 0.53% He from the Pennsylvanian Hermosa Group and the Nav-Anido Creek 1 well tested 0.32% He from the Paradox. Although nearly all the wells on Navajo lands in San Juan County that produced economic helium analyses produced the inert gas from Pennsylvanian reservoirs, the two highest results originated from deeper Devonian carbonate reservoirs.

Opposite the Utah state line on the Arizona side of the Boundary Butte helium play fairway, gas analyses show a significant increase in helium concentrations from Devonian-Mississippian reservoirs towards the Defiance uplift farther south (Conley and Giardina, 1979; Moore and Sigler, 1987). Similar to the Big Flat helium play area of Grand County, the Boundary Butte area records low helium in hydrocarbon-rich Pennsylvanian reservoirs, likely due to dilution and/or reservoir baffles between Mississippian and Pennsylvanian rocks. Helium exploration in the Boundary Butte helium play fairway should focus on shallow structural traps within Devonian-Mississippian reservoirs.

Bowknot Prospect, Emery County

The Bowknot helium prospect is based on a 1.47% He gas analysis from the known helium-bearing Mississippian Leadville Limestone (figure 20) in a remote wildcat well drilled by the Superior Oil Company in 1962 (Moore, 1982). After identifying a prospect from a single-fold seismic survey in the late 1950s, the Bow Knot Unit 14-5 well was drilled near the crest of a north-oriented anticline in the SWSW section 5, T. 26 S., R. 17 E. (SLB&M), 5 miles southwest of the Green River feature known as Bowknot Bend in Emery County (plate 1) (Doelling and others, 2015). The anticlinal structure is truncated by a northwest- to southeast-oriented, high-angle fault observable in well log correlation on the structural top of the Leadville between the 14-5 well and the Federal 2-20 well drilled 3 miles to the south by Megadon Enterprises in 1981 (Utah Division of Oil, Gas and Mining, 2020).

The Davis Oil Company Pool Unit 1 well in section 17, T. 26 S., R. 17 E. (SLB&M) defines the southern boundary of a major paleo-structure with a northwest-oriented, down-to-the-southwest high-angle fault immediately north of the well. Multiple 2-D seismic surveys were performed within the general vicinity of the initial Unit 14-5 exploratory well throughout the 1980s and early 1990s. In 2007, Samson Oil and Gas completed a nearly 100-square-mile 3-D seismic survey in the San Rafael Desert between the Bowknot prospect and Temple Springs prospect farther to the west (plate 1). This prospective helium play fairway averages only three wells drilled per township with additional exploration necessary to further define the geographic extent of the play.

Six DSTs were run while drilling the 14-5 well with “non-flammable” gas encountered from DST #3 from a depth of 6350-6410 feet in a zone of “massive porosity.” Maximum gas rate was 15,000 Mcfd from the lower dolomite section of the Leadville Limestone, which also recorded significant residual oil staining (Utah Division of Oil, Gas and Mining, 2020). The gas analyzed from this well was recovered from DST #2 at a depth of 6270 feet in the Leadville. This low-Btu gas included significant amounts of nitrogen (79.1% N_2) and hydrogen sulfide (0.20% H_2S) with a minor methane component (12.6% CH_4). Despite the significant helium concentration of 1.47% found within the gas stream, this well was drilled and abandoned as a dry hole. Based upon analysis of the 14-5 well and shows in surrounding wells, the Leadville has seen a pervasive and voluminous hydrocarbon charge in this area.

Hanshaw and Hill (1969) note significant groundwater changes in Paleozoic reservoirs west of the Green River, likely due to thinning of Pennsylvanian salt farther west. Public well file reports from the Bow Knot Unit 14-5 well records nearly 1300 feet of Pennsylvanian salt penetrated while drilling the prospect well (Utah Division of Oil, Gas and Mining, 2020). This clearly demonstrates the existence of an effective seal for any helium accumulations below the base of the salt in this area.

The remote and rugged nature of this prospect makes it challenging. Regardless, both SITLA and BLM leases have been issued surrounding the original prospect well and much of the San Rafael Desert. The challenges have been increased by the inclusion of the acreage in the Emery County Wilderness Study Area in early 2019, but a recent BLM initiative to increase helium exploration on federal lands in Utah may make this prospect a viable option for helium-specific operators.

Clay Basin Field, Daggett County

The helium prospect at the Clay Basin field (figure 19) is positioned along the north flank of the Uinta Mountains uplift and on the extreme southern margin of the Green River Basin in northeastern Utah. The Clay Basin field has produced primarily from fluvial channel deposits of the Early Cretaceous Dakota Sandstone (Preston, 1961; Hill and Bereskin, 1993). The structure at Clay Basin consists of a predominantly east-west oriented, elongate, closed anticline that parallels the high-angle, north-dipping Uinta fault located a few miles south of the field (Preston, 1961).

Over 60 wells have been drilled at Clay Basin since the 1927 discovery well drilled by Producers and Refiners Corp (Utah Division of Oil, Gas and Mining, 2020). In the mid-1930s, Mountain Fuel Supply (MFS) acquired and unitized the area, drilling 10 more wells that produced natural gas from the Dakota Sandstone and Frontier Formation before converting part of the field to seasonal natural gas storage.

Only one of the early wells drilled at Clay Basin penetrated the helium-prospective Permian- Pennsylvanian Weber Sandstone. The RD Murphy 6-W/Clay Basin Unit #11 well was drilled and completed in 1946–47, to a depth of 9355 feet in the SENW section 22, T. 3 N., R. 24 E. (SLB&M). Twenty DSTs were performed during the drilling of this well, with four tests in the Weber Sandstone interval producing significant quantities of "non-flammable" gas. An analysis of a gas sample from the Dakota Sandstone noted 0.03% He, but the Weber DST samples do not indicate a test for helium. The well was subsequently plugged back to and produced from the Dakota.

In 1969, MFS re-entered the well, renamed the Clay Basin Unit #11, and deepened it to 11,778 feet in a transgressive sandstone interval of the Cambrian Lodore Formation. During this operation, a DST in the Weber from a depth interval of 9007–9358 feet produced 8500 Mcfd that "would not burn." Although there is no gas analysis in the well file, the depth and date correspond to the USBM analysis documented by Moore (1982). The test result indicated a nitrogen-rich gas stream (80.1% N_2) with 0.48% He and is the only Weber Sandstone helium test at Clay Basin. The well was plugged and abandoned in November 2016.

Between 2008 and 2013, a second Weber penetration was made less than a mile southwest of the Clay Basin Unit 11 well, but no record of a gas analysis was found from this effort. Although there are many wells in the Clay Basin field area in both Utah and Wyoming (Wood and Chidsey, 2015; Toner and others, 2019), only one obtained a gas analysis from the Weber Sandstone. The 0.48% He result is of enough interest to warrant further helium exploration in the deeper Weber Sandstone potential helium play.

Grassy Trail Area, Carbon & Emery County

The Grassy Trail helium play area straddles the Carbon-Emery county line on the north-plunging end of the San Rafael Swell (plate 1) (Preston, 1961). This potential helium play includes the Farnham Dome, Sunnyside, and Grassy Trail gas fields. Production in the area is primarily from faulted plunging anticlines, with internal stratigraphic trapping mechanisms (Hill and Bereskin, 1993). The producing zones have historically been Jurassic-Triassic eolian deposits of the Navajo Sandstone and deltaic horizons in the Moenkopi Formation (figure 20). Similarly, Hanshaw and Hill (1969) note the hydrodynamic environment and intertonguing between Permian-age strata in this area to be favorable for trapping migrating oil and natural gas.

Multiple wildcat wells were drilled in Carbon County by Mountain Fuel Supply Co. from 1959 to 1970 near Sunnyside, one of which had a significant helium show of 1.22% from the Sunnyside Unit 1 well in a nitrogen-rich (60.1% N_2) gas stream from the Triassic Moenkopi Formation at a depth of 5092 feet (Moore, 1982). Craddock and others (2017) report a methane-rich gas stream with a 0.30% He concentration from the Wellington Flats 15-11-18E well drilled by Whiting Oil & Gas Corporation in 2013, which is currently a shut-in oil and gas well operated by Liberty Pioneer Energy Source, Inc.

In Emery County, there are two documented helium tests approximately 5 miles apart and a few hundred feet from the county line. At a depth of 4258 feet, the Grassy Trail Fed 4-32 well (API 43-015-30121) had a helium show of 0.71% from a similar nitrogen-rich (60.7% N_2) gas stream sourced from the Moenkopi Formation (Moore and Sigler, 1987). The completion report for the Fed 4-32 well recorded minor oil (Utah Division of Oil, Gas and Mining, 2020), which may indicate that the helium is dissolved in the oil resulting in the higher helium concentration. Moore and Sigler (1987) show multiple spot samples taken from the Federal Mounds 1 well in February of 1965, which provided a range of 0.52%–0.55% He analyses from the much deeper Mississippian Deseret Limestone (Madison equivalent) at a depth of 8520 feet.

Well file notes for the Federal Mounds 1 well indicate Cambrian rocks were penetrated at a total depth of 9425 feet (Utah Division of Oil, Gas and Mining, 2020). Multiple DSTs were run with significant “non-flammable” gas and brackish water encountered in the Mississippian section (figure 20). Notes indicate the well was plugged back and another DST was run in the Pennsylvanian section, which produced a 1.0% He test from a nitrogen-dominated (73% N_2) gas stream with a significant carbon dioxide (25% CO_2) component. Hill and Bereskin (1993) document a 0.59% He test from the Federal 11-33 at Grassy Trail in a natural gas stream noted in the well file as having 34.9% "non-combustible" gas reported on the well completion report in 1984. The analysis was taken from a shaly, calcareous sandstone interval of the Triassic Moenkopi Formation. The Federal 11-33 remains an orphaned, shut-in oil well formerly operated by Genesis Petroleum US, Inc. and is contracted to be plugged by the BLM in 2020 (Utah Division of Oil, Gas and Mining, 2020).

Five miles to the north of the gas wells at Grassy Trail and Sunnyside is the fault-bounded anticline known as the Farnham Dome carbon dioxide field (Morgan, 2007), which has produced almost 5 Bcf of nearly pure carbon dioxide (~99% CO_2) (Zartman and others, 1961) from stacked reservoirs in the Jurassic Navajo Sandstone and Permian Coconino Sandstone since the discovery well in 1924. This CO_2-rich gas supplied the dry ice plant in Wellington from 1931 to 1979 when the field was abandoned due to lack of a market (Hill and Bereskin, 1993). The Pan American Petroleum Corporation drilled the USA Farnham Dome 1 well to basement at a total depth of 8509 feet (Campbell, 1978). Well control over the area from Campbell (1978) suggests basement-cored faulting has provided significant migration pathways for CO_2-charged groundwater. More recent activity at Farnham Dome occurred in 2007 when Savoy Energy, LLC drilled the Savoy 1 carbon dioxide gas well on the crest of the structure. No significant helium analysis has been recorded at Farnham Dome, but the anomalously high carbon dioxide gas accumulation may be an indicator for helium- and nitrogen-rich CO_2 gas migration (Zartman and others, 1961).

Like other helium plays on basin-uplift transitional areas in Utah, helium-bearing gas in Carbon and Emery Counties is associated with high concentrations of carbon dioxide and nitrogen, with minor amounts of methane. Helium concentration generally decreases as carbon dioxide increases and without an associated high concentration of hydrocarbon gases to make extraction of helium economic, this helium play has a low potential for exploration (Gloyn and others, 2003). If supply and demand further helium exploration in this area, explorationists should focus on hydrodynamics and fluid migration direction. Potential helium prospects must be updip and far enough from CO_2 sources to allow for the CO_2 to be removed from the gas (figure 10, C) by mineralization during long migration (Brown, 2010).

Greater Cisco Area, Grand County

Regionally located on the southwestern flank of the Uncompahgre Uplift (plate 1), the Greater Cisco gas field complex includes: Cisco Dome, Cisco Townsite, Cisco Springs, Cisco Springs-North, Cisco Wash, Danish Wash, and Seiber Nose fields (Preston, 1961; Hill and Bereskin, 1993). The area is situated along I-70, approximately 20 miles west of the Colorado state line. The Utah Division of Oil, Gas and Mining also includes the Harley Dome field as part of Greater Cisco, but, due to the high helium concentrations characteristic of Harley Dome, it is treated separately in this report.

More than 600 shallow wells have been drilled since 1925 (Stowe, 1972) in the Cisco area for oil and gas trapped in the Late Cretaceous Castlegate Sandstone, Mancos Shale, Dakota Sandstone, Cedar Mountain Formation, Jurassic Morrison Formation and the Late Jurassic Entrada Sandstone (figure 21) (Wood and Chidsey, 2015; Utah Division of Oil, Gas and Mining, 2020). Each of the small isolated fields produce from shallow sandstone intervals with hydrocarbons and associated gas trapped by well-defined lateral and vertical seals along the west-northwestern flank of the Uncompahgre mountain front (Hill and Bereskin, 1993).

The highest helium shows were found in wells drilled in the 1960s just north of I-70 along a 6-mile stretch northeast of the old Cisco townsite with a range of helium values from 0.50% to 1.47% (Stowe, 1972; Moore, 1982; Moore and Sigler, 1987). In June 1963, U-Tex Oil Company penetrated the Jurassic Morrison Formation at 1308 feet with their Federal 5 (API 43-019-16259) well in section 10, T. 20 S., R. 24 E. (SLB&M). A DST taken in the Morrison at a depth of 1298 feet recorded 1.47% He and 20.44% N_2 within a methane-rich (76.12% CH_4) gas stream (Utah Division of Oil, Gas and Mining, 2020). A spot sample from the Cretaceous Buckhorn Conglomerate at 842 feet resulted in a helium show of 0.66% from the Pumpelly-Stava 30-81 well. The gas stream was predominantly methane (82.1% CH_4) with a minor nitrogen (13.1% N_2) component. Most wells in this helium play are methane-rich with a minor helium component of 0.30% or less, indicating significant helium dilution from methane generation in nearby source rocks.

Helium shows over 1.0% were all recorded from the Morrison Formation, which also had higher nitrogen concentrations in their gas stream and were sourced from wells near the northeastern edge of the defined hydrocarbon field area. Wells drilled and completed in shallower Cretaceous reservoirs recorded only trace amounts of helium (figure 20). Helium generated in too shallow of strata can lose helium to the surface by diffusion and helium co-generated or associated with hydrocarbon gases will be severely diluted to subeconomic levels (Brown, 2010).

Harley Dome Field, Grand County

Harley Dome, formerly known as Harley anticline (Dane, 1935), is the single, truly defined helium gas field in Utah (figure 3). Numerous wells have encountered significantly high helium concentrations from combination traps in Jurassic reservoirs at depths less than 1000 feet, mostly in nitrogen-dominated (~85% N_2) gas streams with a negligible methane and carbon dioxide component (Moore, 1976, 1982; Moore and Sigler, 1987). In June of 1932, a small area on the crest of Harley Dome, partly in T. 18 S., R. 25 E. (SLB&M) and partly in T. 19 S., R. 25 E. (SLB&M), was designated as the Federal Helium Reserve #2 by executive order, which was later rescinded and reopened for leasing in 1964 (Dane, 1935; Willis, 1994; Oil & Gas Journal, 2013). Although Harley Dome was recognized as a separate field for most of its history, UDOGM has included it as the most northeasterly positioned field of several structurally isolated fields that constitute the Greater Cisco Area since 1978. It is treated separately in this report because it is distinctly different from the Cisco helium play and singularly important because of its high helium concentrations.

Harley Dome is geographically located on a basin-margin transitional area between the Uinta and Piceance Basins to the north and northeast, and the Paradox Basin to the southwest (plate 1). The Harley Dome field is positioned on the northwestern surficial flank of the Uncompahgre uplift, a northwest-southeast oriented remnant of the Late Pennsylvanian Ancestral Rocky Mountains (Case, 1991; Hill and Bereskin, 1993; Willis, 1994). The Harley Dome field has historically been difficult for hydrocarbon exploration and production due to an underpressured reservoir, highly saline formation water, and the nitrogen-rich (38.7%–86.1% N_2) gas stream with a significant helium component of more than 7.0%. Production of natural gas has been minimal and primarily in Cretaceous through Jurassic sandstone intervals in the Dakota Sandstone, Morrison Formation, and the helium-bearing Entrada Sandstone (Hill and Bereskin, 1993; Seneshen, 2018). No public helium analyses are available for the Cretaceous formations penetrated at Harley Dome.

The Harley Dome discovery well was drilled in 1925 in the NENE section 4, T. 19 S., R. 25 E. (SLB&M), essentially on the crest of the structure (Willis, 1994). The operator, H.H. Bashor, initially drilled the Bashor 1 well (API 43-019-11513) to 802 feet, which was later plugged back to roughly 600 feet. The well was then acquired by Tom McGuire in 1926 and subsequently tested 2.25% He from the Morrison in July of 1929 (Dane, 1935; Moore, 1982).

Spot samples of four wells at Harley Dome exhibit significantly high helium concentrations between 6.47% and 7.31% from the Entrada Sandstone (figure 22). Three additional wells had helium shows between 2.25% and 2.51% either from the porous and permeable Entrada or channel sandstone beds within the Morrison Formation farther up section. All seven significant helium-tested wells at Harley Dome are clustered atop a northwest-trending structural dome with roughly 100 feet of closure (Dane, 1935; Willis, 1994). The wells are shallow with helium-bearing intervals in the Morrison at 500 to 600 feet and the Entrada at ~800 to 950 feet. Stowe (1972) documented a subeconomic helium sample (0.2% He) from the Cretaceous Dakota Sandstone at a depth of 930 feet from the Harley Govt 1 well (API 43-019-15046) in section 30, T. 18 S., R. 25 E. (SLB&M). On the Colorado side, marginally economic (< 1.0% He) helium shows are located farther north-northeast, opposite the state line from the Utah San Arroyo gas field (Smith and others, 1991) with a significant drop in helium concentration due to dilution from methane generation and migration from hydrocarbon source rocks in the Uinta and Piceance Basins to the northwest and northeast, respectively (figure 8).

The Harley Dome 2 well, formerly the Weightman-Fallgren #1 well (API 43-019-11514), was drilled in 1926 by the same Denver-based Tom McGuire who acquired the discovery well. The well was sampled twice from the Entrada Sandstone and once in the Morrison Formation in 1931 with significant helium shows of 7.06% and 7.02% from the Entrada and 2.45% He from the Morrison (Dane, 1935; Moore, 1982). In a strategic conservation effort by the federal government in 1944, both the Bashor 1 and Harley Dome 2 wells were ordered plugged by the USGS with significant frustration from the operator. In 1968, the Lansdale Govt. 4 (API 43-019-30003) well was drilled to a depth of 972 feet in the Entrada and produced the highest helium concentration recorded in Utah at 7.31% He from a nitrogen-dominated (86.1% N_2) gas stream (figure 22). The Lansdale Govt. 13 (API 43-019-30008) well was also drilled in 1968 but to a greater depth and subsequently penetrated through 35 feet of granite wash and into Precambrian granitic basement rock (figure 21) at 1805 feet, which is suggested to be a good potential source of U- and Th-rich mineral grains necessary to generate helium (Brown, 2010; Craddock and others, 2017). In east-central Utah, the basal member of the Late Triassic Chinle Formation, a known target for uranium ore exploration in Utah (figure 8) (Shoemaker, 1955; Chenoweth, 1990), overlies basement rock forming a nonconformity (Case, 1991), which may indicate a sedimentary contribution to the high-helium gas at Harley Dome. Well file reports for the Lansdale Govt. 13 well document a spot sample of 10 MMcfd and 6.47% He from 946 feet in the Entrada with commingled helium-rich natural gas from the Morrison at 635 feet (Utah Division of Oil, Gas and Mining, 2020).

Multiple well reports from UDOGM in the vicinity of Harley Dome document near-normal or underpressured Jurassic reservoirs, and the production drive mechanism is by solution gas expansion (Campbell and Bacon, 1976) rather than water encroachment. Dense, laminated siltstones and mudrock of the Jurassic Summerville Formation and impermeable shaly members (e.g., basal Tidwell and upper Brushy Basin Members) in the Morrison Formation provide an adequate seal over most of the helium-bearing Entrada Sandstone in this area (Willis, 1994). Uranium-enriched lenticular sandstone beds in the middle Salt Wash Member of the Morrison Formation are more laterally extensive and contain brine water (Shoemaker, 1955; Barton and others, 2018) and nitrogen-rich gas (43.8% N_2) with a much higher methane component (50% CH_4), indicating a leaky seal. Migrating gas will pick up helium and nitrogen from pore water as it sweeps through permeable formations (figures 6 and 10), in addition to gases dissolved in pore water of dense mudrock adjacent to the gas carrier beds (Brown, 2010). This may help to explain the high-helium gas concentrations found in the Entrada and only minor amounts in stratigraphically higher formations (figure 20).

Anomalously high-salinity formation water (< 36,186 ppm), specifically within the shallow Entrada reservoir, is common in this area of far east-central Utah. Farther north, where the Entrada dips gently (< 10°) northward toward the young Uinta Basin in northeastern Utah (figure 8), water recovered from the Entrada during production testing of a well in SWSW section 24, T. 13 S., R. 22 E. (SLB&M) was analyzed and found to contain average total dissolved solids (TDS) of over 80,000 ppm (Eisinger and Lowe, 1999). The impermeable mudrock of the overlying Summerville and Morrison Formations concentrate the brine in the Entrada Sandstone below. Thus, groundwater salinity increases vertically with depth in the Entrada reservoir. According to Sugisaki (1987) and Brown (2010), both pressure and salinity play a major role in the distribution of helium-rich gas in the subsurface. Shallow, underpressured reservoirs exsolve more helium and nitrogen into the gas phase than in deep, higher-pressured reservoirs. Additionally, formations with high salinity in pore water favor more helium in the gas phase (Brown, 2010).

At the time of this report, the source of the helium (granitic basement vs. sedimentary source) at Harley Dome is unclear. Further studies of inert gases at Harley Dome should focus on hydrodynamics associated with helium charge, specifically: (1) mapping the gas-water contact (GWC), (2) determining the trapping mechanism, (3) determining flow direction and source of water, and (4) determining if there is an active petroleum system charging the Entrada carrier bed.

Despite the decades-long status as the Federal Helium Reserve #2, no commercial helium production took place at Harley Dome until IACX Energy commissioned a proprietary, small-scale, non-cryogenic, helium extraction plant in the area in late 2012 (figure 15, bottom) (Oil & Gas Journal, 2013). The Harley Dome plant enabled IACX and Flatirons Resources to justify drilling the Flatirons Fed. 1-4 helium well on the structure during the summer of 2013 (Utah Division of Oil, Gas and Mining, 2020), by allowing the crude helium to be trucked to market. Subsequently, the Flatirons Fed. 1-4, Lansdale Govt. 4, and the Lansdale Govt. 1 became the first and only wells specifically to produce and market the sale of helium from Harley Dome.

Helium sales from nitrogen-rich gas at Harley Dome took place between 2013 and 2018, when a drop in the price of helium caused the wells to be shut-in. Over the course of five years, gas production from IACX's three operational wells at Harley Dome totaled 642,418 Mcf. Transported pure helium gas totaled 42,120 Mcf (Utah Division of Oil, Gas and Mining, 2020). Personal communication with the operator in spring 2019 suggests that a 7.5% He test had been produced from the Fed. 1-4 well prior to shut-in operations, but without formal documentation this analysis cannot be verified and has been left out of this report. In the spring of 2019, operatorship of the currently shut-in Flatirons wells transferred to IACX.

Lisbon Area, San Juan County

The Lisbon oil and gas field area (figure 16) is a proven (Stowe, 1972), but underdeveloped helium play positioned near the center of the Paradox Basin (figure 25), a Paleozoic feature that encompasses much of the Four Corners region on the Colorado Plateau (Parker and Roberts, 1966), specifically southeastern Utah and southwestern Colorado (figures 8, 12, and 13). The Paradox Basin is a hydrodynamically and structurally complex depression created by periods of surface uplift, folding and faulting, and by episodes of salt flowage and coeval subsidence (figure 17) (Hill and Bereskin, 1993; Nuccio and Condon, 1996). Growth of the salt anticlines initiated in Pennsylvanian time, with intermittent growth continuing today (Bradley, 1975; Condon, 1997). Due to extensive salt flowage and the structural complexity of the area, 3-D geophysical exploration is often necessary in locating the deeper structures. Such issues create difficulties for independents that may have limited exploration resources.

Aside from oil and natural gas, economic resources within the Paradox Basin include: Pennsylvanian potash and other salts and brines (e.g., potassium [K] and lithium [Li]), numerous Triassic-Jurassic sandstone-hosted metallic ore deposits (e.g., radium [Ra], uranium [U], and vanadium [V]) (figure 8), and some of the world's largest accumulations of acidic gas (Shoemaker, 1955; Barton and others, 2018).

The helium-bearing Mississippian Leadville Limestone was an attractive target for early petroleum explorers within the Lisbon field area and remains one of many oil and gas plays in the Paradox Basin (figures 19 and 20) (Seneshen and others, 2010; Chidsey, 2016a,b), the more active plays targeting hydrocarbon-rich zones of the Pennsylvanian Hermosa Group, which includes the upper and lower Paradox Formation (figure 18) (Hill and Bereskin, 1993; Cappa and Rice, 1995; Whidden and others, 2012). The Devonian Ouray Limestone underlies the Leadville in the Lisbon field area (Condon, 1995), which straddles Utah and Colorado (figures 26 and 27). The Ouray has produced only minor amounts of oil and gas from the Lisbon field in Utah and is known to lack effective porosity and permeability for hydrocarbons elsewhere in the basin (Parker and Roberts, 1966).

Although the Mississippian hydrocarbon play fairway is extensive (figure 25), only roughly 100 wells have penetrated the

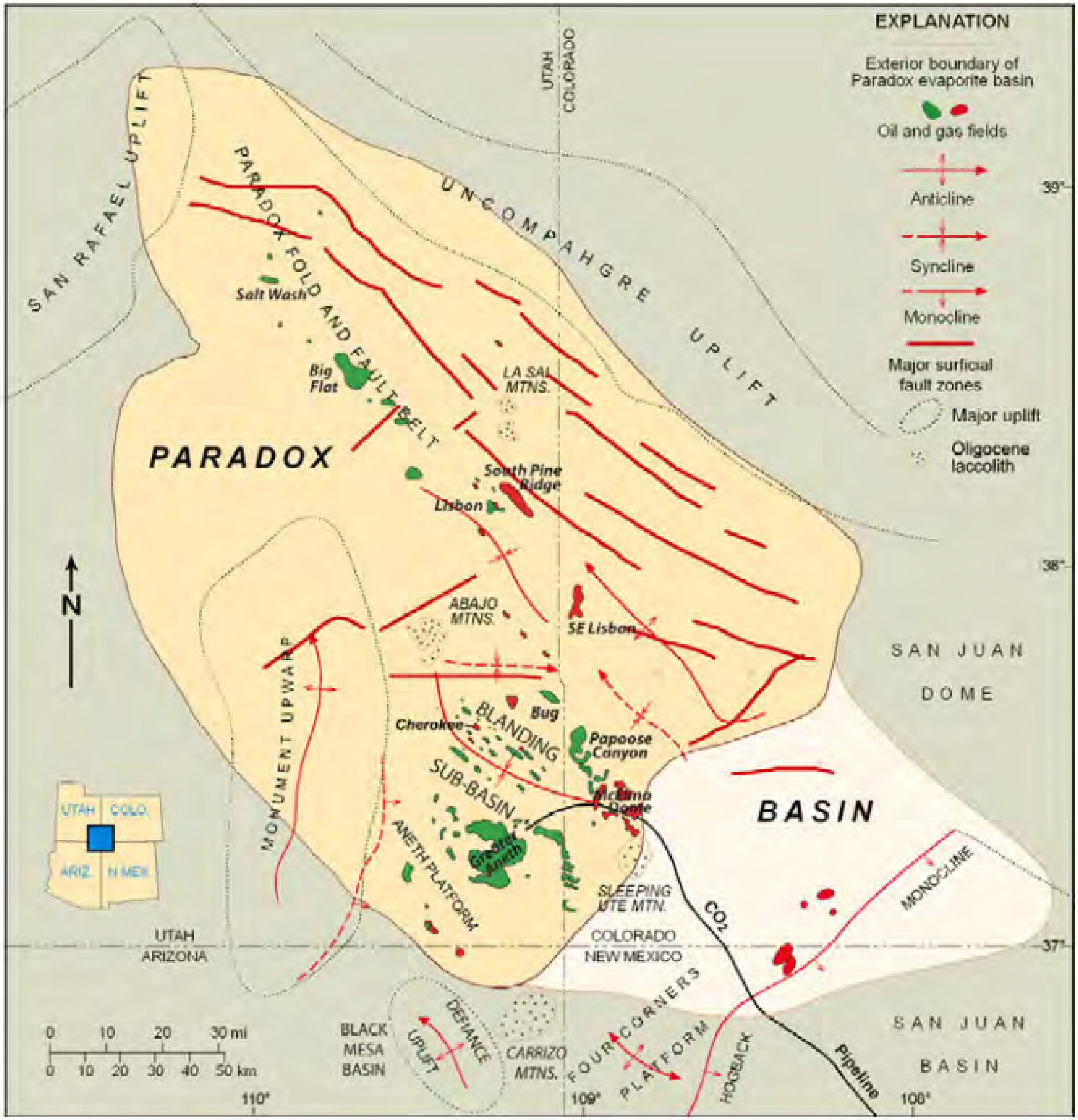

Figure 26. *Generalized area map for the Four Corners region with emphasis on structure and major petroleum fields within the Paradox Basin from Chidsey (2016 b). The northern part of the basin is known as the "Paradox fold and fault belt," and is composed of nearly parallel, northwest-trending faults, anticlines, and synclines. The relatively undeformed Blanding sub-basin and Four Corners platform make up the southern part of the Paradox Basin. Note that the high-carbon dioxide (CO_2) gas produced from Mississippian reservoirs at McElmo Dome in southwestern Colorado supplies CO_2 for enhanced oil recovery to the Greater Aneth field in far southeastern Utah as well as the Permian Basin of West Texas and southeast New Mexico.*

Leadville from the Utah side (Utah Division of Oil, Gas and Mining, 2020), with production primarily from the northwest-southeast trending northern Paradox Basin fold-and-fault belt (Cappa and Rice, 1995; Seneshen and others, 2010). The Leadville has produced over 53 MMbbls of condensate and 854 Bcf of relatively wet natural gas from seven fields in the area with most hydrocarbon production from carbonate reservoirs bounded by basement-involved structural traps within the Lisbon field (Hill and Bereskin, 1993; Seneshen and others, 2010). Predominantly located in T. 30 S., R. 24 E. (SLB&M), the Lisbon field area is situated on a large, faulted anticlinal paleo-structure that encompasses eight geographically defined oil and gas fields over ~50,000 acres in San Juan County. The Lisbon anticline is fully encased by Paradox salt and has structural closure of nearly 2000 feet with a high-angle reverse fault bordering the northeast boundary (Bradley, 1975). The oil and associated gas field was discovered in 1960 by the Pure Oil Company with their No. 1 NW Lisbon (A) well using

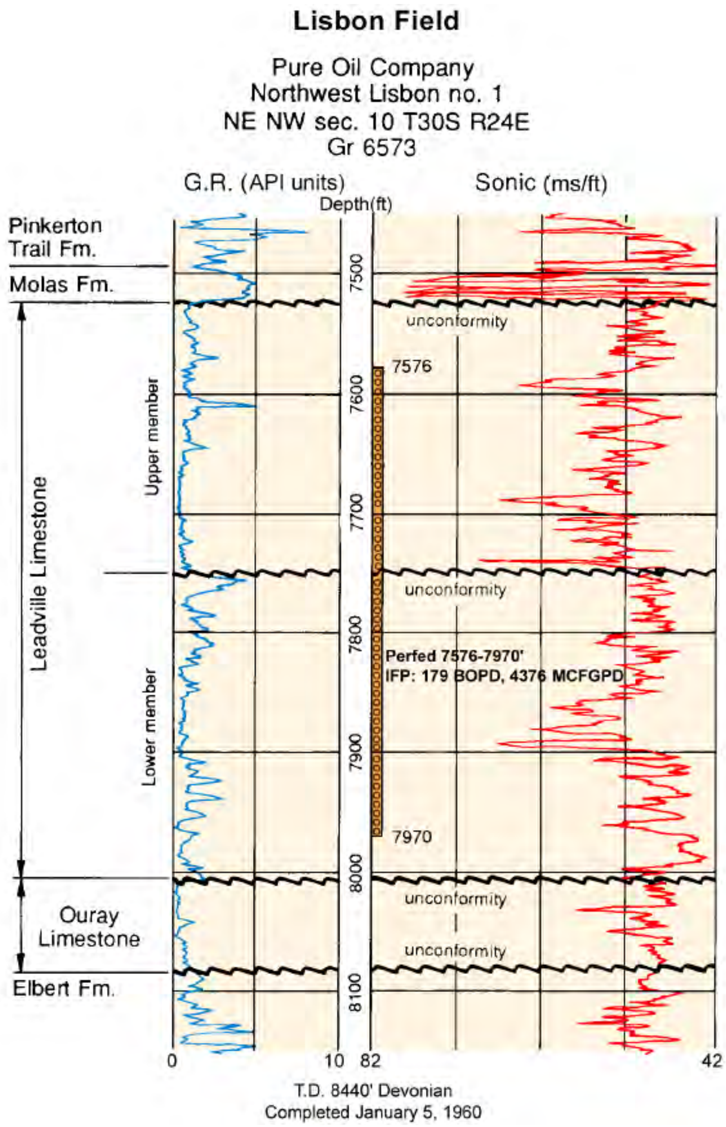

Figure 27. *Typical gamma ray-sonic log of the Mississippian Leadville Limestone from Chidsey (2016 a). Note the Northwest Lisbon no. 1 well was completed as the Lisbon field discovery well in 1960. The well was perforated between 7576 and 7970 feet.*

extensive subsurface (figure 27) and seismic exploration (Preston, 1961; Stowe, 1972). At a depth of 8000 to 9000 feet, the folded and faulted porous zones in the basal McCracken Sandstone Member of the Devonian Elbert Formation and Mississippian Leadville Limestone dolomite beds form the primary reservoirs (Baars, 1966; Hill and Bereskin, 1993), and both are prospective for helium. An expanding gas cap and gravity drainage are the primary drive mechanisms (Seneshen and others, 2010). Campbell and Bacon (1976) report that the gas cap over the Mississippian section of the Lisbon field contains significant amounts of helium and acidic gas.

The high gamma-ray signatures in Devonian-age rocks found in well logs around the Lisbon area and across eastern Utah indicate that the shaly mudrock and dirty carbonate beds of the Devonian Upper Member of the Elbert Formation have a higher radioactive content than the Mississippian section above (figure 28) (Condon, 1995, Utah Division of Oil, Gas and Mining, 2020). A long generation duration is required to generate significant amounts of radiogenic helium per volume of rock (Brown, 2010). Thus, a large volume of source rock is required. Although overall rates of helium generation are low for average carbonates and sandstones, significantly higher generation rates can occur in old shales, granites, and some dirty limestones and dolomites (figure 7) (Bell and others, 1940; Zartman and others, 1961; Brown, 2010). It is likely that the extensive and thick Paleozoic sedimentary section on the Colorado Plateau (Campbell and U.S. Geological Survey, 1981; Condon, 1995; Nuccio and Condon, 1996) has a similar, if not the same, helium generation potential as the underlying crystalline and granitic basement rock. It should also be noted here that petroleum source rocks are not helium source rocks (Swanson, 1960; Brown, 2010). Only a small amount of thermogenic methane from hydrocarbon-rich rocks can significantly dilute a high-helium gas to subeconomic amounts (Brown, 2010, 2019).

Many of the wells in the Lisbon field area have been plugged back or re-completed in the hydrocarbon-rich Paradox For-

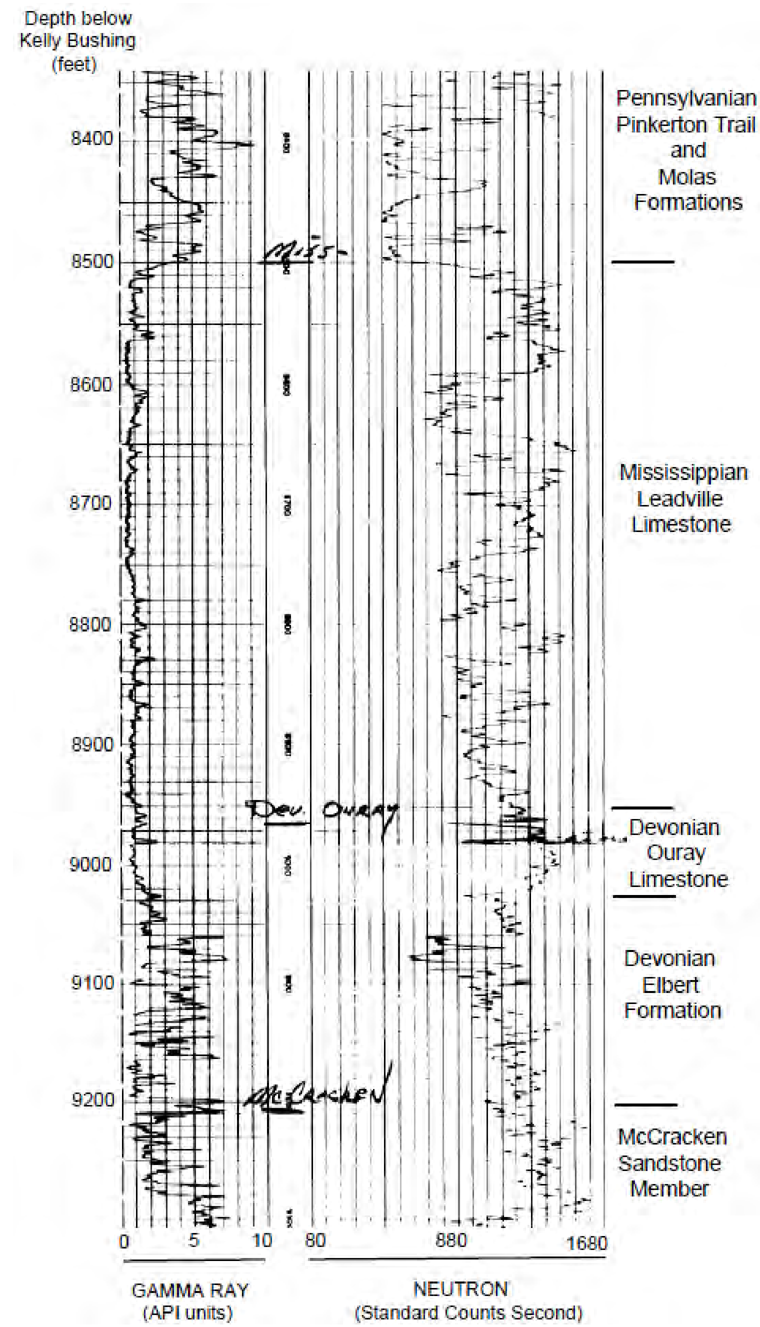

Figure 28. *Gamma-ray and sonic logs, Apache Drilling Co Inc., Apache Federal #1 (API 43-037-10047). NESE section 13, T. 30 S., R. 23 E. (SLB&M). Wildcat well drilled in 1960 just outside of the Lisbon oil and gas field within the Mississippian Leadville Limestone play fairway in San Juan County, Utah. The well was drilled and abandoned as a dry hole. Sourced from the well file from the Utah Division of Oil, Gas and Mining (2020).*

mation farther up section. Produced gas from Lisbon is predominantly methane (~30%–70% CH_4) and carbon dioxide (18%–36% CO_2) with nitrogen (< 21% N_2), hydrogen sulfide (< 1.7% H_2S), and helium (~1.0% He) making up the remainder of the gas stream (Moore and Sigler, 1987; Cappa and Rice, 1995; Craddock and others, 2017). Acidic gas (CO_2 and H_2S) is plentiful throughout the Lisbon area and may be related to bacterial sulfate reduction by hydrocarbons or other organic material (Jenden and Kaplan, 1989; Barton and others, 2018). Although long migration of acidic gases may help to concentrate helium and nitrogen in the gas through mineralization into solids (figure 10, C), sour gas is deadly and extreme caution must be used during exploration and production in this potential helium play fairway.

The helium percentages within the Lisbon field area reach a high of 1.28% He from the Leadville Limestone in the unitized Husky Fed 15-25/Hook and Ladder well located in section 25, T. 29 S., R. 23 E. (SLB&M) (Gage and Driskill, 2003), which is currently a shut-in gas well operated by Paradox Resources, LLC. Most of the wells identified within the Lisbon field have a 1.0% He or lower helium concentration (see appendix) and most of the original wells drilled are currently producing natural gas (Utah Division of Oil, Gas and Mining, 2020). Paradox Resources has infrastructure in place capable of recovering and processing helium at their Paradox Midstream (Lisbon) gas plant located in San Juan County, with a maximum capacity of 60 MMcf per day (figure 16).

Seneshen and others (2010) conducted surface geochemical surveys to evaluate the effectiveness of low-cost, non-invasive methods to identify areas of poorly drained or by-passed oil throughout both the Lisbon and Lightning Draw SE fields. The study suggests that helium and carbon dioxide anomalies in free soil gas at the margins of producing reservoirs could be the most diagnostic indicators of underlying Leadville reservoirs (Seneshen and others, 2010). Produced gas compositions indicate that, in comparison with the Lisbon field, the Lightning Draw SE field contains a lower concentration of hydrocarbons and more nitrogen and helium. The Lightning Draw SE field, located primarily in section 31, T. 30 S., R. 24 E. (SLB&M), currently has two shut-in gas/condensate wells operated by Genesis ST Operating, LLC. Gas stream helium weight percentages from both the Federal 1-31 and Evelyn Chambers Gov. 1 wells report a 1.42 and 1.40 wt % He, respectively (Seneshen and others, 2010). The two gas analyses noted from Seneshen and others (2010) do not reflect reservoir gas, therefore they have been excluded from the associated appendix for this report. However, the analyses may show a correlation to high-helium gas trends in the area. No gas wells from the Lightning Draw SE field were ever tested for helium by the USBM.

Although numerous wells with economic helium shows indicate a potential helium prospect, sour gas is found throughout the Lisbon area (Cappa and Rice, 1995), typically in reservoirs within the Leadville Limestone below the salt and hydrocarbon-productive Paradox Formation (figure 20). Sour gas generally forms where hydrocarbon is exposed to large accumulations of evaporites and from thermal sulfate reduction at depth during maximum burial (Cappa and Rice, 1995; Nuccio and Condon, 1996). Not only is H_2S a poisonous gas, it is capital-intensive to remove from the gas stream and is also highly corrosive to steel equipment, causing operational problems during production (Parker and others, 2011). Without significant helium concentrations, above those documented in this report to make extraction of helium economic, this play has a low potential for direct helium exploration. The helium gas found at Lisbon will remain a potentially profitable component to the carbon dioxide-rich natural gas stream for regional operators connected to the Lisbon gas processing plant (figure 16).

Salt Wash Area, Grand County

The Salt Wash helium play is located a few miles east of the Green River and about 15 miles south of the town of Green River in the northern Paradox Basin, regionally known as the Paradox fold-and-fault belt (figures 25 and 26). Incorporating the Greentown field to the north and Ten Mile field to the south, the Salt Wash field area has documented petroleum production from the Mississippian Leadville Limestone with significant hydrocarbon shows in clastic zones of the Pennsylvanian Paradox Formation farther up section (figure 20) (Preston, 1963; Hill and Bereskin, 1993). Campbell and Bacon (1976) note the Salt Wash field as being a faulted anticline with a free gas-cap reservoir drive mechanism. Helium prospects at Salt Wash are geographically located within the helium play fairway of the Leadville Limestone (figure 25). Westwardly thinning cycles of Paradox salt (Hanshaw and Hill, 1969) form an effective seal to helium-rich gas reservoirs deep in the thick carbonate rock of the Leadville.

The structurally controlled condensate and associated gas accumulations in limestone and dolomite reservoirs of the Mississippian Leadville Limestone was discovered in 1961 using seismic data to define the salt-induced anticlinal structures (Hill and Bereskin, 1993). The discovery well was the Pan American Salt Wash 1, which produced high API gravity oil (55°) and heavy gas-cut brine from the Leadville at 8693-8707 feet (Preston, 1963). The completion report also documented good porosity with hydrocarbon-stained vugs and vertical fractures throughout the Mississippian section (Utah Division of Oil, Gas and Mining, 2020). Moore (1982) include a 1.80% He analysis taken from a DST during drilling through the Leadville at 8553 feet in their published report. The completed Mississippian interval located a few hundred feet below the 1.80% He DST sample was also tested with a note that the DST gauged 7000 Mcf of gas per day of "non-flammable gas." Typical of many wells drilled through the salt and anhydrite zones of the Paradox, the casing collapsed in the Paradox section of this well because of pressure from salt flowage. The well produced 55,961 barrels and 1.2 Bcf of natural gas during its three-year producing life (Utah Division of Oil, Gas and Mining, 2020). Efforts to re-complete in pursuit of shallower shows were unsuccessful and the well was subsequently plugged and abandoned. Although the high helium concentration recorded here may be encouraging, the helium is likely dissolved in the oil, which may be responsible for the high-helium gas percentage and may not be an adequate representation of the reservoir potential.

Five wells at Salt Wash, all located within the center of T. 23 S., R. 17 E. (SLB&M), recorded helium-rich gas ranging from a high of 1.80% to 0.78% He. All the helium tests were from nitrogen-dominated (~78% N_2) low-Btu gas streams (Stowe, 1972; Moore and Sigler, 1987).

The Marland Oil Co. well #1 was drilled in 1926 in section 35, T. 21 S., R. 16 E. (SLB&M) 3 miles south of the town of Green River in an area known for carbon dioxide leaks to the surface through low-temperature springs, seeps, geysers, and abandoned oil wells (Heath and others, 2009). The Marland well recorded "several flows of a non-flammable gas" on submitted drilling reports (Utah Division of Oil, Gas and Mining, 2020). The operator reported that samples of the gas were sent to the "Ft. Worth plant of the Helium Division for analysis," though no documented helium test could be found for this well. The U.S. Helium Production Plant No. 1 in Ft. Worth, Texas, was designed by the Linde Air Products Company in 1918 and completed in 1921 by the U.S. Department of the Navy (National Research Council, 2000). The plant consisted of a laboratory, a separation and compression facility, a helium cylinder storage facility, a pressure reducer house, and a pumphouse. This early 20th century helium plant was the second helium-extraction facility in the United States and a key component of the United States Strategic Materials Program.

San Arroyo Area, Grand County

The San Arroyo area is geographically located along the Book Cliffs escarpment, which forms the topographic and structural boundary between the Uinta and Paradox Basin (figure 8) (Hill and Bereskin, 1993). The San Arroyo play fairway has a northeast orientation that extends from the northeast corner of Grand County, Utah, into Mesa, Garfield, and Rio Blanco Counties of Colorado before an abrupt end on the southern edge of the Douglas Creek Arch near Rangely, Colorado (plate 1). On the Utah side, the San Arroyo helium play includes helium spot samples analyzed from five contiguous, northerly plunging natural gas fields: San Arroyo, Bar X, Bryson Canyon, Stateline, and Westwater (Wood and Chidsey, 2015). Historically, the San Arroyo field has been the most successful with 174.6 Bcf cumulative gas production through 2018. Together the group has produced 319.4 Bcf of natural gas (Utah Division of Oil, Gas and Mining, 2020).

These fields produce non-associated gas from sandstone intervals in the Cretaceous Dakota Sandstone and Buckhorn Conglomerate Member of the Cedar Mountain Formation, the Late Jurassic Brushy Basin and Salt Wash Members of the Morrison Formation, and the Middle Jurassic Entrada Sandstone (figure 21). Small quantities of oil have been produced from the Cretaceous Mancos Shale from several wells (Utah Division of Oil, Gas and Mining, 2020), and minor amounts of natural gas have been produced from the Cretaceous Castlegate Sandstone farther up section. Of these stratigraphic intervals, the Jurassic Morrison and Entrada are the primary helium-bearing reservoir rocks in the San Arroyo play fairway, with the Salt Wash Member a well-known source of uranium throughout the Colorado Plateau (figure 8) (Shoemaker, 1955; Gloyn and others, 2003; Barton and others, 2018).

Eleven wells are on the Utah side in the San Arroyo play fairway with economic helium concentrations ranging from 0.30% to 1.0% He (Stowe, 1972; Moore and Sigler, 1987; Gage and Driskill, 2005). Nine of these helium tests came from the Entrada Sandstone in low-Btu gas streams with significant nitrogen (~25% N_2) and carbon dioxide (~20% CO_2) shows. The other two documented helium analyses were from the Morrison Formation. Many subeconomic (< 0.30% He) helium samples have been recorded in the stratigraphically higher Cretaceous Dakota Sandstone throughout the San Arroyo field area from both Utah and Colorado (figure 1). Most of the wells that sourced and documented spot samples of helium have been plugged and abandoned (Utah Division of Oil, Gas and Mining, 2020).

Utah Gas Corp (UGC) currently recovers crude and purified helium from over 700 natural gas wells across 250,000 acres of mineral leasehold within the San Arroyo field area along the western margin of the Piceance Basin between Utah and Colorado (figure 8) (Utah Division of Oil, Gas and Mining, 2020; Colorado Oil and Gas Conservation Commission, 2020). Helium is processed, along with crude oil, field condensate, and natural gas at UGC's processing plants located near Rangely and Mack, Colorado (plate 1).

Temple Springs Prospect, Emery County

The San Rafael Swell (figure 8) in Emery County is a Laramide-age basement-involved structure (figure 9) that consists of over 11,000 feet of sedimentary strata ranging in age from Cambrian to Cretaceous and includes marine, fluvial, eolian, and continental deposits overlying the basal Cambrian Tintic Quartzite and Precambrian granite and schist (Bartsch-Winkler and others, 1990; Condon, 1995; Allis and others, 2001). The northeast-oriented San Rafael Swell is part of an older anticlinal feature known as the Emery uplift (figure 12), a buried, northwest-trending Paleozoic structure that transects the northern and central part of the San Rafael Swell (Baars and Stevenson, 1981; Bartsch-Winkler and others, 1990). The San Rafael Desert on the eastern flank of the San Rafael uplift includes ~1080 square miles of sparsely explored lands with roughly one dry hole per 15 square miles. The area is bisected by at least two major high-angle faults (plate 1) with a northwest-southeast orientation observable in both well log correlation and publicly available, regional aeromagnetic surveys (Sims and others, 2008). Much of the exploration work was done in the 1950s and 1960s by major oil companies (e.g., Chevron, Humble, Mobil, Shell, and Texaco) and a variety of independents (Doelling and others, 2015; Utah Division of Oil, Gas and Mining, 2020). Many of these wells were cored, and it was common for multiple drill stem tests to be run while drilling (figure 24).

Uranium-vanadium ore deposits (figure 8) and fault-bounded uraniferous breccia pipe structures are well documented within the nearby Temple Mountain district of Emery County (Shoemaker, 1955; Hawley and others, 1965, 1968; Bartsch-Winkler and others, 1990; Chenoweth, 1990). The presence of large volumes of uraniferous ore deposits, asphaltic residue and dead oil staining in the gas column (Utah Division of Oil, Gas and Mining, 2020), and low-temperature springs with associated mineralization along northwest-oriented, surface fault ruptures (Heath and others, 2009) within proximity to the Texaco helium discovery well indicate a significant interplay of volcanogenic, thermogenic, and hydrodynamic controls of several kinds.

According to Hawley and others (1965, 1968), the most likely source of mineralization and economic roll-front ore deposits in the San Rafael Swell and surrounding area is from hydrothermal solution or formational water derived from magmatic sources, coeval with the Laramide orogeny. Hawley and others (1968) postulate that the same ore-forming solutions are responsible for the collapse structures that act as conduits for mineral-rich groundwater to permeate deeper formations. It seems reasonable that the helium-rich gas found at depth in the San Rafael Desert is at least partially influenced by near-surface, uranium-charged groundwater sourced from the breakdown of ore bodies within thick accumulations of Permian- and Triassic-age sedimentary rock. Further geochemical analysis beyond the scope of this paper would be required to test this hypothesis.

The Texaco Temple Springs Unit 1 well drilled in late 1959 and early 1960, in section 14, T. 25 S., R. 13 E. (SLB&M), found predominantly nitrogen (97.2% N_2) gas with a helium component of 2.77% from DST #6 at a depth of 4670 feet (figure 24) in a shaly dolomite interval of the Upper Devonian Elbert Formation (figure 20). The test flowed at 90 psi through a 1-inch choke and recorded a “very strong blow” with a recovery of 2387 Mcf of inert gas that “would not burn” and 220 feet of brackish groundwater (Utah Division of Oil, Gas and Mining, 2020). Ammonium in clays can be released by interaction with brines, and when groundwater with dissolved ammonium becomes oxidized it generates nitrogen gas (Brown, 2017). The helium-bearing nitrogen-rich gas and uraniferous petroleum residue described by Hawley and others (1965, 1968) may indicate that the disintegration of nitrogenous organic compounds by alpha radiation (Bell and others, 1940) plays a part in the high-helium gas found below the San Rafael Desert.

Although the Temple Springs helium discovery well was drilled and abandoned as a dry hole, this result and the 1.47% He test from the overlying Mississippian Leadville Limestone prospect 20 miles to the east at Bowknot, have piqued the interest of helium pure play explorers such as Tacitus Corporation, Twin Bridges Resources, and North American Helium (NAH Utah, LLC). Much of state trust lands and BLM acreage in this area is currently leased by these operators. In August 2019, four applications for permits to drill on BLM lands surrounding the 1959 discovery well were recorded by the Utah Division of Oil, Gas and Mining and the Moab BLM field office.

Temple Springs is a significant helium prospect with further exploration needed to define the geographic extent of the play. The negligible carbon dioxide and low methane content found in the gas stream at Temple Springs is encouraging for further helium exploration and development in the area. The Devonian-Mississippian Emery County helium play fairway is an intriguing target at a time when pure play helium exploration is gaining economic interest.

Woodside Dome Field, Emery County

Woodside gas field, also known as Woodside Dome or Woodside Anticline (Campbell and Bacon, 1976), is geographically located in T. 18–19 S. and R. 13–14 E. (SLB&M), between the north end of the San Rafael Swell to the west and the Book Cliffs escarpment to the east (plate 1). The field is immediately west of U.S. Highway 6 between the towns of Green River and Wellington. The Woodside helium play has historically recorded low-methane, carbon dioxide- and nitrogen-rich gas primarily from the Permian Black Box Dolomite (formerly named the Kaibab Limestone in the San Rafael Swell area) (Preston, 1961; Stowe, 1972; Welsh and others, 1979; Hill and Bereskin, 1993; Condon, 1997). Moore (1982) documents additional significant nitrogen and carbon dioxide shows in the Pennsylvanian Hermosa Group, the Triassic Chinle and Moenkopi Formations, and the Jurassic Entrada Formation (figure 20).

Woodside Dome is one of the larger subsidiary folds associated with the Laramide episode of deformation along the San Rafael anticline, which forms the northwest edge of the Paradox Basin (Bartsch-Winkler, 1990). The asymmetric structure of Woodside Dome trends in a north-south orientation along the eastern flank of the north-plunging end of the San Rafael Swell (figure 8) (Hill and Bereskin, 1993; Condon, 1995). The area of closure is roughly 12,800 acres, with maximum structural relief of 800 feet (Gloyn and others, 2001). The western limb terminates along a west-dipping, basement-involved reverse fault (Preston, 1961).

By executive order, Woodside Dome was set aside as the United States Helium Reserve #1 in March of 1924 (Dobbin, 1935) after the Utah Oil Refining 1 Fitzhugh (Woodside 1 Fitzhugh) discovery well in SWSE section 12, T. 19 S., R. 13 E. (SLB&M) encountered 1.33% He at a depth of 3120 feet, in a nitrogen-rich (68.1% N_2) gas stream with a significant carbon dioxide component (28.4% CO_2) from the Black Box Dolomite (Preston, 1961; Moore and Sigler, 1987). The well reached a depth of 3375 feet and was completed as a shut-in helium gas well in 1924. Reports in the well file note that gas samples were sent to government officials in Washington, D.C., and plans to plug and abandon the well soon followed. This discovery well never produced marketable helium and further exploration for hydrocarbons continued on the structure (Utah Division of Oil, Gas and Mining, 2020).

In 1962, Humble Oil & Refining Company drilled the Woodside Dome Unit #1 well (API 43-015-10505) in the SESE of section 12, T. 19 S., R. 13 E. (SLB&M), to test several members of the deeper Paleozoic formations for oil and gas. The Unit #1 well penetrated the Cambrian Tintic Quartzite at a depth of 8431 feet and ran multiple DSTs in the Mississippian, Pennsylvanian, and Lower Permian sections before being abandoned as a dry hole (Utah Division of Oil, Gas and Mining, 2020). Although no helium sample documentation can be found within the UDOGM well file, Moore and Sigler (1987) documented a helium show of 0.30% from the uppermost Pennsylvanian Hermosa Group and 1.03% from the "lower Cutler beds" of the Permian Cutler Formation, (formerly the Elephant Canyon Formation in the northwestern part of the Paradox Basin [Condon, 1997]).

Holly Resources Corporation re-entered the Unit #1 well in 1969 to a total depth of 3800 feet and renamed it the Federal #44-12 well. The drilling report for the Federal #44-12 well documents three perforation stages, all within the Permian Kaibab Formation, also known locally as the Black Box Dolomite (Welsh and others, 1979; Condon, 1997), which found a "heavy stream of salt water." Issues occurred downhole with a leaking bridge plug and the well was immediately plugged and abandoned (Utah Division of Oil, Gas and Mining, 2020). No mention of a helium test was given in the well file, but the date and formation of a spot sample of 1.51% from a nitrogen- and carbon dioxide-rich (64.4% N_2 and 33.0% CO_2) gas stream from the Permian Kaibab equivalent from Moore and Sigler (1987) match the UDOGM drilling report and further verified the helium potential at Woodside.

In 2007, Bill Barrett Corp. (BBC) drilled the Woodside #1 (API 43-015-30701) in the SESE of section 12, T. 19 S., R. 13 E. (SLB&M) to test several members of the Pennsylvanian Paradox Formation and the deeper Mississippian section for hydrocarbons. BBC completed a gas well between intervals 5010 and 5672 feet, but the well was subsequently shut-in upon completion due to lack of pipeline access. Recent interest in pure play helium exploration resulted in the Woodside Dome #1 transfer of operatorship from BBC to Twin Bridges, and then to IACX Energy, LLC in the spring of 2013 (Utah Division of Oil, Gas and Mining, 2020).

IACX permitted the Woodside Dome 2 helium well (API 43-015-30766) later in 2013, with the survey stake 30 feet north of the Woodside #1 well. The helium prospect was drilled into the Permian Black Box Dolomite to a depth of 3327 feet. UDOGM well file notes indicate the helium well was plugged back to 3290 feet and completed openhole from 3161 to 3265 feet within the Black Box Dolomite. Publicly available gamma ray-sonic logs indicate that the completed interval for the helium prospect well was in a zone of high radioactivity (Utah Division of Oil, Gas and Mining, 2020). This validates work done by Bell and others (1940) who note that zones of impurity within the Kaibab Limestone elsewhere on the Colorado Plateau are highly radioactive. At the time of this report no gas analysis or production has been verified and the potential helium well remains shut-in.

The Woodside Dome 3 well was permitted and drilled by IACX into the Permian Kaibab equivalent to a depth of 3160 feet in late 2018. The Black Box Dolomite was found to be "wet" and the well was shut-in pending evaluation for deepening to the Paradox Formation or operations to plug-and-abandon the location. To date, no helium has yet to be sold from this perspective play.

Wildcat Helium Prospects

Several wildcat oil and gas exploration wells have encountered helium in Utah (see appendix). To the extent that it has been judged reasonable to do so, several of these wells have been included in the discussion of nearby helium-bearing fields and play fairways that exhibit similar geology. A brief description of events and analysis is discussed below from significant outliers.

In 1971, Kimbark Operating drilled the Fed. Fish Creek 1 well in section 22, T. 38 S., R. 20 E. (SLB&M), San Juan County, on the Comb Ridge Monocline positioned along the eastern flank of the Monument Upward and in the helium play fairway of the Mississippian Leadville Limestone (figures 25 and 26). This well had a significant helium show of 1.34% from a natural gas stream (53.8% CH_4, 27.3% N_2) sourced from the Pennsylvanian Paradox Formation Ismay-Desert Creek interval (figure 20) at a depth of 2050 feet. The helium discovery well was drilled to a total depth of 3610 feet in the Mississippian Leadville Limestone and abandoned as a dry hole (Utah Division of Oil, Gas and Mining, 2020). The Fish Creek 1 well is now located inside the Shash Jaa Unit of the Bears Ears National Monument (plate 1). Helium exploration on the steep eastern limb of the Monument Upwarp to the east and southeast of this discovery well is necessary and encouraged.

In 1963, Texas Pacific Coal & Oil Co. drilled and abandoned the USA B 1 well as a dry hole in section 9, T. 35 S., R. 25 E. (SLB&M), San Juan County. Drilling reports submitted to UDOGM indicate multiple drill stem tests had been recovered from the Devonian-Mississippian section. The depth of DST #1 correlates with the 0.4% He analysis from the Leadville Limestone reported by Moore and Sigler (1987) from a depth of 7034 feet. The gas analysis documented a low-methane, carbon dioxide-rich (88.6% CO_2) gas stream (Utah Division of Oil, Gas and Mining, 2020).

The most westerly outlier, the Escalante Unit 2 well, was drilled in the SESW section 29, T. 32 S., R. 3 E. (SLB&M) in Garfield County to a depth of 3878 feet by Phillips Petroleum Company. Submitted drilling reports from 1961 indicate "continuous flow of non-flammable gas" beginning at 1360 feet while coring. A partial gas analysis at a depth of 1606 feet reported 89.4% CO_2 and 0.082% He. At a depth of 2260 feet, a 0.30% He spot sample from the Triassic Moenkopi Formation (figure 20) was taken while drilling (Utah Division of Oil, Gas and Mining, 2020). The USBM database shows a similar helium test from a carbon dioxide-rich (93.1% CO_2) gas stream of the Mississippian Leadville Limestone, but further study of log tops submitted with the completion report indicate this analysis was likely from the Permian section.

CONCLUSIONS

Helium is a rare and exhaustible resource found in recoverable quantities during natural gas production in very few gas fields around the world, many of which are nearing depletion. In the United States, helium can be a profitable byproduct during the extraction and processing of natural gas from proven helium-rich conventional gas fields. It is likely that billions of cubic feet of critically important and valuable helium gas are wasted annually during the production of natural gas. The peculiar properties of helium (e.g., light weight, small size, chemically inert, ultra-cool liquid temperature, and highly diffusive) make it an element that can be used in a variety of commercial, industrial, medical, defense, and research applications as both a liquid and a gas. Continued demand for helium will depend on a range of factors, but for many cutting-edge technologies and medical diagnostic applications helium is unique and has no known replacement.

Since 1962, the federal government has maintained the only significant long-term, large-scale storage facility and pipeline for crude helium. The Bush Dome reservoir and federal storage facility in the Cliffside gas field near Amarillo, Texas, is the single-most important depository of helium in the world. A 1996 legislative ruling for the federal government to divest of all helium assets by fall 2021 is nearing completion. Without further helium exploration in the United States, this critical resource will become increasingly scarce, creating a potentially volatile industry as we depend on fragile overseas supply lines to fulfill our increasing helium demand.

Helium occurrences throughout Utah and across the Colorado Plateau have been influenced by a combination of mantle and crustal processes. Helium migration initiates with the alpha decay of uranium and thorium from mineral grains. Recrystallization and diffusion concentrate helium into pore water and groundwater over tens to hundreds of million years. Migrating volcanogenic and thermogenic gases sweep helium and nitrogen from old pore water. Recrystallization of acidic gases into solid minerals over long migration distances helps to concentrate helium and nitrogen in the gas phase. Thus, the longer the migration duration the more nitrogen- and helium-rich the gas.

Helium-rich gas in Utah is not limited to areas of proven oil and gas production or reservoir rock of a particular age or type. Carbon dioxide and nitrogen may be significant carrier gases for helium in the subsurface. Due to significant helium dilution by methane generation, helium is not typically found in basin centers where most hydrocarbons are produced. In general, Paleozoic rocks typically will have had more time to generate and collect more helium than younger rocks, but this relationship is based on the older (Paleozoic) helium- and nitrogen-rich groundwater that fills the pore spaces rather than the age of the rock itself. Thus, understanding the hydrodynamics of a prospective helium play is critical. Dissolved helium in migrating groundwater will exsolve from the liquid phase at lower reservoir temperatures and pressures, which may help to explain the occurrence of high-helium gas accumulations in some shallow reservoirs along basin-uplift transitional areas.

The highest helium concentrations in Utah are found beneath shallow structural traps within the underpressured Jurassic Entrada Sandstone reservoir at a depth of ~1000 feet. Significant economic helium potential may exist within the extensive, yet relatively unexplored Devonian-Mississippian reservoirs of the Elbert Formation, Ouray Limestone, and Leadville Limestone. This helium play contains nearly 40% of the wells with helium concentrations over 0.30% in the gas stream, with the majority sourced from carbonate reservoirs of the Leadville Limestone. Trapped and separated from methane dilution from the hydrocarbon-rich Pennsylvanian section by multiple layers of salt and bedded anhydrite, the Devonian-Mississippian helium play fairway encompasses much of southeastern Utah. On the Navajo Nation farther south, the Boundary Butte field area has significant helium shows from analyses taken within clastic reservoirs of the Paradox Formation, as well as high-helium gas stratigraphically lower in the Devonian Ouray Limestone. Laterally and vertically sealed arkosic granite wash of the Permian Cutler Group has recorded significant helium shows along the southwestern flank of the Uncompahgre uplift on the Colorado side, yet remains almost entirely unexplored in Utah.

In the immediate future and with the availability of portable, small-scale helium recovery units and truck-mounted shipping containers for simplified transportation, non-flammable gas streams with a significant helium component (1.0%–7.0% He) are likely to be the near-term focus of pure play helium exploration in Utah. However, gas fields with significant methane production in areas where helium is likely should also be explored. With natural gas prices lingering in a marginally economic range for the foreseeable future, recovery of helium might make sense for improving the economics of natural gas wells.

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APPENDIX

Helium gas shows in Utah as of December 2019:

https://ugspub.nr.utah.gov/publications/misc_pubs/mp-174/mp-174.xlsx