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FOCUSED ISSUE: HELIUM

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For additional information, contact:

Executive Editor, *The Mountain Geologist*, RMAG
730 17th Street, Suite B1
Denver, CO 80202
(720) 672-9898
mgeditor@rmag.org
www.rmag.org

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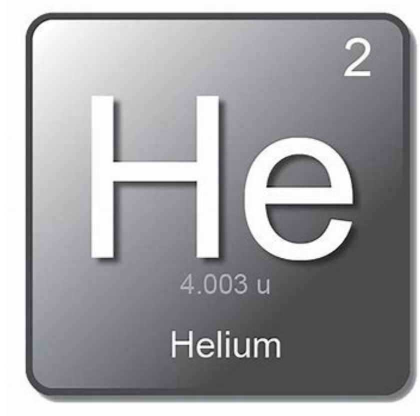
Helium extraction facility in Arizona provided by IACX.

PREFACE

This addition to the Mountain Geologist of a Helium issue was the result of a very successful helium symposium hosted by Rocky Mountain Association of Geologists in Denver March 22nd to March 23rd. The conference was also an exceptional financial success for RMAG. The conference was attended by over 300 people from the USA and Canada, representing not only geologists and engineers but midstream and processing companies as well. Presented here are five papers. It is generally difficult to get presenters to convert their presentations to a technical paper as it requires a significant amount of time and effort. Many people have a difficult time with doing technical writing and as such there is a reluctance to pursue such an effort despite some relaxing of the requirements and guidelines. We are fortunate that these five individuals were kind enough make that effort to share their thoughts and ideas with the Mountain Geologist readers.



Helium in 2023 is a critical element in short supply selling for $550 (US) per MCF. Without helium our present society would grind to slower pace because of its lack. Helium has become critical for welding, cryogenics, medical and military. Of course the most critical consumption is always party ballons; need to keep the kids happy.

The Bureau of Land Management facility at Cliffside is up for sale and the Russian-Ukrainian war has disrupted at least 10% to 20% of the world supply of helium. Small Juniors or Independents in Southeastern Alberta and Southwestern Saskatchewan, Canada and in the Witwatersrand, South Africa are developing new fields that are allowing these two countries to potentially become world class producers. Qatar is expanding its ability to extract helium. Several historical areas such as the Holbrook Basin, Black Mesa Basin, Apishapa Uplift, Four Corners Platform, Harley Dome, Texas Panhandle—Hugoton Field, Paradox Basin and Central Uplift in Kansas are seeing increased development and exploitation. The main producing area in the USA at Big Piney—La Barge being produced for helium as a by-product of carbon dioxide production by Exxon keeps chugging along. Some interest is developing in exploration areas back east such as Precambrian rift areas in Kentucky and in northern Minnesota near Duluth.

The increased interest in helium is only hampered by the major cost of the processing facility that has to be put into place to extract the element. In an increasing negative attitude in society toward hydrocarbons some operators focus on helium with nitrogen only as the host gas. Others are plagued by the host gas carbon dioxide. It requires re-injection, sales or venting which is a difficulty unto its own with the permitting and regulatory process being long and difficult. The advantage of having the host gas being natural gas is that it makes power requirements less costly.

Please enjoy these five papers and hope it helps in understanding helium in a more positive light as an opportunity to increase revenue.

—Steve Tedesco
Executive Editor for The Mountain Geologist

Helium – Relationships To Other Reservoir Gases And Some Implications For Exploration: The New Mexico Example[1]

RONALD F. BROADHEAD[2]

1. Manuscript received June 16, 2023; Accepted September 25, 2023.

2. Retired/Emeritus, New Mexico Bureau of Geology and Mineral Resources, a Division of New Mexico Tech, Socorro, NM 87801 USA

ABSTRACT

Helium (He) is the second most abundant element in the universe after hydrogen but is relatively rare on earth. He occurs as two stable isotopes, ^3He and ^4He. ^4He is the dominant isotope in crustal gases and is a radiogenic decay product of uranium and thorium mainly in granitic basement rocks. ^3He is dominantly primordial and primarily originates from the earth's mantle. ^3He may also be formed by radiogenic decay of ^6Li (Lithium) which may be found in argillaceous sediments deposited in evaporitic settings. Although He occurs in most natural gases, it almost always occurs in extremely low, subeconomic concentrations, less than 0.1%. It is rare in concentrations more than 1%. A very few small reservoirs have gases with more than 7% He.

Other gases that constitute the dominant components of helium-bearing natural gases are nitrogen (N_2), carbon dioxide (CO_2), and methane (CH_4). The highest He concentrations occur where the dominant gas is N_2 but most He has historically been produced as a byproduct of gases that are hydrocarbons. Hydrocarbons are generated from petroleum source rocks. Their presence in a reservoir is dependent upon the presence of a mature source rock in the basin and a migration path between the source rock and the reservoir. Large accumulations of CO_2 in the southwestern U.S. resulted from the degassing of rising Tertiary magmas and subsequent migration of the gases into crustal reservoirs. N_2 appears to originate mostly from degassing of the mantle but may also be formed in some strata by the thermal maturation of kerogens or by diagenetic alteration of clays or organic compounds in red bed sequences.

The presence of economic concentrations of He in reservoir gases is dependent not only on an adequate source of ^4He generated from granitic basement rocks but also on accommodating flux rates of N_2, CO_2, and CH_4. These gases differ in their origins, places of generation and rates of generation, migration and emplacement. While basement-derived ^4He and N_2 enter reservoirs at slow rates over long periods of geologic time, hydrocarbons and CO_2 enter the reservoir over much shorter time periods and dilute the ^4He and N_2. Basement-derived gases may be characterized by differing N2:He ratios which may indicate greater rates of He production within the crust in some areas.

Exploratory drilling for He on Chupadera Mesa in the late 1990's and early 2000's encountered He-rich gases in Lower Permian strata. Isotopic analyses suggest that 93% of Chupadera Mesa He originated from radiogenic decay in crustal rocks while 7% is derived from the mantle or with a possible contribution by evaporitic Permian shales. Marked differences in the CO_2 concentrations in different strata indicate that some strata acted as carrier beds for magmatically-derived CO_2 while strata with N_2-rich and CO_2-poor gases were isolated from CO_2 sources.

INTRODUCTION

Helium is thought to be present in trace amounts in all natural gases but is uncommon in concentrations of more than 0.1 mole percent. In the United States, only 17.6% of all natural gases contain more than 0.3 mole percent He (Tongish, 1980). The majority of helium-bearing natural gases are comprised of one or more of three major reservoir gases: Nitrogen (N_2), carbon dioxide (CO_2), and methane (CH_4). Helium is a minor constituent that is obtained as a byproduct of gas production. Historically, most He in the United States has been obtained as a byproduct of natural gases that were produced for their methane content. Helium has been extracted from produced gases in New Mexico since 1943 (Casey, 1986). All commercial production of helium in the state has been from Paleozoic reservoirs located on the Four Corners Platform in extreme northwestern New Mexico (Fig. 1). Helium content of the produced gases ranges from 3.2% to 7.5% (Broadhead, 2005; Broadhead and Gillard, 2004). The major gas in most of the reservoirs is N_2 but significant percentages of CH_4 are present in most of the reservoirs (Broadhead and Gillard, 2004). Although in most natural gases one of the three major components (CH_4, CO_2, N_2) is dominant and comprises more than 90% of the gas, in some natural gases two or all three of the major gases are present in significant percentages so that no single component is dominant.

It is the object of this paper to examine the relationship of elevated amounts of He to varying amounts of the three major reservoir gases and to examine geologic conditions that control the varying associations with the major reservoir gases. This paper further develops work previously undertaken by the author in New Mexico and therefore represents the New Mexico example of the relationship of He to the major reservoir gases, the resulting implications for He exploration. After a general review of the origins and geologic conditions leading to the emplacement of He and the major reservoir gases, the relationships of He to the major reservoir gases in New Mexico are reviewed with an emphasis on gases in the Permian Basin of southeastern New Mexico. Finally, more geologically detailed analyses are given for two occurrences of natural gases with abnormally elevated concentrations of He: 1) the Pecos Slope Abo gas pools on the Northwest Shelf of the Permian Basin and 2) the Chupadera Mesa area of central New Mexico (Fig. 1). Although natural gas production has not been established from Chupadera Mesa, the area is of interest because exploratory wells have recovered gases that contain the highest known concentrations of He in New Mexico outside of the productive reservoirs on the Four Corners Platform. Helium has not been extracted from the CH_4-dominated gases produced from the Pecos Slope Abo pools because separation of He from the gas was not economically viable in the late 1970's and early 1980's when the fields were developed; those reservoirs were produced for their CH_4 content.

GEOLOGY OF HELIUM AND THE MAJOR RESERVOIR GASES

Helium does not occur alone in the reservoir. It is always a minor gas that occurs in the presence of one or more major gases: N_2, hydrocarbons (chiefly methane), and carbon dioxide. Helium has the smallest molecular diameter and the lowest density of any of these gases (Table 1). The low density gives it the most upward buoyant force of the four gases. Because of its small molecular size and buoyancy, He can leak through seals that may contain the major reservoir gases (Hunt, 1996; Tedesco, 2022). Salient features of each of the gases are summarized

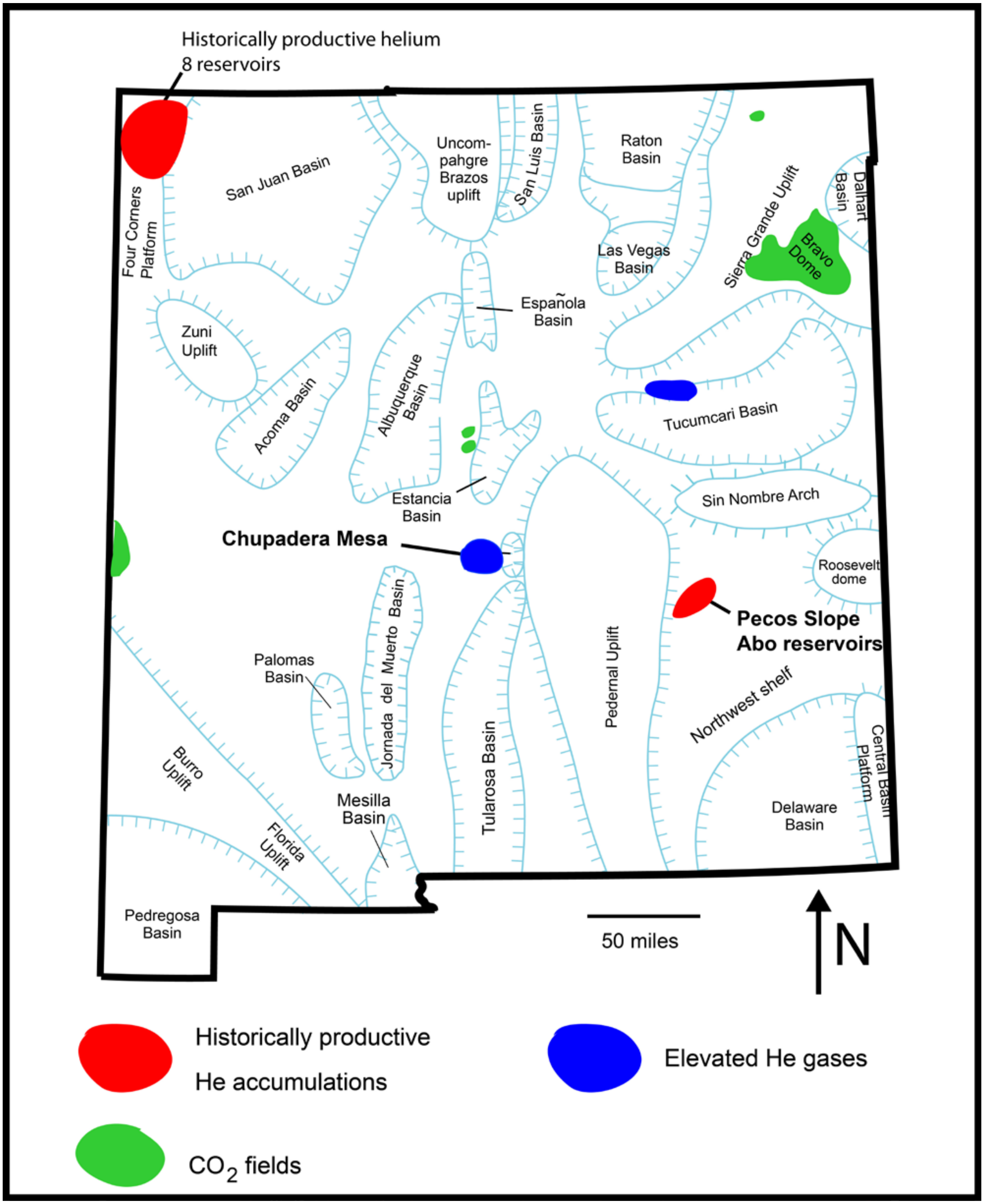


Figure 1. Reservoirs productive of helium or CO_2 and selected reservoirs containing elevated levels of helium in New Mexico. Geologic base from Broadhead (2017).

TABLE 1

Diameter and density of helium molecules and the major reservoir gases.
Diameters from Hunt (1996. Densities from Rumble (2020).

Molecule	Diameter, nanometers	Density, 25 °C, g/L
He	0.2	0.1636
N_2	0.34	1.1449
CH_4	0.38	0.6556
CO_2	0.33	1.7989

below with emphasis on origin of the gas in the reservoir and timing of introduction into reservoirs.

HELIUM GAS

Helium has two isotopes, ^3He and ^4He. ^3He is the dominant form of He on earth but is rare in reservoir gases (Mamyrin and Tolstikhin, 1984; Oxburgh et al., 1986; Hunt, 1996). ^3He is derived almost entirely from the mantle. Mantle-derived ^3He is primordial He and dates from formation of the earth. A small amount of ^3He may be derived from neutron capture by ^6Li in lithium-rich sediments (Hiyagon and Kennedy, 1992; Mamyrin and Tolstikhin, 1984; Oxburgh et al., 1986). ^4He is the dominant form of helium in reservoir gases. ^4He is derived from radiogenic decay of uranium (U) and thorium (Th) in crustal rocks (Hunt, 1996; Jenden et al., 1988; Oxburgh et al., 1986; Ballentine and Lollar, 2002). It is formed by alpha emission of ^{238}U, ^{235}U, and ^{232}Th. The half-life of each of these emission decays is extremely long (Table 2), indicating that ^4He generation is an ongoing process that is continuous over lengthy periods of geologic time. Uranium and Th disseminated in granitic basement rocks are major sources of ^4He although ^4He may also be derived from U and Th concentrated in orebodies. Transport of ^4He out of basement rocks appears to be predominantly related to the formation of fracture and fault systems that form migration pathways for the movement of the gas out of otherwise impermeable basement rocks (Giggenbach et al., 1991; Oxburgh et al., 1986; Poreda et al., 1986). Hence, periods of tectonic activity may result in episodic increased migration of ^4He into crustal reservoirs although once fractures are formed migration will eventually slow down and be proportionate to the generation rate in the granitic basement. In contrast, the main migration mechanism of ^3He out of the mantle into crustal reservoirs appears to be the devolatization of rising magmas (Giggenbach et al., 1996; Oxburgh et al., 1986; Poreda et al., 1986). Accumulation of ^3He in crustal reservoirs may therefore be dependent on episodes of magmatic intrusion.

The proportion of He in any reservoir that is derived from radiogenic decay in the crust versus the proportion that is derived from migration out of the mantle can be estimated from isotopic analysis of the He (Oxburgh et al., 1986). The ratio of ^3He:^4He in any gas sample can be normalized to the ratio of- ^3He:^4He in the atmosphere (1.41×10^{-6}; expressed as the variable R). Mantle-derived He has R values between 6 and 10. The average value for crustal-derived He is less than or equal to 0.04 and the maximum R value for crustal-derived He is 0.08 in most cases. Although no major accumulations of lithium (Li)-derived crustal ^3He have been recognized, the presence of even small amounts of Li-derived ^3He in a gas may influence the R value and therefore the determination of the proportion of He in a sample that is mantle derived (Oxburgh et al., 1986; Mamyrin and Tolstikhin, 1984).

NITROGEN GAS

Nitrogen (N_2) in natural gases has diverse sources (Hunt, 1996; Tedesco, 2022). Degassing of the earth's mantle and transport of N_2 into the crust during volcanism and intrusive igneous activity is a major source of N_2 in crustal reservoirs (see Holloway and Dahlgren, 2002;

TABLE 2

Half-lives of alpha forming emission decays. Data from Holden (2020).

Radioactive element	Half life, billion years
^{238}U	4.47
^{235}U	0.703
^{232}Th	14.0

Ballentine and Lollar, 2002). The N_2 is released from igneous rocks such as granites through fractures and slowly migrates upward into overlying crustal strata and therefore migrates similarly to ^4He. Therefore, higher fluxes of N_2, similar to He, may be associated with elevated levels of fracturing and faulting in crystalline basement.

N_2 can also be released from sedimentary kerogens during thermal maturation of kerogens associated with sedimentary burial. During early stages of maturation, ammonia (NH_3) is formed and is subsequently oxidized to N_2 in oxygen-bearing pore waters (Hunt, 1996). N_2 is also released by maturation of coals in two peaks, one at lower maturity and one at higher maturity (Klein and Juntgen, 1972; Boudou and Espitalie, 1995). Production of ammonia during early diagenesis has also been noted (Pironon and Grishina, 1995).

Nitrogen-rich gases are also present in red bed sedimentary sequences (Hunt, 1996). This association has variously been attributed to ammonia formed by kaolinitization or chloritization of smectite (Brown, 2017) or by reaction of ferric oxide in the red beds with organic compounds that contain nitrogen or ammonia (Guseva and Fayngersh, 1973 cited in Hunt, 1996). Tedesco (2022) cites release of N_2 from evaporites by thermal or chemical processes. N_2 may also originate as atmospheric gas trapped in pore waters (Hunt, 1996).

CARBON DIOXIDE GAS

Carbon dioxide (CO_2) is a common constituent of natural gases. Most natural gases contain less than 1 mole percent CO_2 but some natural gases, such as those found in the Bravo Dome field of northeastern New Mexico (Fig. 1) are almost pure CO_2 (Anderson, 1959; Broadhead, 1990; Broadhead et al., 2009). CO_2 in natural gases has many possible origins and the CO_2 in any one reservoir system may have multiple sources, although a single source is dominant in most systems. The following are thought to be the more common sources form most of the CO_2 found in natural gases (Wycherly et al., 1999; Whittier, 1994; Hunt, 1996).

1. *Mantle/magmatic degassing*. The CO_2 originates in the mantle and is presumably primordial. It is transported to the crust primarily by rising magmas that carry the CO_2 upward as a dissolved gas phase. CO_2 may also migrate upward via deep-seated faults. Confining pressure on the magmas decrease as they rise upward and CO_2 is exsolved as a separate phase. Gases emitted from active volcanoes are primarily water vapor and CO_2 (e.g. MacDonald, 1972; Baubron et al., 1990; Giggenbach, 1996; Giggenbach et al, 1991). If the magma does not escape to the surface as a volcano or lava flow and forms an intrusive body such as a dike, sill, laccolith or batholith, the exsolved CO_2 will migrate into permeable reservoirs that have been pierced by the magma. One in the reservoirs, it may be redissolved into the reservoir waters and migrate in solution. The timing of CO_2 migration will be controlled by the timing of magmatic activity which may last for hundreds of thousands to millions of years. Isotopes of noble gases indicate that the CO_2 in the giant Bravo Dome CO_2 field of northeastern New Mexico has a mantle source that was transported into the crust via magmatism (Staudacher, 1987; Gilfillan et al., 2008). Apatite U-Th geochronology has been used to determine that the time CO_2 was emplacement was 1.2 to 1.5 million years ago (Sathaye et al., 2014).

2. *Regional metamorphism*. Regional metamorphism of basement rocks releases CO_2 gas. Presumably this is a major source only where the basement contains large amounts of calcium carbonate, which is not applicable to New Mexico.
3. *Contact metamorphism of carbonate rocks*. CO_2 is formed by magmatic heating of carbonate rocks which may be a local source for CO_2.
4. *Contact metamorphism of coals,* which is a local source for CO_2.
5. *Thermal degradation of organic matter*. CO_2 is generated along with methane (CH_4) from kerogen early in the source-rock maturation process. Peak CO_2 generation is attained before peak CH_4 generation. Humic, nonmarine kerogen produces more CO_2 than sapropelic marine kerogen. Both CO_2 and CH_4 should be present in the system if this process is a major mechanism for CO_2 production.
6. *Dissolution of carbonate rocks by groundwater undersaturated with respect to $CaCO_3$*. This presumably happens at shallow depths.

HYDROCARBON GASES

The major hydrocarbon gas present in reservoirs is methane (CH_4). Lesser amounts of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}) may also be present. Methane as well as other hydrocarbon gases and crude oil originate in petroleum source rocks upon thermal maturation resulting from elevated temperatures associated with deep burial in the subsurface (Hunt, 1996; Magoon and Dow, 1994). Upon attaining sufficient temperature, kerogens in the rocks are converted into hydrocarbon gases and crude oils. Because source rocks are shales or finely crystalline limestone with ultra-low permeabilities, the generated hydrocarbons remain in the rock. This results in an increase in internal pressure within the source rock as the hydrocarbons are generated. When the internal pressure becomes sufficiently high, a network of microfractures forms which results in expulsion of the hydrocarbons into adjacent carrier beds (Lewan, 1987; Yang and Mavko, 2018). Microfractures will reach maximum development at or near peak oil generation. Therefore, maximum hydrocarbon expulsion occurs at or near peak oil generation and may not occur during early stages of hydrocarbon generation. Secondary migration of expelled hydrocarbons through the carrier bed is quick (as fast as 63 mi/100,000 years) compared to the time it takes to generate the oil and gas within the source rock (England, 1994). An example from the Permian Basin is the Simpson-Ellenburger petroleum system on the Central Basin Platform where the elapsed time from attaining vitrinite reflectance (R_o) 0.8 until R_o 1.0 was approximately 30 million years (see Katz et al., 1994). This is the time period of maximum hydrocarbon expulsion from the source rocks of the Simpson Formation (Ordovician).

RATES OF HELIUM EMPLACEMENT COMPARED TO MAJOR RESERVOIR GASES

Generation of helium and emplacement into crustal reservoirs is a slow process, even in terms of geologic time. The half-lives of the alpha decay reactions that result in the formation of ^{4}He are approximately equivalent to the age of the earth for ^{238}U and three times the earth's age for ^{232}Th (Table 2), resulting in slow but continuous ^{4}He generation. However pulses of He migration out of granitic basement may result during tectonic episodes associated with fracture formation in the basement.

The migration of N_2 out of the mantle, through the lower crust, and into shallow crustal reservoirs also appears to be a very slow but continuous process. Other sources of N_2 have a faster flux rate than the N_2 that is mantle derived. Although the time required for generation is poorly understood, N_2 that results from alteration of clay minerals or reaction of ferric oxides obviously postdates deposition of the sediments and may be related to transitory diagenetic conditions in the subsurface. N_2 that results from early-stage thermal maturation of kerogens will be generated over a relatively short period of time, less than the time required for maturation of a petroleum source rock. The effect of non-basement derived N_2 is therefore to dilute He and basement-derived N_2 in the reservoir.

CH_4 and associated hydrocarbon gases will be expelled out of the source rock and into adjacent carrier beds once the source rock has attained sufficient thermal maturity to approach peak oil generation and expulsion will continue past peak oil generation until the kerogens approach generative exhaustion. Subsequent secondary migration through carrier beds and into the reservoir is then very fast. The whole process from significant expulsion from the source rock until the source rock is near exhaustion may only take a few 10's of millions of years.

Reservoir entry of CO_2 derived from magmatic activity will be essentially coincident with the timing of the magmatism. That the Bravo Dome field was filled with CO_2 in less than one million years indicates that CO_2 may take the least time for reservoir entry among He and the three major reservoir gases.

The net effect of the differing flux rates for He, mantle-derived N_2, CH_4, and CO_2 is that He and N_2 enter the reservoir at the slowest rate of He and the major gases. Geologically short periods of magmatism may result in the introduction of large volumes of CO_2 that dilute the He and CO_2. Similarly, periods of hydrocarbon generation and expulsion from source rocks result in dilution of He and N_2 over short periods of time. N_2 derived from non-mantle sources will also dilute He and mantle-derived N_2.

METHODOLOGY

The work documented in this paper was primarily dependent upon 943 analyses of gas composition from natural gas samples obtained mostly from oil and gas exploration wells drilled throughout New Mexico. A minor amount of the analyses is from water wells, springs and surface seeps. These were published as the New Mexico Helium Database in Broadhead and Gillard (2004). Additional data from Chupadera Mesa wells was subsequently received and added for the present work. Most of the analyses were obtained from the U.S. Bureau of Mines gas analyses program which in later years was administered by the U.S. Bureau of Land Management. To this were analyses reported in the published literature and analyses contributed by the private sector for work undertaken by the author at the New Mexico Bureau of Geology and Mineral Resources. For the New Mexico Helium Database, data were added or corrected including stratigraphic unit from which the gas sample was obtained and other data fields such as well location, and depth to gas production were not provided or were incorrect in the original data (see Broadhead and Gillard, 2004). Also, stratigraphic nomenclature was standardized.

For this project, cross plots of He content (in mole percent) and content of the major reservoir gases (N_2, CO_2, and hydrocarbons) were made. Heating value of the gas (in BTU/ft^3) was used as a proxy for hydrocarbon gas content because not all available analyses included the heavier hydrocarbon gases. These cross plots were made for gases that occur in Pennsylvanian- age and in Permian-age reservoirs on a statewide basis. For the Permian Basin area of southeastern New Mexico (Eddy, Lea, Chaves and Roosevelt Counties), plots of He content vs. N_2, CO_2, and heating value were made for reservoirs of 1) Pennsylvanian, 2) Permian, and 3) Silurian or Ordovician age. When incorporated with geology and an understanding of the origins of the different gases it was possible to develop insights into the relationship of helium to the various major reservoir gases in New Mexico and how these relationships differ among reservoir systems of different ages, and to a limited extent, different areas. Calculation of the ratio of N_2 to He content provided further insights.

For two areas that the author has studied in more detail and for which sufficient gas analyses were available (the Pecos Slope Abo gas pools on the Northwest Shelf of the Permian Basin and the Chupadera Mesa of central New Mexico) it was possible to develop additional insight into relationships between He and the major reservoir gases and implications for He exploration. For Chupadera Mesa, helium isotope analyses not available elsewhere lent themselves to increased understanding of the origin of He in that area.

GEOLOGIC RELATIONSHIPS OF HELIUM TO THE MAJOR RESERVOIR GASES IN NEW MEXICO

The relationships of the major reservoir gases in New Mexico vary from basin to basin and to some extent among different stratigraphic intervals within a single basin. In general He content of gases increases with N_2 content where CO_2 is either absent or is present in small amounts (Fig. 2). A plot of helium content vs. the heating value of Pennsylvanian gases reveals that helium content decreases with increasing heating value (Fig. 3). Heating value is used as a proxy for total hydrocarbon content so that samples that were only analyzed for methane but not for C_{2+} can be included. A similar plot of He content vs. CO_2 content in Pennsylvanian gases reveals a different relationship (Fig. 4a); gases with greater than 1% He are limited to gases with less than 20% CO_2 whereas gases with less than 1% He contain 0% to 8.2% CO_2.

The relationship of He content to CO_2 is somewhat different for Permian reservoirs on a statewide basis.

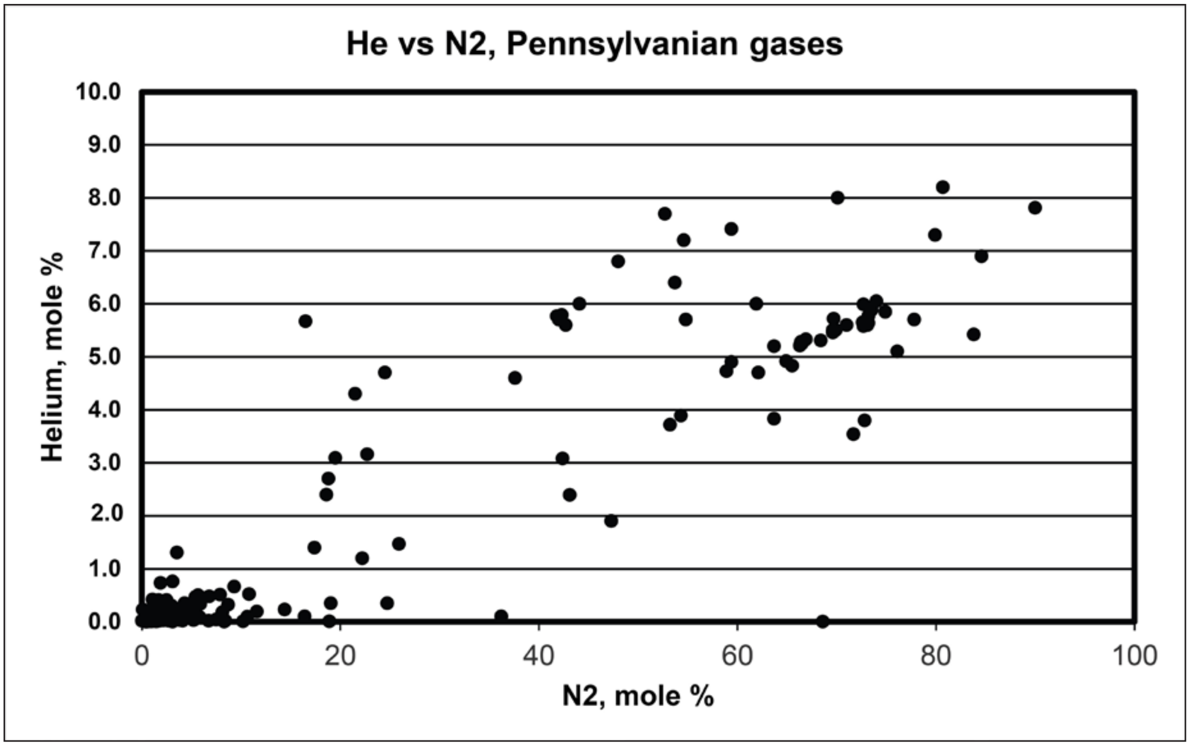


Figure 2. Plot of helium content vs. N_2 content of gases in Pennsylvanian-age reservoirs of New Mexico.

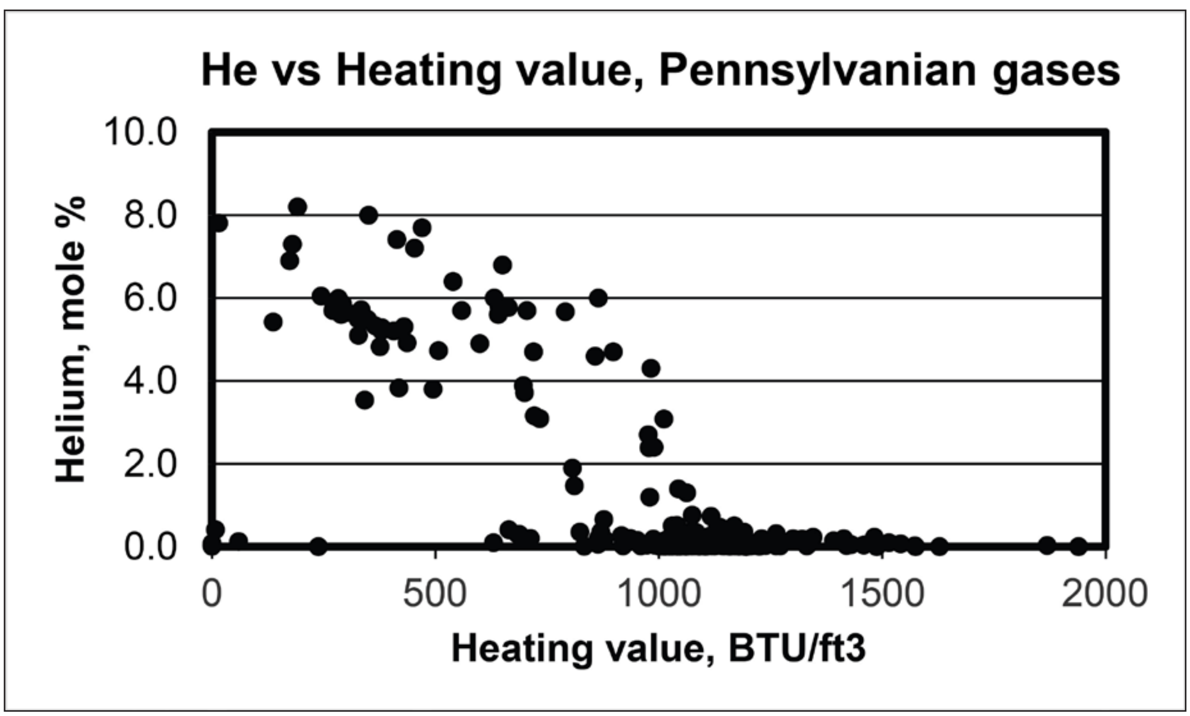


Figure 3. Plot of helium content vs. heating value of gases in Pennsylvanian-age reservoirs of New Mexico.

Several wells with CO_2 between 20% and 60% Fig. 4b) occur in central and south-central New Mexico. The wells in Fig 4b with greater than 90% CO_2 are located in the Bravo Dome area of northeastern New Mexico and the St. Johns CO_2 field in west-central New Mexico.

A plot of He vs N_2 for Pennsylvanian gases in the four counties (Eddy, Lea, Chaves, Roosevelt) that encompass the New Mexico part of the Permian Basin (Delaware Basin, Central Basin Platform, Northwest Shelf, Roosevelt Dome; Fig. 1) indicates a similar relationship of increasing He vs. increasing N_2 but with decreased He content (maximum of 0.348%; Fig. 5). The gases in these wells consist dominantly of hydrocarbons (Fig. 6) which have diluted both the He and N_2 content. Some reservoirs contain greater than 5% N_2 but have less than 0.1% He content.

A plot of He vs. N_2 for gases in Silurian and Ordovician reservoirs in the Permian Basin counties indicates a similar trend of increasing He and N_2 (Fig. 7). The reservoirs found in the wells depicted in this plot are located on the Central Basin Platform and on eastern part of the Northwest Shelf. The majority of samples form a linear trend with helium increasing along with N_2 and a zero intercept of both the N_2 and the He axes. This is consistent with a source in the basement with similar migration pathways for both gases. The average ratio of N_2:He along this trend is 25.6. Gases to the right of the trend have N_2:He ratios greater than 25.6, ranging from 60 to 161. This may be caused by either a secondary non-basement source for the N_2 in some areas or by increased leakage of the smaller and more buoyant He molecules through the seals in selected traps.

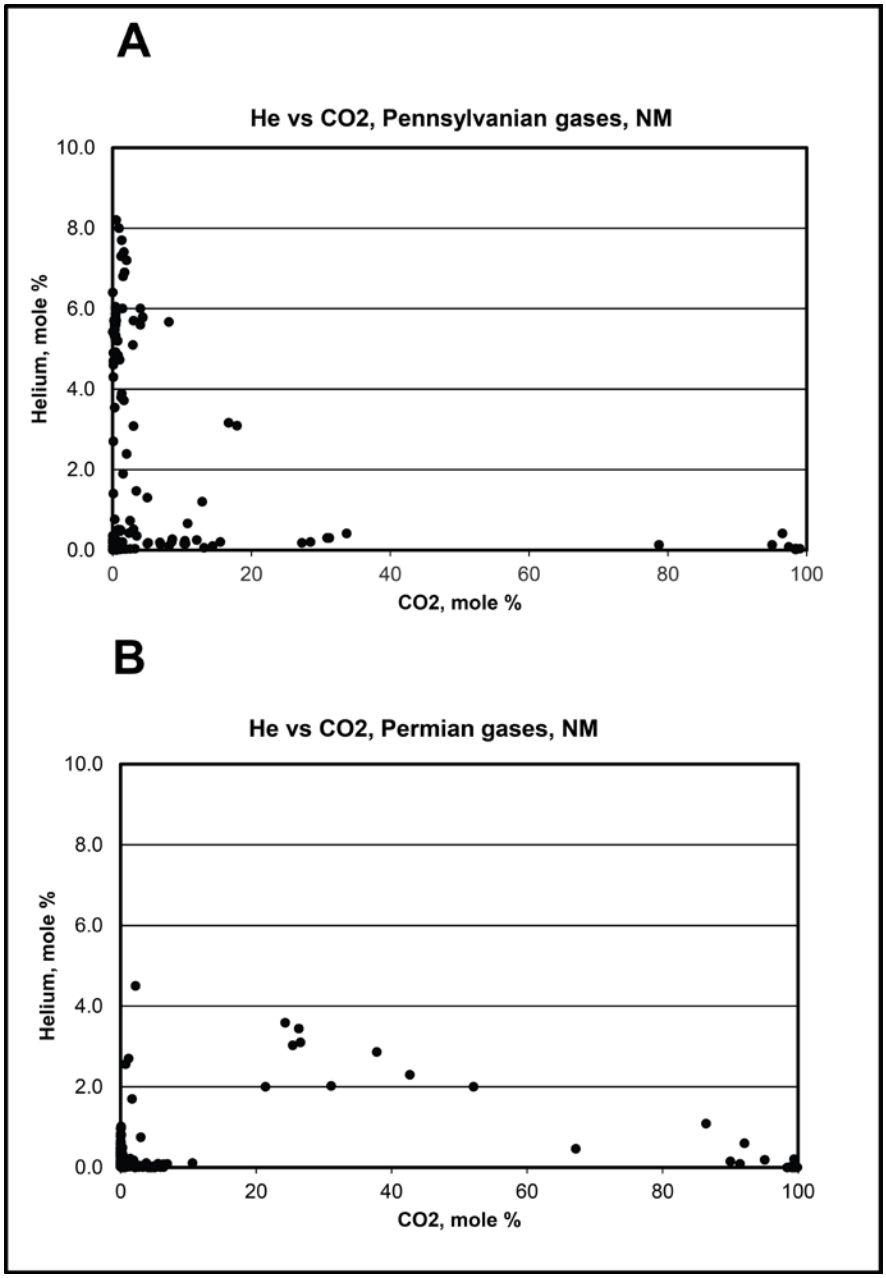


Figure 4. Plot of helium content vs. CO_2 content in **A**, Pennsylvanian-age reservoirs of New Mexico, and **B**, Permian-age reservoirs of New Mexico.

A plot of He vs. N_2 for Permian gases in southeast New Mexico reveals two different families of gases (Fig. 8). One family of gases is located within the Pecos Slope Abo reservoirs which is located near the northwestern limit of the Northwest Shelf (Fig. 1). The gases in the Pecos Slope Abo reservoirs are similar to the Silurian and Ordovician gases discussed above as they form a linear trend with a zero intercept of both the He and N_2 axes. The other family of gases has lower He content but variable N_2 content that ranges from a few percent to greater than 80%. The other major gases present in these Permian reservoirs are hydrocarbons, again principally CH_4. Given that there is no obvious associated increase of He with N_2 in the second

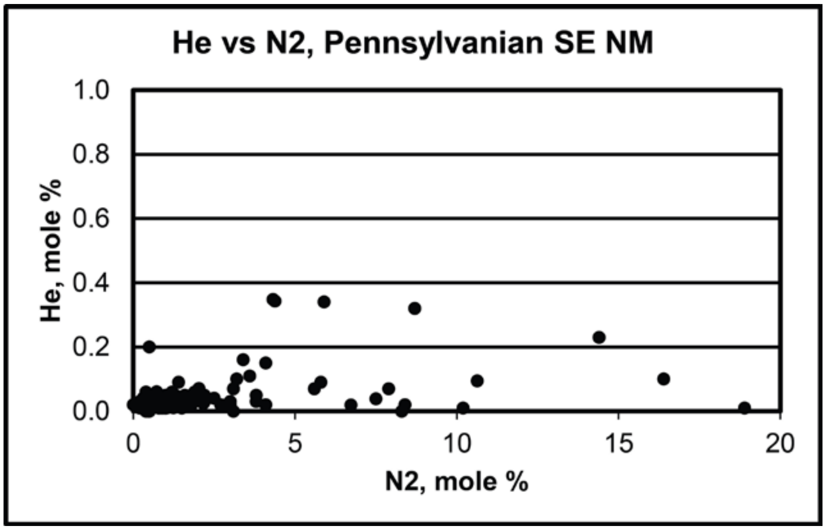


Figure 5. Plot of helium content vs. N_2 content of gases in Pennsylvanian-age reservoirs of southeastern New Mexico.

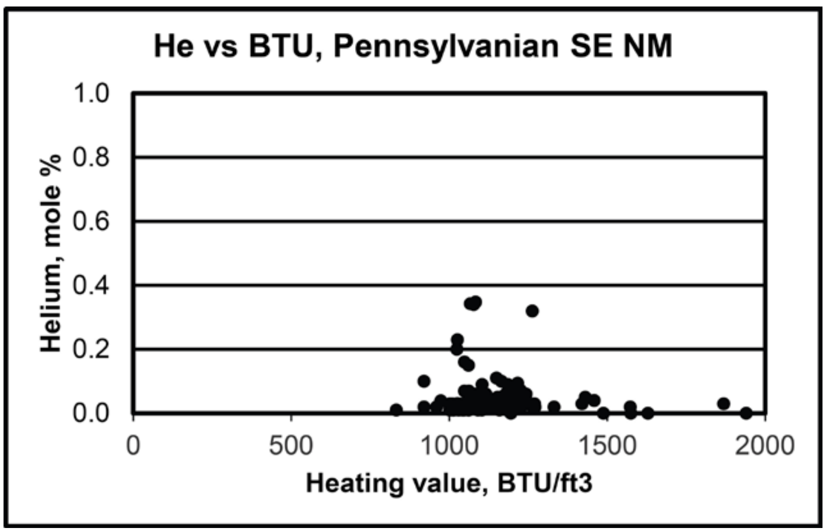


Figure 6. Plot of helium content vs. heating value of gases in Pennsylvanian-age reservoirs of southeastern New Mexico.

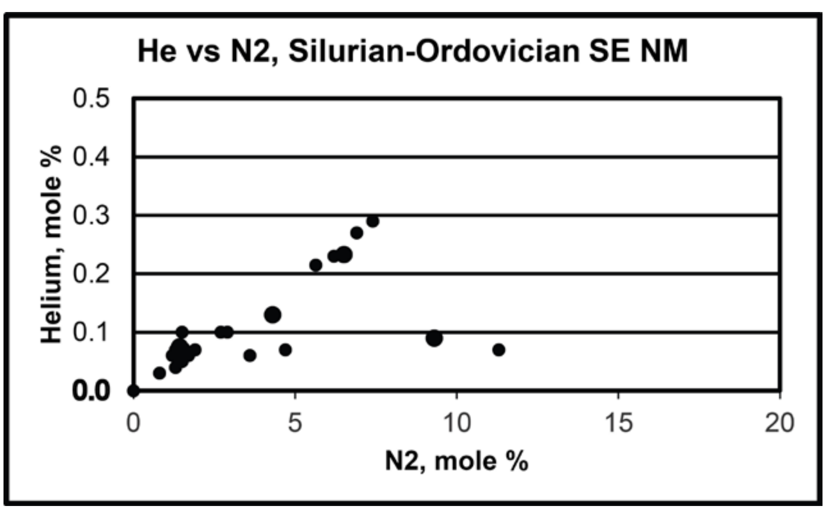


Figure 7. Plot of helium content vs. N_2 content of gases in Silurian and Ordovician age reservoirs of southeastern New Mexico.

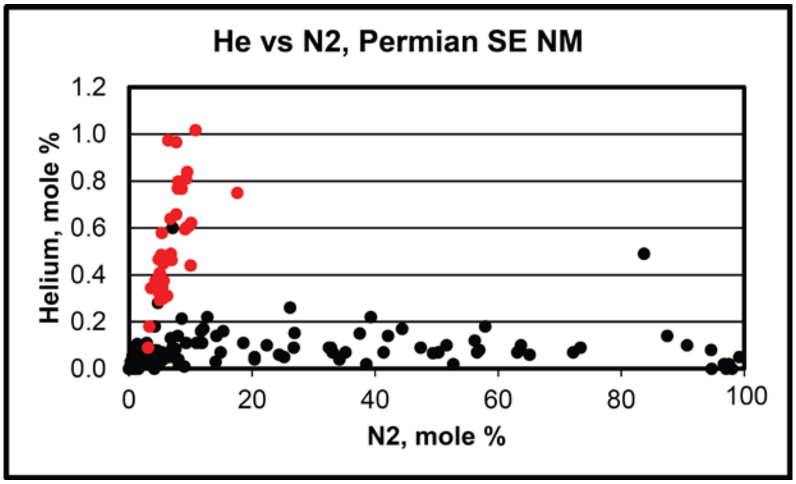


Figure 8. Plot of helium content vs. N_2 content of gases in Permian-age reservoirs of southeastern New Mexico.

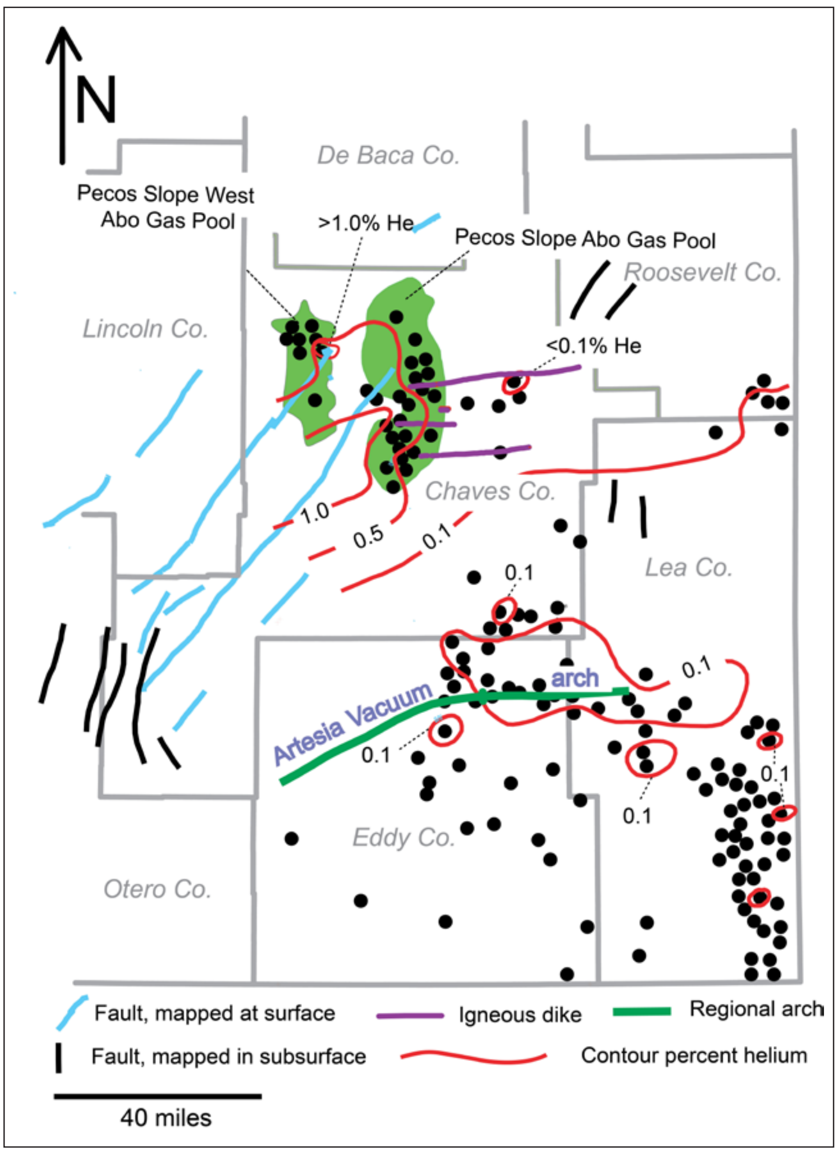


Figure 9. Contours of helium content, in mole percent, of Permian gases in southeastern New Mexico and outlines of Pecos Slope Abo and Pecos Slope Abo West gas pools. Black dots mark the locations of wells with analyses of helium content of Permian gases. Faults and igneous dikes mapped at surface from Kelley (1971). Faults mapped in subsurface from Broadhead and others (2009). From Broadhead (2005). Reproduced with permission of the New Mexico Bureau of Geology and Mineral Resources.

family of gases and the very large N_2 contents in most of the samples, it seems likely that most of the N_2 comes from non-basement sources. Possible sources for this excess N_2 include diagenetic production of ammonia from by alteration of smectites within red bed clastics that are abundant in the Permian section, or by reaction of ferric oxides in the red beds with organic compounds in kerogen that contain N_2. Release of N_2 from evaporites is also a possible source for the N_2 in these gases. Given that the upper parts of the Permian section have not been buried very deeply (Hills, 1984), it is also possible that some of the N_2 was produced from kerogens during early diagenesis.

PECOS SLOPE ABO GAS RESERVOIRS

As discussed above, the gases in the Pecos Slope Abo reservoirs exhibit a linear relation between He and N_2 content (Figs. 1, 8). The Pecos Slope Abo reservoirs are formed by fine-grained fluvial-deltaic redbed sandstones of the Abo Formation (Broadhead, 1984; Bentz, 1992). The sandstones are sealed by red mudstones. Within the reservoirs He content of gases ranges from 0.09% to 0.974% and averages 0.48% (Broadhead and Gillard, 2004; Broadhead, 2005). Other gases in the reservoir are mostly hydrocarbons (CH_4). He content and N_2 content increase with proximity to northeast-southwest-trending high-angle strike-slip faults that transect the Northwest Shelf (Fig. 9). The He, along with the N_2, migrated upward through the faults into the Abo. Anhydrite beds in the lowermost part of the Yeso Formation (Fig. 10) provide a vertical seal for the fault and prevented the He from escaping to the surface.

For the Pecos Slope Abo gases, the average N_2:He ratio is 14.4. This is 56% of the average N_2:He ratio of the previously discussed Silurian-Ordovician gases on the Central Basin Platform and the eastern part of the Northwest Shelf. The relatively higher He contents of the Pecos Slope gases may be the result of relatively impaired migration of mantle N_2 at Pecos Slope when compared to the Central Basin Platform/eastern Northwest Shelf or it may be the result of greater He production in the Precambrian at Pecos Slope and therefore increased He potential.

CHUPADERA MESA HELIUM OCCURRENCES

Chupadera Mesa is located in central New Mexico (Figs. 1, 11). It is a broad upland bordered on the west by the northern part of the Jornada del Muerto Basin. Upper Paleozoic strata in the subsurface, Upper Paleozoic strata thin eastward as they onlap Precambrian rocks of the Pedernal Uplift, a north-trending tectonic uplift that was part of the Ancestral Rocky Mountains (Broadhead, 2009). Pennsylvanian strata thin eastward where they are erosionally truncated by the overlying Abo Formation (Lower Permian) on the western flank of the Pedernal Uplift. In the subsurface of Chupadera Mesa, buried Ancestral Rocky Mountain uplifts of Pennsylvanian age are present that are bounded by high-angle faults. The faults do not penetrate to the surface but fault-bounded horsts and grabens are expressed at the surface as anticlines and synclines. Numerous Middle Tertiary and Quaternary intrusive and extrusive igneous rocks are exposed at the surface (Fig. 11). Several exploratory wells drilled on Chupadera Mesa have

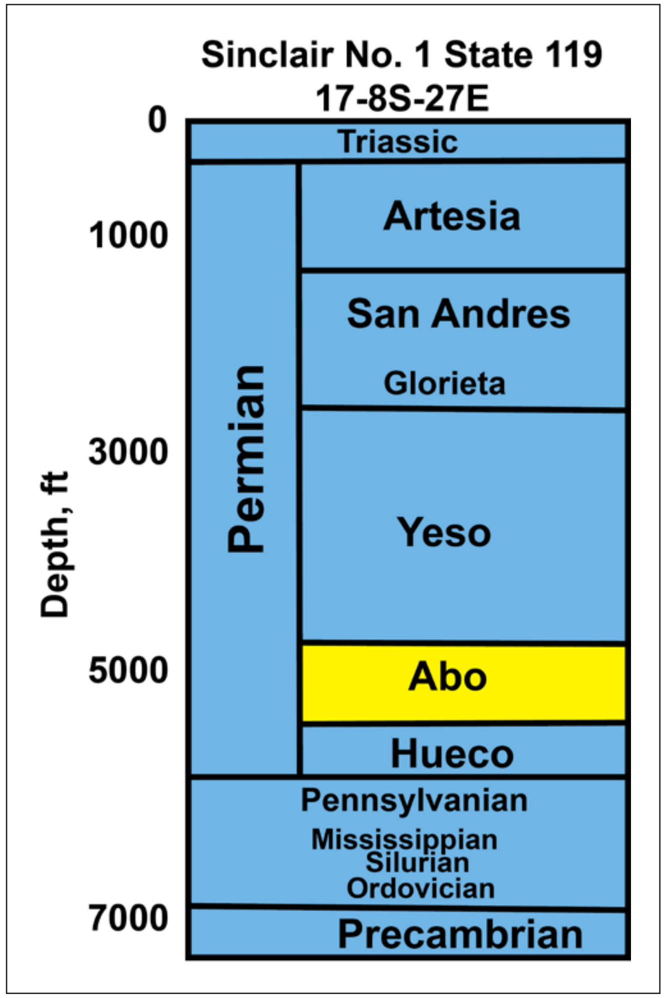


Figure 10. Strata encountered in the Sinclair No. 1 State 119 well, representative of the stratigraphy at the Pecos Slope and Pecos Slope West Abo gas pools.

encountered diabase laccoliths, sills and dikes within Precambrian granodiorites as well as in red shales of the Abo Formation (Lower Permian).

Since 1901, 47 petroleum exploration wells have been drilled in the Chupadera Mesa area (Fig. 11; Broadhead, 2009). Most wells were drilled on surface anticlines. None established production.

The last round of exploration took place between 1996 and 2008 when six wells were drilled (Fig. 12). The wells were drilled for oil exploration. None encountered oil or significant amounts of hydrocarbon gases due to a paucity of thermally mature source rocks (Broadhead, 2009). However, noncombustible gases were encountered in three of the wells (Fig. 12). These wells are located on a structurally high feature that may account for entrapment of the gases in otherwise water-saturated sandstones (Broadhead, 2009). The He-enriched gases were encountered mostly in fine-grained red fluvial sandstones of the Abo Formation (Lower Permian) in the Dulce Draw State and the No. 3 Cathead Mesa wells. The interval from which the gas sample in the No. 1 Cathead Mesa well was recovered included the Abo, the underlying Atokan (Lower Pennsylvanian) section and uppermost part of Precambrian basement. The gas sample from the Abo sandstone in the No. 3 Cathead Mesa well is the highest known He concentration (3.44%) in New Mexico outside of the productive reservoirs on the Four Corners Platform.

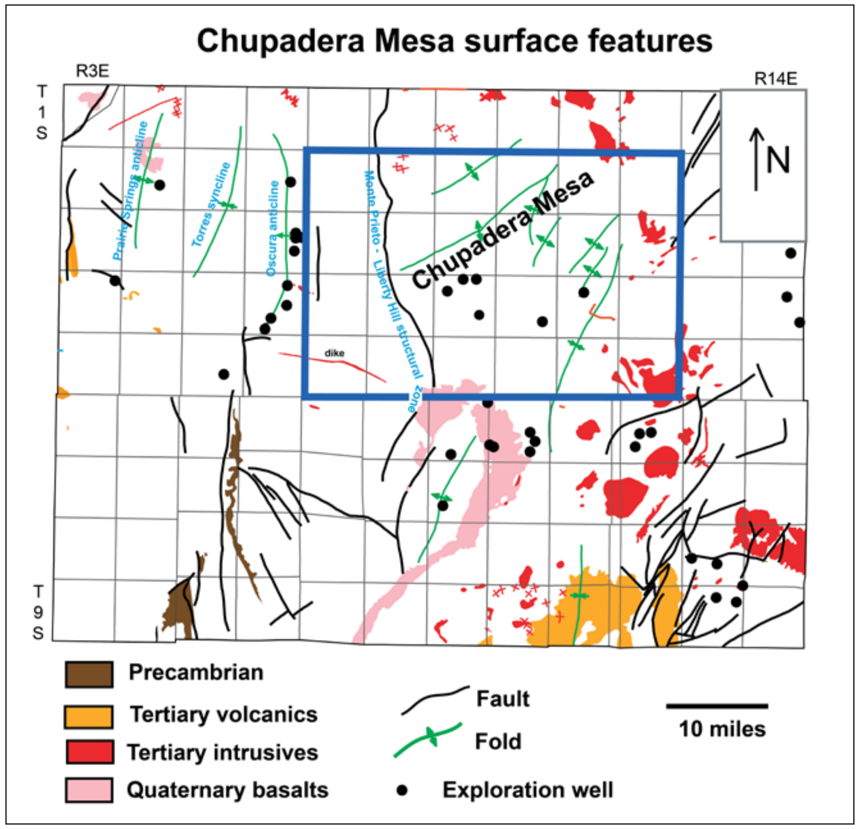


Figure 11. Location of major structures mapped at the surface and outcropping Tertiary and Quaternary intrusive and extrusive volcanic rocks, Precambrian outcrops, and the locations of exploration wells in the Chupadera Mesa region of central New Mexico. Structures from Wilpolt and Wanek (1951), Wilpolt and others (1946), New Mexico Bureau of Geology and Mineral Resources (2003), and unpublished work. Locations of intrusive and extrusive rocks and Precambrian rocks from New Mexico Bureau of Geology and Mineral Resources (2003). Blue rectangle demarks the area of the map shown in Figure 12. Modified from Broadhead (2009) with additional structures added and wells updated.

Of interest are gas samples from two sandstones within the Abo in the No. 1 Dulce Draw State well (Fig.13). These sandstones are separated by 80 ft of red shales which provide a seal. The upper sandstone between depths of 3064 and 3074 ft has gas with 3.25% He, 69.25% N_2, 25.4% CO_2 and 1.96% CH_4 with an N_2:He ratio of 21.3 (average analyses of 3 samples). The lower sandstone between depths of 3154 and 3170 ft has gas with 0.19% He, 4.60% N_2, 95.09% CO_2 and 0.12% CH_4 with an N_2:He ratio of 24.2. It is concluded that the CO_2 from Middle Tertiary intrusive magmas invaded the He and N_2 bearing sandstones to different extents with the lower sandstone having been invaded more completely than the upper sandstone. The similarity of the N_2:He ratios suggests that each sandstone had similar He concentrations before Middle Tertiary magmatic activity introduced CO_2 into the reservoirs. Of additional interest is that the Abo sandstone in the No.1 Cathead Mesa well contains less than 1% CO_2 indicating that CO_2 invasion was minimal. This is an example of how He and CO_2 contents of He-rich gases can vary substantially in a region characterized by magmatic intrusions that can introduce CO_2 into He-bearing reservoirs.

Helium isotope analyses performed on the gas sample from the Abo in the No. 3 Cathead Mesa well resulted in a $^3He/^4He$ R value of 0.515 (Broadhead, 2009). This is

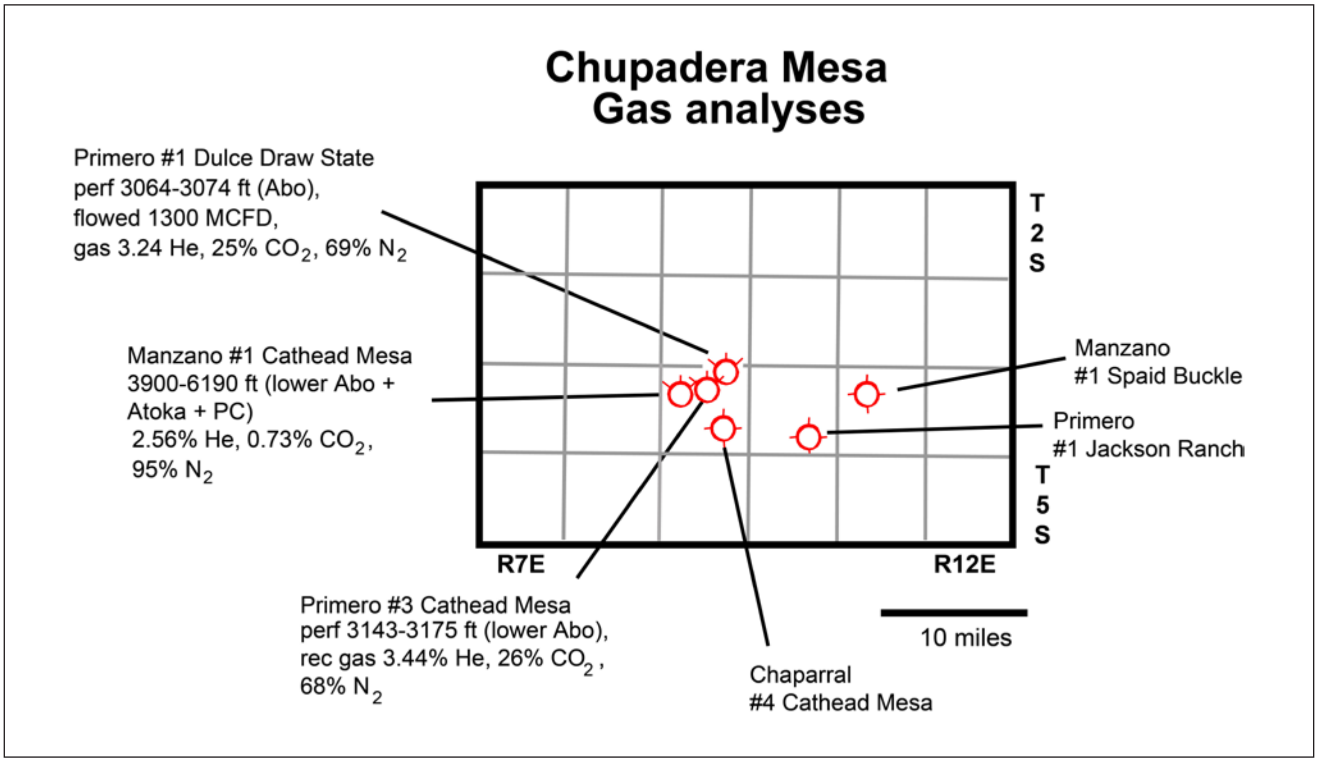


Figure 12. Analyses of gas samples recovered from exploration wells drilled in the Chupadera Mesa region.

significantly more than the upper limit for crustal-derived He but considerably less than the minimum value of 6 for mantle-derived He (see Oxburgh et al., 1986) and suggestive of a mixed crustal and mantle origin for the He in the Abo with perhaps 93% of the He originating from crustal basement rocks and 7% originating from the mantle. The Precambrian granodiorites in the region are obvious sources for the crustal derived component. Faults that bound the underlying horsts and grabens and fractures associated with those faults formed migration pathways for the ^4He and accompanying N_2 to escape from Precambrian basement. The mantle-derived component may have been transported in the magmas that formed the Middle Tertiary intrusive rocks. However, the lowermost Yeso Formation in the area, which helps provide a seal for the Abo, contains salt beds and therefore may provide a partial source for the ^3He if enhanced ^6Li concentrations are associated with the evaporitic lower Yeso depositional environments.

CONCLUSIONS

Helium is a minor gas that is accompanied by the major reservoir gases: nitrogen (N2), carbon dioxide (CO_2), and methane (CH_4). Helium occurs as two stable isotopes: ^3He and ^4He. Most helium in crustal reservoirs is ^4He. ^3He is almost all primordial and enters crustal reservoirs as a result of outgassing of the mantle. ^4He, on the other hand, is generated in the earth's crust by alpha decay of ^{238}U, ^{235}U and ^{232}Th, primarily in granitic basement rocks. The long half-lives of the alpha decay reactions (4.4 billion years for ^{238}U) result in slow but continuous production of ^4He from basement rocks. Most N_2 appears to originate from degassing of the earth's mantle and migration into crustal reservoirs is also an ongoing and very slow process. However, in some places N_2 is generated from alteration of nitrogen-bearing strata in the upper part of the earth's crust. CO_2 enters crustal reservoirs by devolatization of rising magmas that originate in the upper mantle.

While generation and transport of He and N_2 are slow even in the context of geologic time, transport and emplacement of CO_2 into reservoirs is relatively fast and may take less than 1 million years to fill a giant reservoir, such as at Bravo Dome in northeastern New Mexico. Hydrocarbon gases, which are dominantly CH_4, originate from thermal maturation of kerogens in kerogen-rich petroleum source rocks. Most generation and expulsion of CH_4 from source rocks may take place over a time period of a few million years to a few 10's of million years. The net effect is that ^4He and N_2, which enter reservoirs very slowly over long periods of geologic time, may be diluted by relatively quickly generated and migrated CO_2 and/or CH_4.

Mantle-derived ^4He and N_2 appear to enter crustal reservoirs via a slow migration mechanism with established fixed N_2:He ratios. As documented by examples from the Pecos Slope Abo reservoirs on the Northwest Shelf of the Permian Basin and Silurian-Ordovician reservoirs on the Central Basin Platform and eastern part of the Northwest Shelf, the N_2:He ratios differ from area to area and may indicate differing rates of ^4He generation in the basement. Different areas may therefore hold different He potential based on differing generative capacity of the basement.

In areas of intrusive magmatism, such as Chupadera Mesa of central New Mexico, different reservoirs within the same stratigraphic unit may exhibit significantly different CO_2 contents of gases within those reservoirs. These reservoirs may have elevated He content and similar N_2:He ratios, indicating that He and N_2 originally migrated out of basement and filled the separate reservoirs with gases of the same composition but that magmatically-derived CO_2 subsequently invaded the reservoirs to different extents. This resulted in some reservoirs with gas comprised mostly of CO_2 and diluted He content and other reservoirs with little CO_2 but significantly elevated He. Therefore, the presence of one reservoir with gas that is dominantly CO_2 does not necessarily indicate that other reservoirs within the stratigraphic succession also contain the same high percentage of CO_2. Consideration should be given to testing and sampling gases from each potential reservoir separately.

ACKNOWLEDGMENTS

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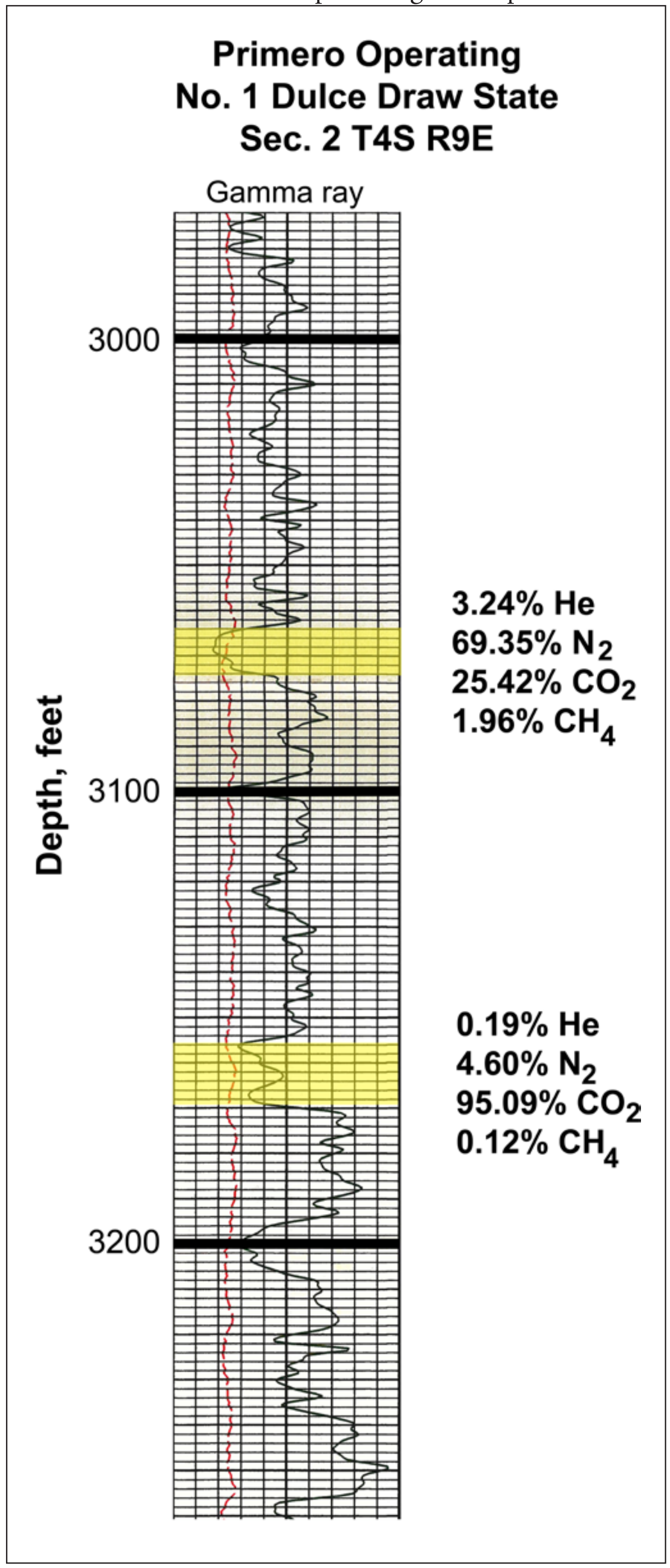

Figure 13. Gamma-ray log within the Abo Formation (Permian) in the Primero Operating No. 1 Dulce Draw State well indicating the two sands (in yellow) from which gases were recovered and analyzed. See Figure 12 for well location.

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THE AUTHOR

Ron Broadhead

Ron Broadhead received his B.S. in Geology from New Mexico Tech and his M.S. in Geology from the University of Cincinnati where he studied Devonian shales under the late Paul Potter. He worked for Cities Service Oil Company in Tulsa and Oklahoma City and has been with the New Mexico Bureau of Geology and Mineral Resources (a Division of New Mexico Tech) since 1981. He retired from New Mexico Tech in 2020 and was granted emeritus status by the university. At the Bureau, major research projects have included the New Mexico petroleum source rock project, subsurface and petroleum geology of the Permian, San Juan, Tucumcari, Raton, Las Vegas and Estancia Basins as well as helium-rich and CO_2-rich natural gases of New Mexico. He also supervised the Bureau's core and subsurface information libraries. He taught subsurface and petroleum geology at New Mexico Tech beginning in 1982 and continues to teach part-time in retirement. His numerous society activities include serving as editor of Search and Discovery, the online journal of AAPG, from 2011 through 2018.

Recent Developments in Helium Exploitation in southern Saskatchewan and adjacent areas of Montana and Alberta[1]

DUNCAN MACKENZIE

1. Manuscript received July 11, 2023; Accepted July 11, 2023.

INTRODUCTION

The following is a survey of a re-emerging helium exploration and production area located at the northwest rim of the Williston Basin located in southwest Saskatchewan, southeastern Alberta, and north central Montana. The Williston Basin is one of the two major sub-basins of the Western Canadian Sedimentary Basin; the other being the Alberta Basin foreland basin, east of the Cordillera. From a slow 2016 start, 21st century helium production from the area already exceeds the total from area's 1960s and 70s production heyday. As mid-continent legacy helium storage and production decline, the importance of this area's net-zero helium production can only grow.

The fairway lies east of the Bow Island Arch on the Sweetgrass Arch structural complex in southeastern Alberta and adjacent Montana, approximately on SW-NE trend (Fig. 1) with the "enigmatic" (Kreis et al., 2004) Great Falls Tectonic Zone (GFTZ), believed to separate the Battlefords and Assiniboia domains of the Archean Hearne Province. There is consensus on the NW-SE trend of the GTFZ: however, Bosman et al. (2021) provide two location interpretations: one slightly north, termed "GFTZ allied structures", spatially aligned with helium shows and production from Swift Current, Saskatchewan, southwest through helium shows and production at Rudyard, Montana, and in the Kevin Dome area, at the Alberta-Montana boundary. The second, southern interpretation, aligned with Mueller (Mueller et al., 2007), is termed the GFTZ (Fig. 2). This area accounts for all Canadian production & substantially all resources of 2.0 BCM (72 Bcf). US Rocky Mountain Region resources of 4.1 BCM (148 Bcf) (Goodin & Hamak 2023) includes non-producing (as of August 2023) Montana helium.

Reserves and production from Cambro-Ordovician basal clastics dominate the fairway to date. The Devonian Souris River dolomitic limestone is the second producing formation. Ordovician Red River carbonates and correlatives have established prospectivity. Reservoir quality rock in these formations can overlap spatially: they can be productive in the same wellbore, as at Battle Creek, Saskatchewan, where Devonian helium was first was tested in 1952, and in the 16-29 Home Oil/Thor Resources Knappen well eight km (five mi) north of the Montana-Alberta boundary, now producing helium from Devonian and Cambrian reservoirs (Fig. 3).

It is likely that helium from Cambrian and Devonian reservoirs has a common source in the crystalline Precambrian basement. Inert gas isotope systematics elaborated by Danabalan (2017) connect inert gases hosted in Cambrian reservoir at Mankota, Saskatchewan to those in Devonian and Ordovician reservoirs 280 km (175 mi) southwest, at Rudyard, Montana.

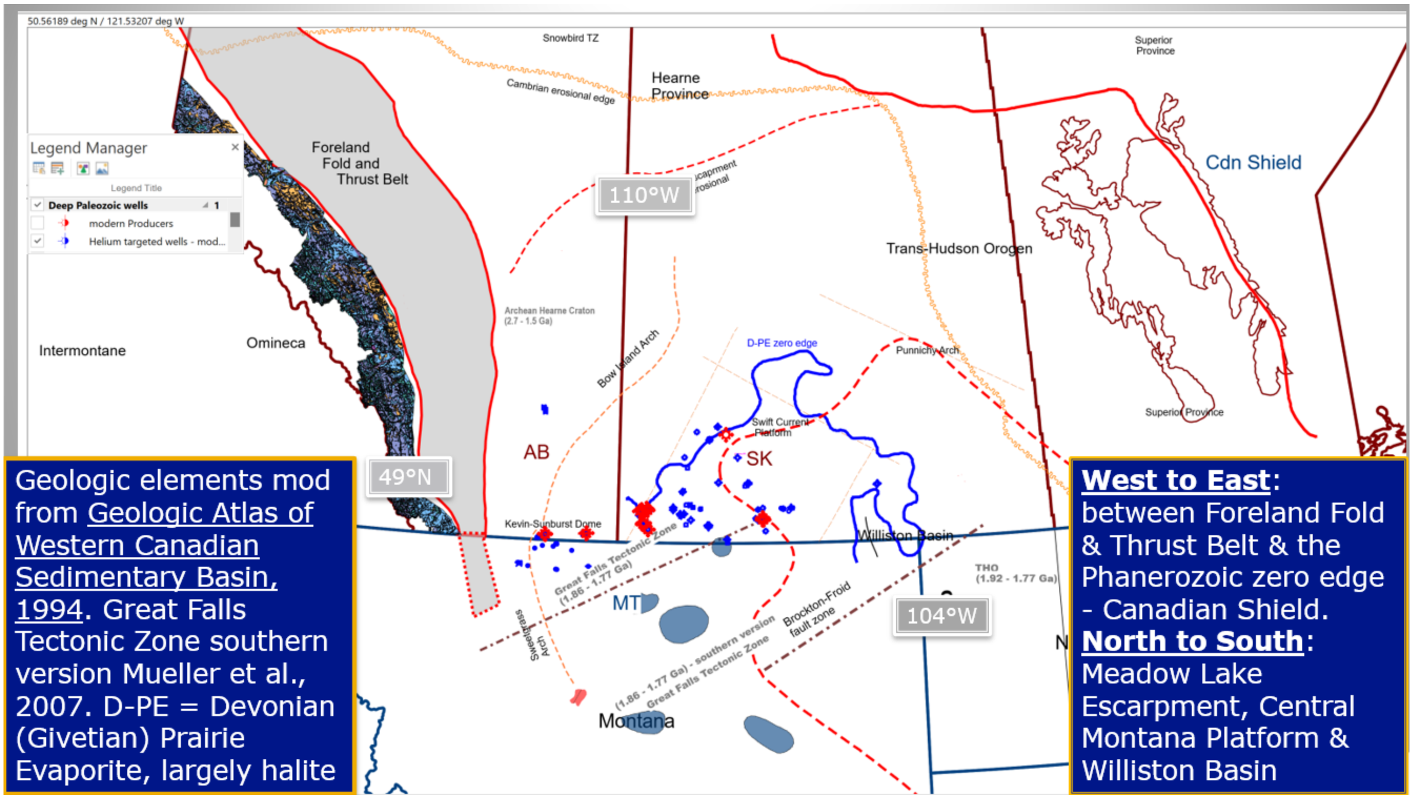

Figure 1. Key geologic elements of the Western Canadian Sedimentary Basin (WCSB) and adjacent Montana and North Dakota.

The basal clastic and Devonian dolomitic limestone reservoirs host helium and other inert gases from a common source, and can share a trapping mechanism. Carbonate reservoirs may be more prone to abrupt lithologic changes, adding to reservoir risk but providing opportunity for stratigraphic traps. Variably silicified impermeable marine shale seals basal clastic reservoirs, and meter to tens of meter scale Devonian Duperow and Souris River anhydrites or anhydrite occlusions seal dolomitic limestone reservoirs. The dynamics of gas transport to and the concentration of helium in the reservoir types are constrained but not fully defined: the process may be advective, diffusive, or both (Cheng et al., 2021). The presence of two or more prospective formations means it is possible to expand the fairway: Devonian dolomitic limestone may be an exploration target where the Cambro-Ordovician reservoir is absent, there is insufficient trapping structure, the seal is absent or breached, or the basal clastic reservoir is untested or otherwise not viable due to depth. Conversely, carbonate porosity may be occluded by evaporites, where Cambrian system clastics are prospective.

THE REGION

The intracratonic cross-border Williston Basin lacks physiographic definition at its northwestern limit in Canada. The limit is conventionally the regional -1500 meter (-4900') Precambrian unconformity subsea contour (Fig. 3). The significance for helium exploration is that west of this contour and east of the northeast-plunging Bow Island Arch element of the Sweetgrass Arch no petroleum system exists deeper than the Mississippian Madison formation. Therefore, industry lost interest in drilling to the Precambrian after majors Shell, Marathon, Imperial, and Texaco abandoned mid-century attempts to find oil-bearing Devonian structures in the international boundary/GFTZ area. For decades, little rock or fluid data were gathered from helium-bearing strata in Devonian through Cambrian systems. The crystalline Precambrian basement helium source rock remained largely unevaluated, over tens of thousands of square miles. While it is known that basement U and Th content is about twice Canadian Shield and global averages (Herring, 2012), this is based on 182 unevenly distributed rock samples (Burwash and Cumming, 1976). Through these decades, little was done beyond petroleum industry seismic targeting Mississippian and younger geologic systems, with occasional remote sensing surveys. Although there are varied candidates for helium sourcing, including the radioactive shales in the sedimentary column, atmospheric helium dissolved in groundwater, and the mantle, producible helium requires contribution from granitic (acid) basement source rock (Danabalan 2017, Danabalan et al. 2022, and Cheng et al., 2021, 2023).

Laterally continuous Williston Basin stratigraphy and crystalline helium source-rock basement means Cambro-Ordovician, Devonian, and Mississippian helium systems can equally occur in southern Saskatchewan, eastern Montana, and adjacent North Dakota, proximal to the basin center, at subsea elevations below the -1500 metre Precambrian unconformity contour. This is evident in southeastern Saskatchewan, where multiple deep oil and gas analyses show helium exceed the traditional 0.3 mol% economic limit. Not all Montana gas analyses are public, but there is evidence of inert gas in the Fort Peck Reservation area, and 115 km (75 mi) south at the northwest end of the North-Dakota-Montana Cedar Creek Anticline. In Burke County, North Dakota there is 0.37% helium in the Ordovician at Holte-BND #1 API 3301300722, 24 km (15 mi) south of the international boundary, at 3266 m (10714') subsurface or 2439 m subsea (8002'). The Ordovician Winnipeg formation analysis contains ~50% alkanes by volume, but its 47% nitrogen fraction and He/N2 (7.9 x 10-3) is comparable to southwest Saskatchewan Paleozoic helium. This suggests commonality with northwest Williston Basin edge analyses, with a helium-dilutive hydrocarbon overlay.

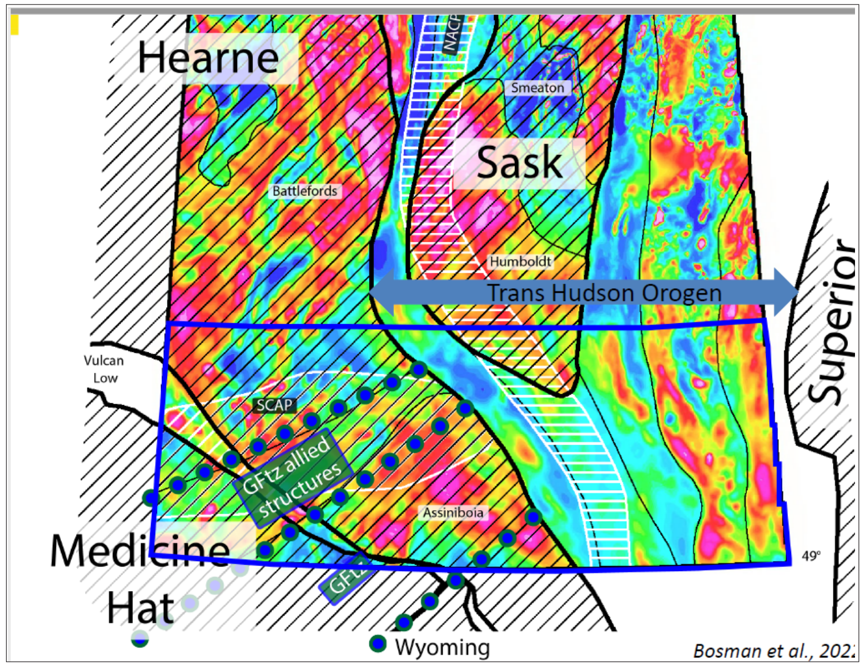

Figure 2. Great Falls Tectonic Zone and related structures (base map: total field, aeromagnetic).

In contrast, at the northwest limit of the Williston Basin, where the Precambrian contour is higher elevation than -1500 metre subsea, distal from the thermally mature North Dakota basin center, hydrocarbons have neither migrated to nor been generated in Paleozoic formations older than Mississippian. Thus, in these Devonian and Cambro-Ordovician reservoirs, helium carrier gas is non-hydrocarbon, in contrast with Panhandle-Hugoton, but in common with Harley Dome, Utah. Regional helium is "net-zero," simplifying ESG (Environmental, Social, and Corporate Governance), and allowing "pure play" helium companies. Furthermore, oil does not occupy pore space, making sufficient volume of raw gas easier to attain, while the absence of supercharged hydrocarbon systems prevents helium dilution. In the Williston Basin center, where the Precambrian basement is in approximately 5000 m (16000') below surface, great depth is itself a disadvantage. Regardless of the targeted fluid, overburden pressure is a reservoir risk factor, and deep operating conditions limit the pool of helium players. With respect to helium itself, ultra-high pressure is also a gas composition risk (Tongish 1980, Brown 2010, 2019), because helium under extreme overburden pressure will not incline to de-gas from pore water. Paleozoic helium significantly deeper than 2600 m (8500'), comparable to legacy tests and modern helium production at Mankota, Saskatchewan, will not be evaluated here.

Conversely, northeast, the play limit is the zero edge of the Western Canadian Sedimentary Basin Phanerozoic wedge and the emergence at surface of Precambrian granitic helium source rock. There is no fixed geographic limit "inboard" or southwest of the Canadian Shield zero edge, but economic helium at 1% concentration requires

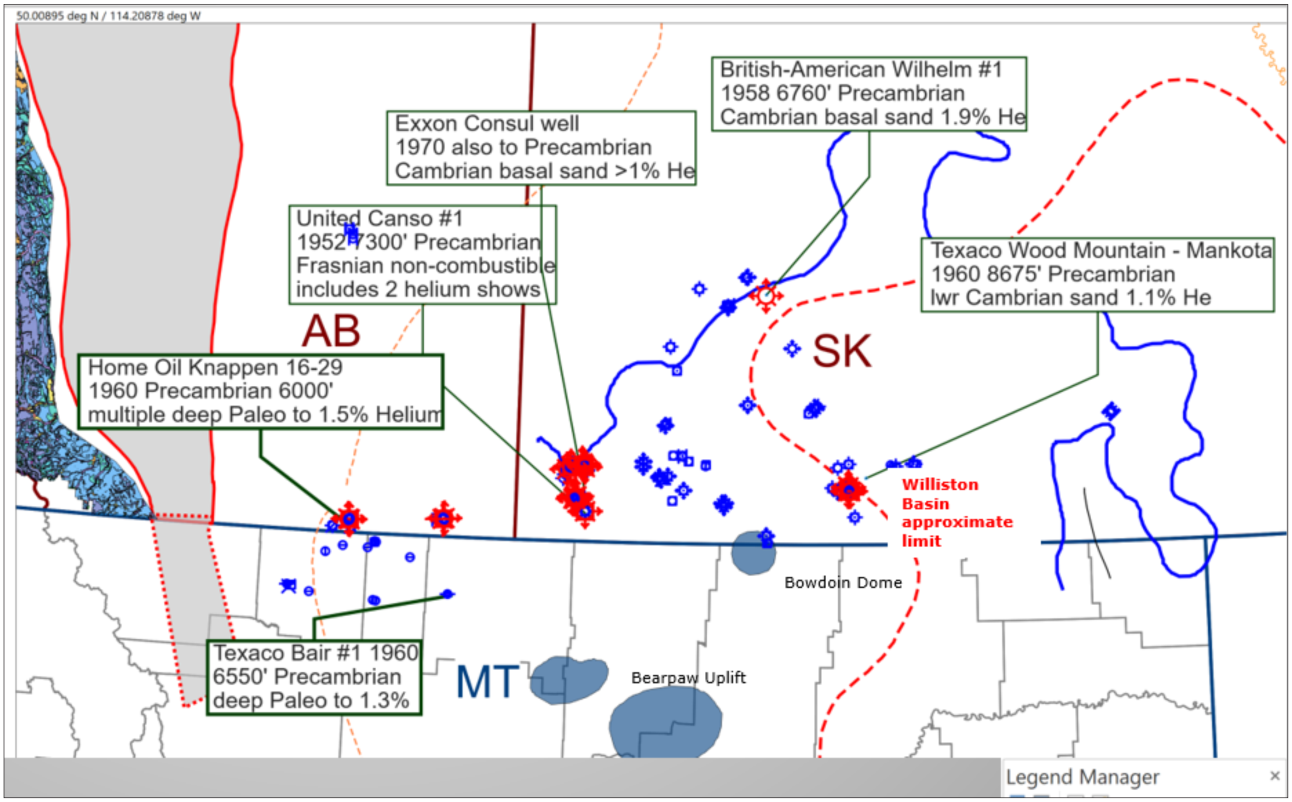

Figure 3. WCSB and Montana legacy deep Paleozoic helium shows to 1970 and helium exploration wells 2012 to 2023.

high raw gas volumes: for scale, the Province of Saskatchewan's goal of 10% of the 2030 world market requires ~70 Bcf/2 BCM of produced gas annually. This somewhat constrains the prospectivity of a compelling gas analysis (2% helium, 90% nitrogen, the balance CO2, and alkanes) from the Ordovician lower Winnipeg at Lake Manitoba) at depth of 305 – 327 m (1000 – 1075') from Hemisphere Helium Peerless 14-17-020-05W1, drilled 1962 (Nicolas, 2018 Table GS2018-9-1); due to normal reservoir pressure not exceeding ~3 MPa/500 psi. Thus, the northeastern prospective limit may be in Manitoba, southwest of the four large Manitoba lakes, near the western limit of the Canadian Shield (Fig. 1). Whatever its economic future, the strong Ordovician Winnipeg formation basal clastic helium gas show near Lake Manitoba is 1100 km (700 mi) northeast of Devonian and Cambro-Ordovician helium at the Alberta-Montana border. This indicates the extent of the basal clastics helium trend, plausibly extending from the eastern limit of the Montana Thrust Belt, southwest of current helium activity, to the great Manitoba lakes.

At the western limit, either side of the international boundary, the foreland fold and thrust belt violates a condition of helium exploration – tectonic quiescence or stable platform conditions (Danabalan et al. 2022). Basal clastic helium prospectivity is likely to extend as far southwest as Glacier and Cascade Counties and adjacent areas of Alberta. Mountainous terrain, foreland basin depth and repeat section, as well as the dilutive presence of acid gas and prolific hydrocarbon generation in Paleozoic formations northwards along the foredeep in Alberta limit helium prospectivity. State, provincial, and federal parks as well as First Nations land on both sides of the 49th parallel impose constraints on development to the west.

Devonian helium shows near Calgary (Steveville, Alberta at 50.7°N 111.6°W) and Medicine Hat, as well as the Prud'homme, Saskatchewan (core analyzed for residual noble gas by Advanced Hydrocarbon Stratigraphy), 52.3°N 105.9°W, or 230 mi north of the international boundary, give an idea of the regional deep Paleozoic helium system: 1300 km (800 mi) on a southwest-northeast axis, defined by Cambro-Ordovician prospectivity, and a third this distance on a northwest-southeast axis, defined

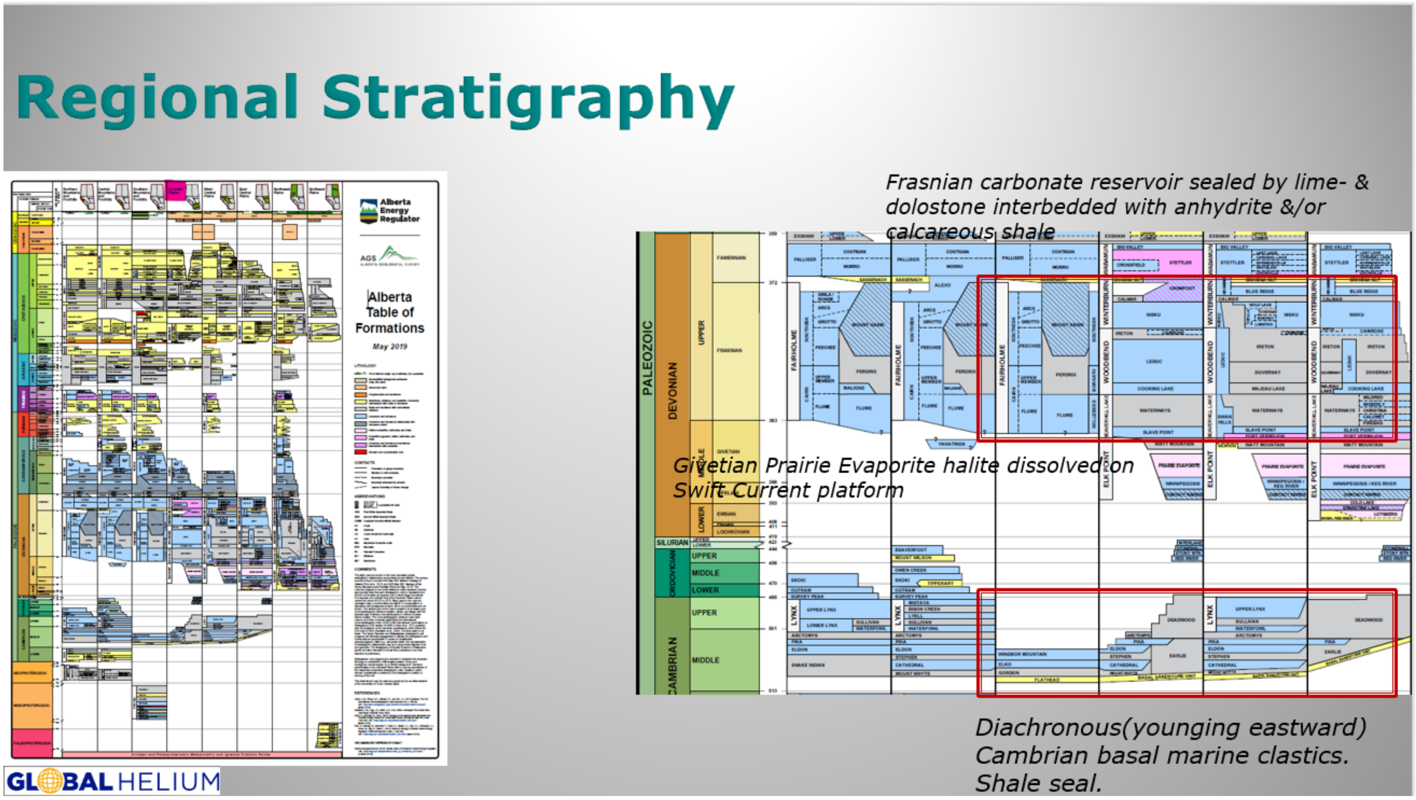

Figure 4. Stratigraphy, southwest Saskatchewan and adjacent Alberta and Montana.

by inert gas in Devonian system reservoir, giving an area of some 550,000 km2 (two hundred thousand mi2). Southeast and northwest geographic limits are more loosely constrained than the northeast and southwest fairway extent (Fig. 1).

Further northwest, around latitude 55°N and longitude 118°W, lies the Peace River Arch. Here, Petroliferous Devonian Granite Wash superposes the Precambrian unconformity. This helium-bearing basal clastic unit is petroliferous, and distinct from the southwest to northeast GFTZ aligned non-combustible helium trend discussed here.

STRATIGRAPHY

The crystalline basement of the Western Canadian Sedimentary Basin and adjacent areas of the United States is known through remote sensing (gravity, magnetic, and gamma-ray surveys), by extrapolation from the Canadian Shield, relatively rare geophysical well logs and drill cuttings, and from rarer-still Precambrian cores. 182 un-weathered Precambrian cores were analyzed in the 1970s, showing higher helium feedstock, U 4.13 ppm and Th 21.1 ppm, than for the Canadian Shield as a whole: given the million square km-scale of the basin and less-than-ideal distribution of Precambrian core, this is not a firm conclusion (Burwash and Cumming, 1976). In the west, Middle- and Late-Cambrian dominantly fine-grained siliciclastics and thick carbonate sequences lie unconformably on the basement (Fig. 4). In the east, in Saskatchewan and eastern Montana, Cambrian and Ordovician fine-grained siliciclastics persist, with coarser grained shoreline deposits younging eastwards, following the encroaching Cambrian sea (Mossop and Shetsen, 1994). The Ordovician and Silurian section in the region has been substantially eroded, and includes shale, sandstones, calcareous dolomite, and dolomitic limestone, with the Silurian Stonewall and Interlake formations being largely dolomite. The Devonian section of shale, thick cycles of limestone, dolomite, and dolomitic limestone, is substantially eroded: the oldest remaining rocks are from the Elk Point Group of the middle Devonian Eifelian stage. The Elk Point Group contains the Prairie Evaporite halite. This halite formation can be up to 150 m (500') thick, and is extensively mined for potash production. The Prairie Evaporite zero edge largely aligns with the Swift Current Platform and (possibly by coincidence, or as an indicator of deep sub-vertical fluid conduits) early Paleozoic helium discoveries. Mappable anhydrites of five to ten m (15 to 35 ft) scale are found in the Souris River and Duperow formations (Givetian and Frasnian age), up section of the Prairie Evaporite: their lateral persistence and lack of solubility relative to halite makes them more likely candidates as effective sealing formations than the Prairie Evaporite. Cambrian through Devonian geologic systems, with the likely addition of lower Mississippian rocks are all prospective helium reservoirs in southern Saskatchewan and Alberta, and neighboring Montana. Much of the Mississippian section is eroded, as are all Pennsylvanian and Permian rocks. Mesozoic Era rocks are variably present at km-scale thickness in the Western Canadian Sedimentary Basin (stratigraphy, Fig. 4). Helium and other non-combustible gases may be present in Mesozoic reservoirs, either, or a mix of generated *in situ,* or leaked from Paleozoic reservoirs below. If the gases are leaked, a deeper helium system is indicated, directly below, or with lateral offset. There is no evidence to date of commercial volumes of helium producible from Mesozoic reservoirs.

DISCOVERY 1952 – 1971

The following six legacy wells, excepting Tidewater Eastend Crown #1 1952 (15-11-006-20W3), which flowed unanalyzed non-combustible gas, are numbered chronologically, in the order they appear in Table 1. Mankota/Texaco Wood Mountain 12-10 and 10-03 were a two well drilling program of suspended and ultimately re-entered wells: the first drilled, 12-10, is evaluated.

WELL 1: UNITED CANSO #2, SASKATCHEWAN

Paleozoic helium was first encountered in 1952 in the border region between the Rocky Mountains and the Williston Basin at United Canso #2 04-31-003-26W3, drilled to basement at 2370 m (7773'). This was at Battle Creek, southwest Saskatchewan, 240 km (150 mi) northeast of Great Falls, Montana, and 350 km (220 mi) southwest of Regina. The discovery of non-combustible gases including helium in Devonian strata draped on a Precambrian monadnock was inadvertent. Imperial Oil plugged back the United Canso #1 well in petroliferous Jurassic strata after running 47 bottom hole DSTs. Three Devonian gas shows were non-combustible. Two of the three were analyzed. Both contained helium. The first analysis was from the rarely tested Duperow formation, superposing the prospective Souris River. This is likely DST #22, midpoint 1713 m, (5620'). The gas analysis "by a government laboratory" is referred to in the well file, but does not survive: gas from the Duperow was cited in Report 49 (Sawatzky et al. 1960) as 81.7% CO2, 13.5% nitrogen, 0.14% helium, and 5.66% "other gases", likely alkanes, possibly including hydrogen. Acid gas exceeding single digits is rare on the Great Falls Tectonic Zone helium trend, excepting the Kevin Dome at the Montana-Alberta border. The second Devonian analysis was reported as the prospective Dawson Bay member of the Manitoba Group, of which the Souris River is also a member; no acid gas is attributed to this interval. The analysis is likely from the Souris River formation, DST #31, midpoint 1868 m (6127'). With just a 150 m (500') separation, carbon dioxide has declined from 80% (DST 22) to none reported. The DST #31 gas analysis was 95.2% helium, 0.47% nitrogen, and 4.5% other gases. Disregarding acid gas, the helium-nitrogen ratio in the Duperow (DST #22) is on the order of 1 x 10-2, consistent with nitrogen-dominant Paleozoic non-combustible gas in the region. Presence of the Cambrian Basal Clastic Unit at United Canso #1 is consistent with the e-logs, but no tests were run. Another 1952 well, Tidewater Eastend Crown #1, (15-11-006-20W3 – three townships north, six ranges east of United Canso #2) recovered MMCF/d scale flow-rate Devonian non-combustible gas. This gas was not analyzed.

A second well discussed below (Mobil et al. Battle Creek 101 10-25, Well #6) was drilled to the Precambrian 2225 m (7300') in 1971, a mile south-southwest of United Canso #1. 10-25 tested 0.91% helium from the basal Cambrian clastic unit, at total gas test rate of 300000 m3/d (10 MMCF/d) or ≤3000 m3/d (100 mcf/d) helium. Nitrogen was 97%, CO2 1.51%, and alkanes <1%. Apart from this 1971 well, nothing further was learned of Battle Creek deep Paleozoic reservoir or fluid chemistry for 64 years after Battle Creek helium discovery in 1952. Unlike 20th century US helium sources, notably the Panhandle-Hugoton Field, no parallel hydrocarbon system spurred development of helium-bearing strata. A twin of Mobil Battle Creek 10-25 (102 10-25) had produced more than 43 MMCF of helium by April 2023

(Government of Saskatchewan production data). The pool is operated by North American Helium.

WELL 2: BRITISH AMERICAN WILHELM 1-9, SASKATCHEWAN

In 1958, 1.9% helium was encountered in a basal Cambrian clastic interval near Swift Current SK, northeast of Battle Creek, 145 km (90 mi) due north of the international boundary. British American Oil abandoned the BA Wilhelm (Swift Current) 1-9 well, again suggesting inadvertent discovery. 6.5 million m3 (230 MMCF) of helium was produced here from four development wells between 1963-77: production has re-started from a well drilled in 2021. The reservoir at Wilhelm was positioned at the base

TABLE 1

Wells.

Well	***Lithologies***	***Deposition (clastics)***	***Original test flow rate***	***Pool status***	***Cambrian isopach, TD in feet***	***Structure timing***	***Other***
1952 04-31 United Canso **Battle Creek SK**	Devonian Carbonates Cambrian clastics	Marine clastics: Cambrian fan delta?	<10 mmcf/d (<285 e3 m^3/d)	Pool on production at township scale. North American Helium (NAH)	677 & 7300: Precambrian topography 100s of feet scale	Early? Drape on Precambrian highland	47 BH DSTs over 4 months. Devonian helium, Mesozoic & Mississippian hydrocarbons.
1958 01-09 BA Wilhelm **Swift Current SK**	Cambrian clastic & non-clastic sedimentary (chert)	Marine clastics, near shore, silica-rich water column?	<10 mmcf/d (<285 e3 m^3/d)	Legacy production & 2021 re-start. Canadian Helium Inc.	410 & 6755: Precambrian topography	Early? Drape on Precambrian highland	Cambrian helium. No hydrocarbons any system.
1960 12-10 Texaco-Intl. Helium Wood Mountain **Mankota SK**	Cambrian clastics		>>10 mmcf/d (>>285 e3 m^3/d)	Suspended re-entry. Weil Resources & new pool (NAH)	885 & 8675	NE flank of Bowdoin Dome – Cretaceous to Paleogene uplift. Timing of previous or subsequent uplift if any unclear. Closest to Williston Basin	Cambrian helium. Sand – shale sequence lwr wet sands. No hydrocarbons. Stratigraphic and/or structural trap?
1960 Texaco Bair #1 25-041 05077 **Rudyard MT**	Devonian Carbonates. Cambro-Ordovician carbonates & clastics	Marine shoreface sandstone – brachiopods old & new wells.	<10 mmcf/d (<285 e3 m^3/d)	No production. Global Helium operated 2012 offset well drilled, completed, and flow tested.	992 & 6550	Late – Cenozoic intrusion?	Devonian & Ordovician helium. Cambrian gas cut mud non-combustible?
1960 16-29 Home Oil **Knappen AB**	Devonian Carbonates. Cambrian clastics	Marine clastics	<10 mmcf/d (<285 e3 m^3/d)	Pool producing from re-entry and modern offsetting well. Thor Resources.	1047 & 5697	Late – Cenozoic intrusion?	Multiple non-combustible gas analyses including helium. Mesozoic & Mississippian hydrocarbons.
1970 Exxon 10-25 **Battle Creek SK**	Devonian Carbonates Cambrian clastics	Marine clastics: Cambrian fan delta?	=10 mmcf/d (=285 e3 m^3/d)	Pool on production. NAH	673 & 7325	Early - Precambrian highland.	Cambrian helium. Entire Paleozoic drilled despite United Canso (UC) Devonian non-combustible gas. Mesozoic alkanes with high nitrogen and CO_2.

of the Cambrian section, as at Battle Creek (Fig. 4). Log control is poor, but the reservoir appears to differ from Battle Creek, and is described at neighboring Gulf Canada 03-10 as fractured siltstone and chert. Porosity in the tested zones is up to 14%, with sub-Darcy permeability. There was similar quantitative core analysis at BA Wilhelm 1-9, but little core description. Gulf Canada 03-10 rates of 54000 to 186000 m3/d (1.9 to 6.5 MMCF/d) are lower than at the shoreface or deltaic sands at Mankota and Battle Creek, over a greater gross reservoir interval of 45 m (145'). Reservoir is shallow compared to the Battle Creek and Mankota fields: maximum depth is 2050 m (6750'). The reason is topographic relief relative to basement 185 m (600'), itself ~200 m (650') above the arbitrary Williston Basin boundary at the Precambrian subsea -1500 m (-4900') cutoff. Burwash notes authigenic silica at BA Wilhelm 1-9, as a sealing agent (Burwash and Cumming 1974). Helium concentration at Swift Current-Wilhelm is almost twice as high as other, higher gas volume Saskatchewan production.

By 1960, the Cold War and the imminent Apollo program elevated helium's significance above "lifting gas" status. One result was Saskatchewan Department of Mineral Resources Report 49, Helium Prospects in Southwest Saskatchewan, (Sawatzky et al., 1960). Report 49 described existing shows, and accurately sign-posted future helium discoveries. An addendum notes Texaco's remarkable 1960 discovery of Cambrian helium at Mankota SK, on the northeast flank of the cross-border Bowdoin Dome, 130 km (80 mi) north of Glasgow, Montana. But mid-century helium demand was ultimately met by the Panhandle-Hugoton field, and for decades, no new survey of helium resources in the western border region was produced. This has decisively changed in recent years: in 2016, Yurkowski of the Saskatchewan Geologic Survey published Helium in Southwestern Saskatchewan (Yurkowski, 2016), followed by a comprehensive update in 2021 (Yurkowski, 2021) and further work in 2022 (Yurkowski, 2022).

WELL 3: TEXACO WOOD MOUNTAIN 12-10, SASKATCHEWAN AND WELL 4: TEXACO R.E. BAIR #1 HILL COUNTY, MONTANA

The Texaco-International Helium Wood Mountain Mankota 12-10 discovery on the northeast flank of the Bowdoin Dome (Val Marie Arch) was described in the Addendum to Report 49 (Sawatzky, et al., 1960). It is the first of four significant 1960 wells. Both 12-10, and offsetting well 10-03 encountered reservoir quality Cambrian five-meter-thick marine sandstones at 2560 m (8400'), hosting nitrogen dominant 1.2% helium. Northwest-southeast areal extent is at least one mile and a half, plausibly sub-parallel to paleo-shoreline. There is no other public evidence of reservoir extent. DST flow rates are unavailable, but log notes indicate up to 450000 m3/d (16 MMCF/d), at the high end of regional flow rates. Good reservoir quality is borne out by production of over 1.5 million m3 (51 MMCF) of helium from the two wells, after Weil Resources' 2016 re-entry. The wells have since watered out: uniquely, they are the only wells testing wet reservoir in separate Cambrian clastics below the gas zone. 12-10 and 10-03 are also the only legacy wells with reservoir quality Cambrian marine sandstones tens of m (<100 ft) above, rather than directly superposing the Precambrian unconformity. Surviving core from 10-03 shows medium to coarse-grained glauconitic reservoir sandstone, with generally well-rounded quartz grains (Fig. 5, and Dixon, 2008).

Neither Int. Helium Mankota 2-7 in 1965 nor Weil Mankota 9-9 in 2019 encountered the Cambrian helium-filled marine sandstone. At Weil 9-9 geophysical well logs are unavailable in the Deadwood interval, below production casing. No other Cambrian system test data were gathered at Weil Mankota 9-9. The 9-9 well's only reported function was disposal of <100,000 barrels of water into Jurassic strata. Until 2021 when North American Helium discovered a similar Cambrian shoreface sandstone ten of meters above the basement 15 km (ten mi) west southwest at approximately 49.3°N 107.1°W (Township 4, Range 9 West 3, Dominion Land Survey Township and Range system) Texaco – International Helium's 1960 explorationists were uniquely successful at Mankota. The Texaco Wood Mountain wells are on a subtle structure compared to other early regional helium discoveries, making the discovery even more impressive. Trapping structure is likely related to uplift of the Laramide Bowdoin Dome. However, it should be noted that compared to the Knappen 16-29, (Well #5, discussed below), on the north flank of the Kevin Dome, the Wood Mountain wells are further from topographic expression of the Bowdoin Dome, to the extent that they are 50 km (30 mi) rather than eight (five mi) northeast. Unlike 16-29, Mankota wells are also on the far side of the water course (the Frenchman River)

Figure 5A. Texaco-International Helium 10-03 Cambrian Deadwood conglomerate sandstone core, 1961.

which is deflected around the Bowdoin Dome, discussed below. The trap may be as much stratigraphic as structural, and 3D seismic at Mankota did not produce better drilling locations until North American Helium's nearby Mankota West discovery.

Less still is known of Montana's border areas. In 1960 Texaco encountered Paleozoic helium again, this time in the Devonian Souris River and Ordovician Red River formations. Because Well #4 (Bair No. 1) is also Texaco, and inert gas isotopes from its 2012 twin well (Weil No.1) were analyzed with the Wood Mountain wells, it is discussed in conjunction with the Texaco Wood Mountain wells. Bair #1 is in section 28 T34 Range 9E Rudyard, Hill County, Montana 30 km (20 mi) south of the international boundary and 30 km (20 m) west of longitude 110°W, which forms the Alberta-Saskatchewan border. Nitrogen-dominant helium and Mesozoic hydrocarbons are trapped on the Rudyard Anticline, a township-scale flexure on the east flank of the Sweetgrass Arch. The well was abandoned after six DSTs. Two DSTs recovered helium in the 1% range at a total rate of 115000 m3/d (4 mmcf/d). It is plausible that gas cut mud recovered from the deepest DST (six) in Cambrian reservoir is also non-combustible: no Cambrian petroleum system has been discovered

Figure 5B. Texaco-International Helium 10-03 Cambrian Deadwood conglomerate sandstone core, 1961.

nor has a dominant non-combustible gas stream up section from petroliferous reservoir been observed. Bair No.1 was drilled to the Cambrian system at 1996 m (6550'): the well file does not refer to helium as exploration target and references a shallower projected TD, although this may be prognosis error. Texaco's Chinook, Montana office did not appear to share Calgary-office exploration priorities in 1960, or Bair No.1 might have been further evaluated. The Rudyard resource, and the 2012 flow tested well (Weil #1) are now assets of Global Helium Corp. Rudyard is the sole "Original Six" discovery for which the pool remains unproduced. Montana remains largely unexplored, despite approximately 30 instances of Paleozoic non-combustible gases in exploration wells, in multiple counties. Montana is likely to see first helium in 2024 from one or more of five exploration wells in Toole County, northern Montana. including WNG 10-21 from which Avanti Helium tested 575000 m3/d (20 MMCF/d) raw gas from the Cambrian Flathead, a middle Cambrian basal sandstone unit, and/or Global Helium-operated Weil #1 from the Devonian Souris River and Ordovician Red River formations.

Mankota, Saskatchewan and Rudyard, Montana lie 280 km (175 mi) apart, with gas in distinct reservoirs. Nonetheless there are notable similarities in inert gas isotopic systematics. Danabalan 2017 locates both Mankota and Rudyard in the Great Falls Tectonic Zone (GFTZ), a relatively young Meso- to late Paleoproterozoic feature separating the Medicine Hat block of the Archean Hearne Province from the Wyoming Province (Fig. 1). While the boundaries, exact orientation, and origin of the GFTZ remain uncertain, the northeast-southwest strike of the GFTZ connects the two wells. Strike-parallel lineaments and deep high-angle faults make the GFTZ a Cratonic feature plausibly related to Paleozoic helium accumulations.

Danabalan (Danabalan, 2017, Table 4.1, appended) shows the gas in geographically and stratigraphically distinct Rudyard Weil #1 and the Texaco-International Wood Mountain wells. Both common neon isotopic ratios (20Ne/22Ne and 21Ne/22Ne) differ by less than 5%, although that is generally true on the northwest rim of the Williston Basin, regardless of strata. $^{40}Ar/^{36}Ar$ variance between the Rudyard and Mankota gases may be more diagnostic. While the difference is greater than for the neon isotopes, at approximately one quarter, it is about half the variance shown at Harley Dome, Utah, the other nitrogen-dominant gas stream Danabalan investigates. Cheng 2021 data show the similarity of $^{40}Ar/^{36}Ar$ at Rudyard and Mankota is striking, compared to regional Mississippian and Mesozoic inert gases, in which $^{40}Ar/^{36}Ar$ is an order of magnitude less than that seen at Harley Dome; less still compared to GFTZ (coincident with the northwest rim of the Williston Basin) wells from the same region (Cheng et al. 2021, extended data).

The evident difference between Rudyard and Wood Mountain gas is greater mantle contribution to the former, in that 3He/4He is almost three times higher at Rudyard: Higher CO2 at Rudyard also suggests mantle contribution. It should be noted that although the Rudyard 3He/4He is on the order of atmospheric (0.70 Ra), other isotopic ratios such as 4He/20Ne diverge from atmospheric values by orders of magnitude. This precludes air and favors the mantle as the source of the 3He exceeding expected radiogenic crustal helium production. This is geologically plausible, due to decreasing intensity of Eocene magmatism, a likely mantle-basement conduit, southwest to northeast, i.e., Rudyard to Wood Mountain (Connolly 2012, Danabalan 2017).

WELL 5: 16-29 HOME OIL KNAPPEN, ALBERTA (BORDER WITH TOOLE COUNTY, MONTANA)

Alberta's more than century-old well count is at half a million wells. Despite this, westwards from the Saskatchewan border at 110°W, along the 49th parallel towards the Cordillera, little is known of the deep Paleozoic. Home Oil DST'd Paleozoic helium, again in 1960, at 16-29 Home Oil Knappen. 16-29 is the fourth of six wells in Table 1, eight km (five mi) north of the international boundary, adjacent to Toole County, Montana. As in southwest Saskatchewan and Rudyard, the carrier gas is dominantly nitrogen, with variable CO2 migrated from or co-genetic with the 85 BCM (3 Tcf) accumulation at Kevin Dome, and low alkanes. Thor Resources began production in 2019, six decades after discovery. 2 million m3 (70 MMCF) of helium has been produced to June 2023, from completions in Cambrian and Devonian reservoirs. The commanding structure is the 2000 km2 (750 mi2) Kevin Dome, mostly in Montana, but which has 300 meters (1000') relief from the international boundary eight km (five mi) north to the Milk River (Fig. 6). Milk River hydrography is notable: it rises in Montana, flows around

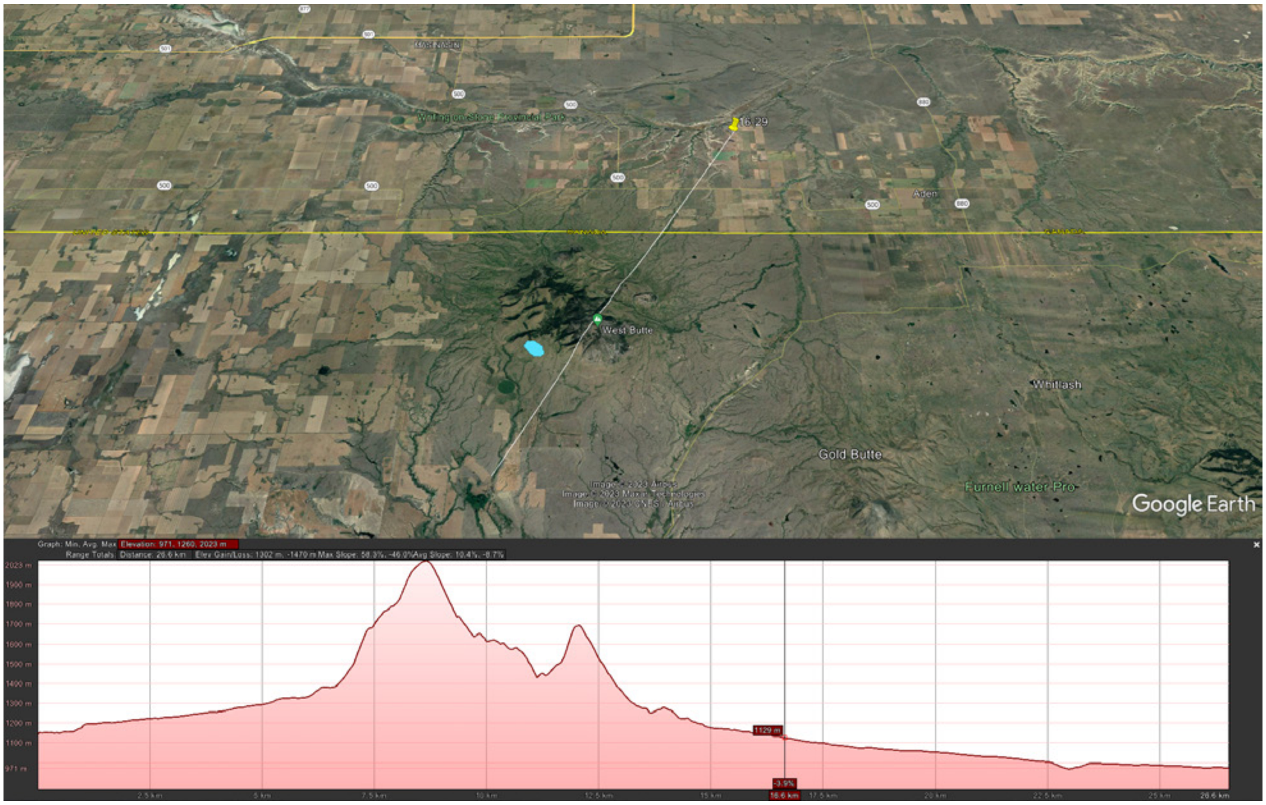

Figure 6. Elevation profile – southwest flank of West Butte, Montana, northeast to 16-29 Knappen Alberta helium well.

the north flank of the Kevin Dome into Canada; and then turns south into the United States, 70 km (40 mi) east of Kevin Dome. It is unusual for rivers flowing north of the 49th parallel to drain into the Gulf of Mexico. (The Milk River/Missouri/Mississippi tributary Frenchman River in Saskatchewan is also located along the Paleozoic helium trend.) U/Th/He thermochronology (measurement of diffusive He-loss during nuclear decay allows inference of rock cooling chronology) and apatite thermochronology can be variably interpreted (Adeniyi 2019), but point to pulses of Kevin Dome cooling and exhumation from the Late Cretaceous to Miocene. Plausible interpretations are consistent with a schematic cross section from the Geophysical Atlas of Western Canadian Hydrocarbon Pools, (Fig. 7, Anderson et al. 1989, right panel, Burwash & Cummings 1974, left panel). As well as containing ~85 BCM (3 TCF) of naturally occurring CO2, the Kevin Dome is variably petroliferous on both sides of the border, on the north side in late Paleozoic through Mesozoic reservoirs.

Reservoir fluid and structural history distinguish Kevin Dome-area helium the from Swift Current, south central Saskatchewan, despite nitrogen-dominant inert gas in Cambrian basal clastic units at both. At Swift Current, unlike the Kevin Dome, the structure does not appear to trap hydrocarbons in younger reservoir, despite proximal Mesozoic hydrocarbons. A reason for this is that Precambrian highlands drowned by eastward transgressing Upper Cambrian sea and draped by sediment may not form a trapping structure up-section in the Mesozoic. Intrusions at Swift Current are believed to be Proterozoic (Burwash and Cumming, 1974, Mossop and Shetsen 1994), unrelated to events forming the Kevin Dome, or the Laramide Bowdoin Dome south of Mankota. The Bowdoin Dome also traps late Cretaceous fuel gas, distal from the northern flank where helium is produced from Cambrian strata.

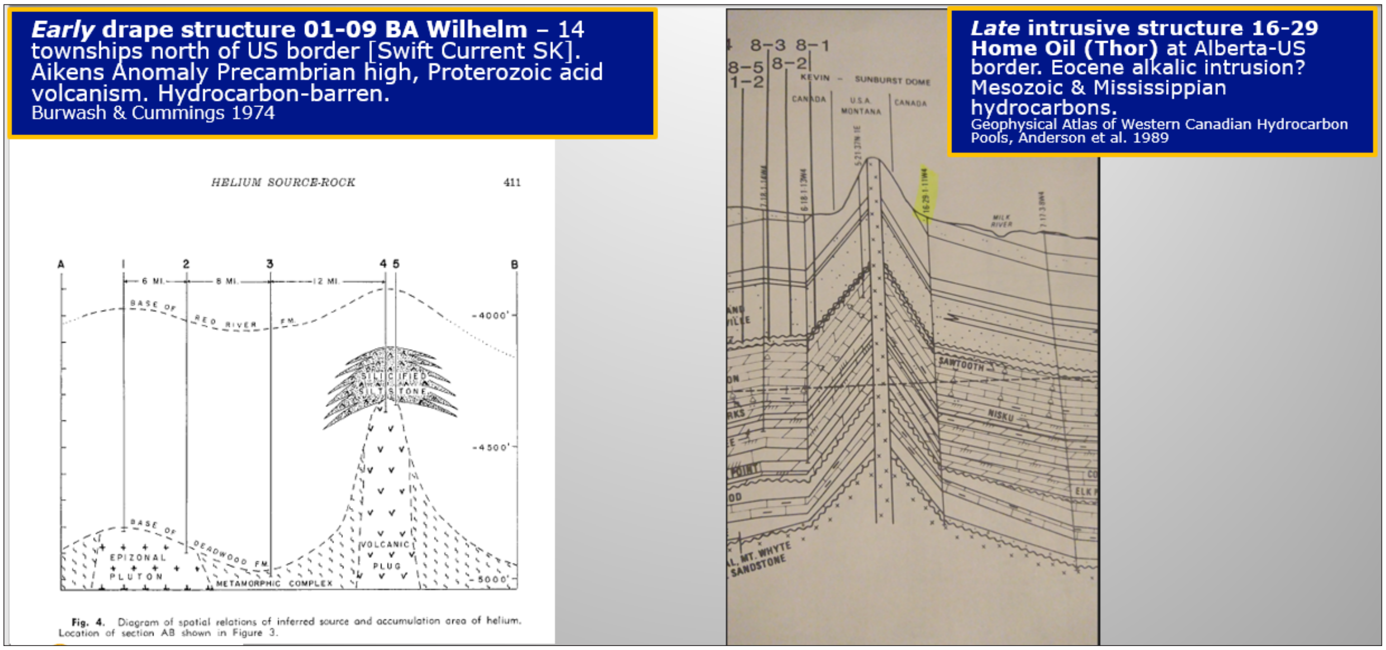

Figure 7. Schematic sections of sediment drape over Precambrian highland, Swift Current, Saskatchewan, and Paleogene uplift 20 miles (30 km) east of the Coutts border crossing between Montana and Alberta.

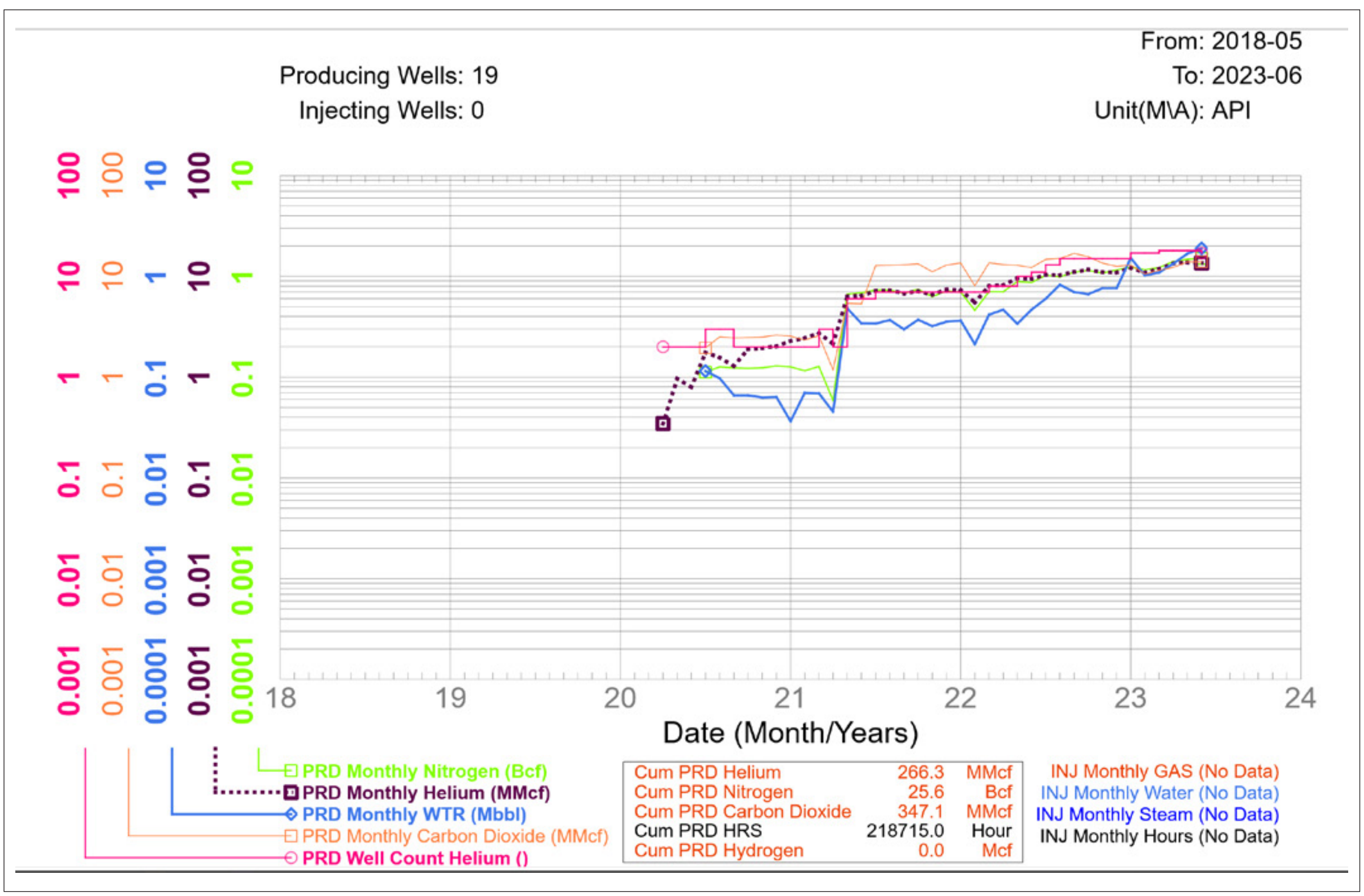

Figure 8. Saskatchewan and Alberta helium production, March 2020 to June 2023, Government data.

WELL 6: MOBIL BATTLE CREEK 10-25, SASKATCHEWAN

The final legacy discovery was a return to Battle Creek. Here, Exxon found helium in the Cambrian basal clastic unit at the Exxon 10-25 well (101/10-25-003-27W3) in 1971, at 2225 m (7300'); an unsurprising result, given the 1952 Devonian helium discovery at nearby United Canso #2. Helium at Battle Creek is trapped on a Precambrian topographic highland, as at Swift Current, but one that also traps Mesozoic and Mississippian hydrocarbons, like the young trapping structures at Knappen, Alberta, and Rudyard, Montana. Exxon 10-25 DST'd 282000 m3/d (10 mmcf/d) of 0.9% helium, 96.7% nitrogen, and approximately 2% combined CO2 and C1. Bottom hole DSTs also recovered Mississippian and Mesozoic oil and gas, but the well was never produced and definitively abandoned in 2010. Gas exsolved from undifferentiated Mississippian Madison Group heavy oil (API 11°) contains an unusual combination of four non-combustible gases in the two to eight mole percent range: hydrogen and sour gas both exceed two mole per cent, combined with six and eight percent CO2 and nitrogen. There is also a trace (0.08 mol %) of helium. The Mississippian helium to nitrogen ratio of 0.010 resembles the Cambrian basal clastic unit (9.30 e-3). The Cambrian basal clastic units form the backbone of helium production in the region to date. Ichaso (Ichaso et al. 2022) studied seven cores at Battle Creek-Consul SK (map in appendix). They interpret Cambrian basal clastics as various iterations of a shoreface complex, including deltaic sandstones, in a prograding marine depositional environment. This means reservoir may be found on structure flanks, and implies reservoir risk, due to "bald highs" and/or limited well control delineating paleo-shorelines. Exxon 10-25 has a relatively thin pay zone of 6 m (20'), towards the top of the structure: North American Helium's producer at 102 10-25 offset found more than twice the Cambrian basal clastic reservoir thickness, 100 m (330') down structure.

HELIUM PRODUCTION 1.0

Early and mid-20th century helium production was government-focused. As World War I was concluding, City of Medicine Hat-area Mesozoic helium was produced as a lifting gas for the evocatively-named "Board of Inventions and Research of the British Admiralty." Short-lived effort was expended to produce 60,000 cubic feet from helium concentration of 0.3% in Cenomanian fuel gas (Satterly, 1959, Sawatzky et al., 1960). 1963-1977 production of approximately 6.5 million m3 (0.23 Bcf) of nitrogen-dominant Paleozoic helium for the Apollo Program from four wells at Swift Current-Wilhelm was more meaningful. However, absent fuel gas, there was no economic basis for production as US government agency helium demand declined in the 1970s. Canadian Helium inc. re-started production in 2021, to meet private-sector demand. Swift Current-Wilhelm was a mid-20th century preview of 21st century "helium as sole revenue source" rather than "helium as fuel gas by-product".

HELIUM PRODUCTION 2.0

Weil Group Canada ltd. blazed a trail in 2016 by re-entering the two Texaco-International Helium wells at Mankota, SK. Cumulative helium production reached 1.5 million m3 (50 MMCF) by 2018, when the wells appeared to water out. Sustained regional production re-started in spring 2020, with two wells, a re-entry and new drill respectively from private companies Thor Resources and North American Helium. From these beginnings, Saskatchewan now has 17 wells including dual completions producing 345,000 m3 (12 MMCF) of helium per month by Q2 2023, with multiple drilled and completed wells. Alberta's handful of wells produce 86,000 m3 (3 MMCF) per month by Q2 2023, also with multiple drilled and completed wells. Montana has seven drilled wells. Montana helium production is likely to begin in the first quarter of 2024.

In November 2021, the Government of Saskatchewan released a Helium Action Plan, (Government of Saskatchewan, 2023) setting a goal of 10% of world helium production by 2030. At 2023 world production of about 185 million m3 (6.5 Bcf), this would quadruple Saskatchewan's helium production from likely 2023 end-of-year production rate. Production of 1.9 million m3 (650 MMCF/year) would be just under 1% annually of the USGS 2023 estimate of Canadian helium resources, or half of one percent of United States Rocky Mountain Region resources.

Further context is that while there are only 19 producers, there are approximately 150 well events from 2020, which counts wells (each completion counts as one), licensed wells, dry holes, and producers. The absence of a legacy gathering system comparable to hydrocarbon infrastructure means helium production increases will be uneven. On the exploration side, deep-well density is still low on the Great Falls Tectonic Zone-aligned helium trend. While there have been and will be dry holes, it is reasonable to expect improved exploration results as experience is gained, and sufficient well-bore data are gathered to tie to seismic effectively and to allow reservoir visualization in three dimensions. First quarter 2020 regional helium industry production re-start also coincided with the onset of Covid-19. While contentious geopolitics had displaced focus from the pandemic by 2022, Covid-19 entailed profound challenges for collaborative and creative geoscience, as well as raising capital, facilities engineering and design, production engineering, procurement, and field operations. Production steadily increased from 2020 nonetheless; 21st century cumulative production already exceeds Apollo-era volumes (Fig. 8).

Trucking purified gas 1200 mi (2000 km) to the U.S. mid-Continent raises the question of liquefaction. The Saskatchewan Research Council released Helium Liquefaction in Saskatchewan (Emery et al, 2023) in May, 2023. All options are viewed to have positive Return On Investment: whatever is settled on, a new northern helium hub is being built out, the first north of Shute Creek, WY.

The northern helium hub is net-zero, simplifying ESG and facilitating "pure play" helium. Deep Paleozoic is nitrogen-dominant, located stratigraphically below extant hydrocarbon systems. At the end of 2022, Alberta and Saskatchewan had 176,891 oil and gas industry gas composition analyses in the public domain. Most are Mesozoic: helium is greater than or equal to 0.5 mol% in over 2000 cases, skewed but not limited to Paleozoic reservoirs. Montana has approximately 1,600 available gas analyses – mostly from the Bureau of Land Management and the USGS – contain less than 100 examples of helium exceeding 0.5 mol%. Montana gas analyses are not systematically in the public domain. Lack of gas data is a challenge for Montana helium exploration, and can cause operators to rely somewhat on extrapolation of known Canadian helium gas trends south of the 49th parallel. However, relying on wells drilled between 1970 and 2015 was not a great deal more fruitful on the Canadian side; south of 53°N, (therefore excluding the Peace River Arch), there were only 189 new gas analyses from the Devonian or deeper, to add to 62 pre-1970 deep Paleozoic gas analyses (Fig. 9). Nonetheless, these gas analyses were sufficient to establish a reasonable indication of the non-combustible gas trend following the GFTZ from Montana to south-central Saskatchewan and beyond, using nitrogen mol% as a well-constrained helium proxy (Fig. 10). Where acid gas or hydrocarbons can overprint the helium signature, in Devonian carbonate reservoirs or Williston Basin-proximal analyses respectively, a helium-to-nitrogen ratio map can improve the noble gas signal (Fig. 11). To date, H2S has not been evident on the GFTZ helium trend.

The numerical dominance of analyses from Mesozoic reservoir raises the question of whether and how anomalous helium in these gas streams can be used to find commercial Paleozoic helium gas (Fig. 12) trends. This remains a work in progress: Global Helium, working with GeoChemical Insight (Dave Seneshen, Ph.D., principal) is nevertheless going a step further and using analysis of gases dissolved in Cenozoic aquifer water as an exploration tool This follows a similar attempt to use shallow aquifer geochemistry to solve hydrocarbon exploration puzzles in Saskatchewan in the 1980s by Dyck and Dunn, 1986, referenced in Yurkowski, 2021.

Sparse, low density southwest to northeast non-combustible Paleozoic gas data points consistent with the southwest to northeast GFTZ were also observed (although not at the time identified with the GFTZ) in 1989: high helium analyses were proposed as a prospecting tool for uranium exploration, since isotopically-dominant 4He is a radiogenic product of uranium decay. In Fig. 13, GFTZ-trend Paleozoic inert and on-combustible gas anomalies are described as "interesting phenomena" relative to uranium and diamond (kimberlite) exploration (Harper, 1989).

DRILLING EVOLUTION

The baseline for 21st century helium-targeted drilling has been vertical wells, 1700 – 2600 m (5500' - 8500') deep, deepening west-to-southeast, following Williston Basin subsidence. Good rig releases are in the 12-day range for the deeper Saskatchewan wells. Deviated wells and multi-well pads are beginning to appear. There have been few fracs to date, as quality reservoir has been "rifle shot" targeted. Surface facilities, essentially nitrogen rejection units, amount to six in Saskatchewan and one in Alberta, with a second likely to be commissioned before the

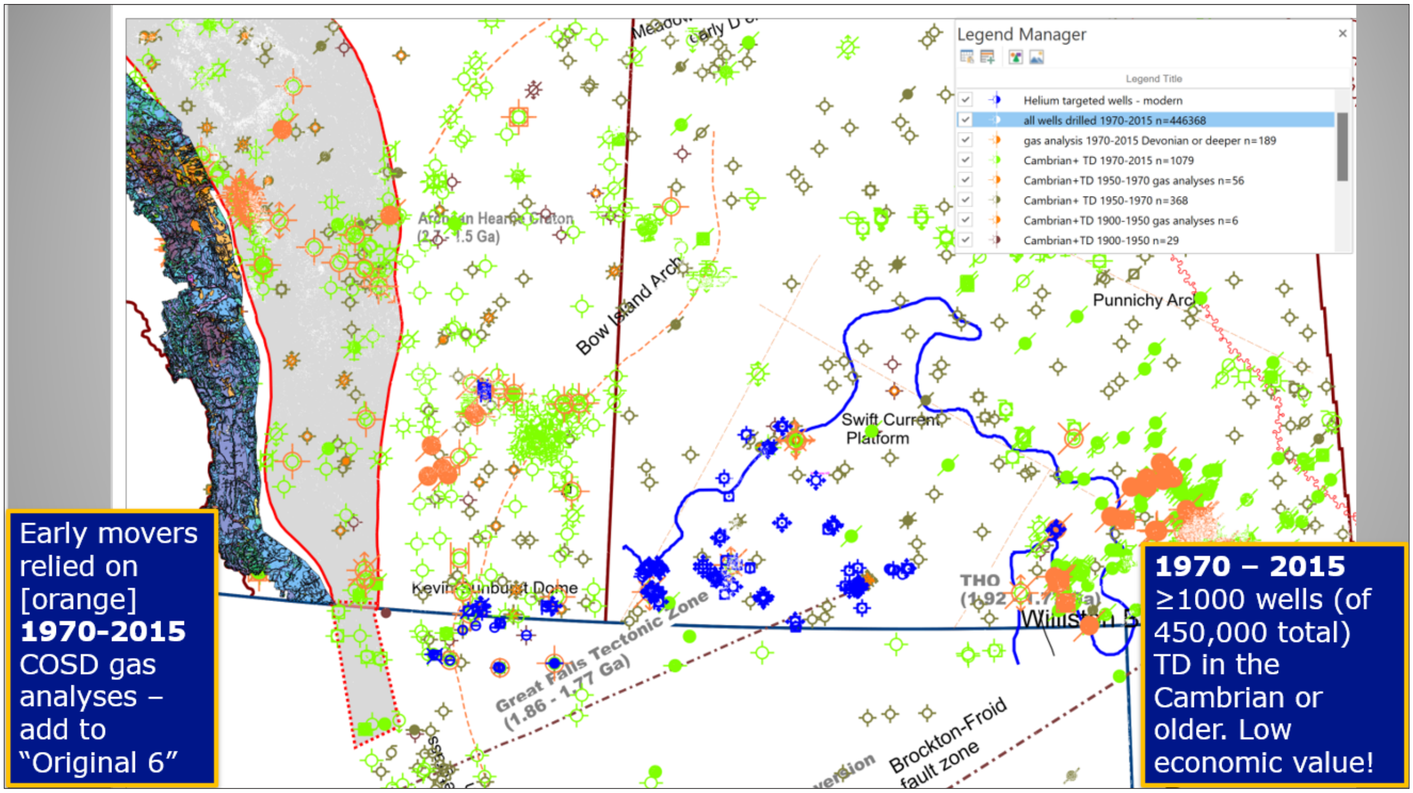

Figure 9. Distribution of 189 total Devonian or older gas composition analyses, 1970 – 2015, southern WCSB and adjacent Montana.

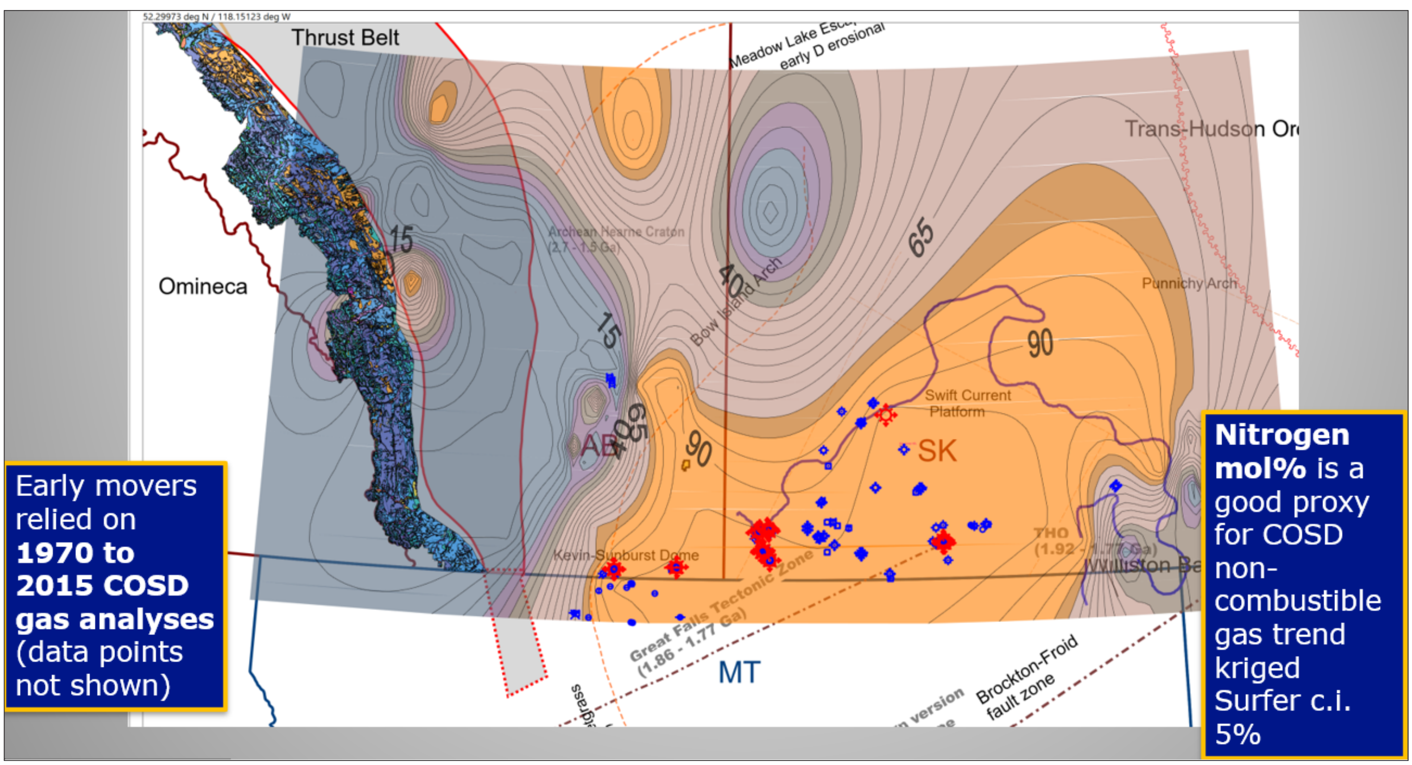

Figure 10. Nitrogen mol%, Devonian and older reservoirs, 1970 – 2015.

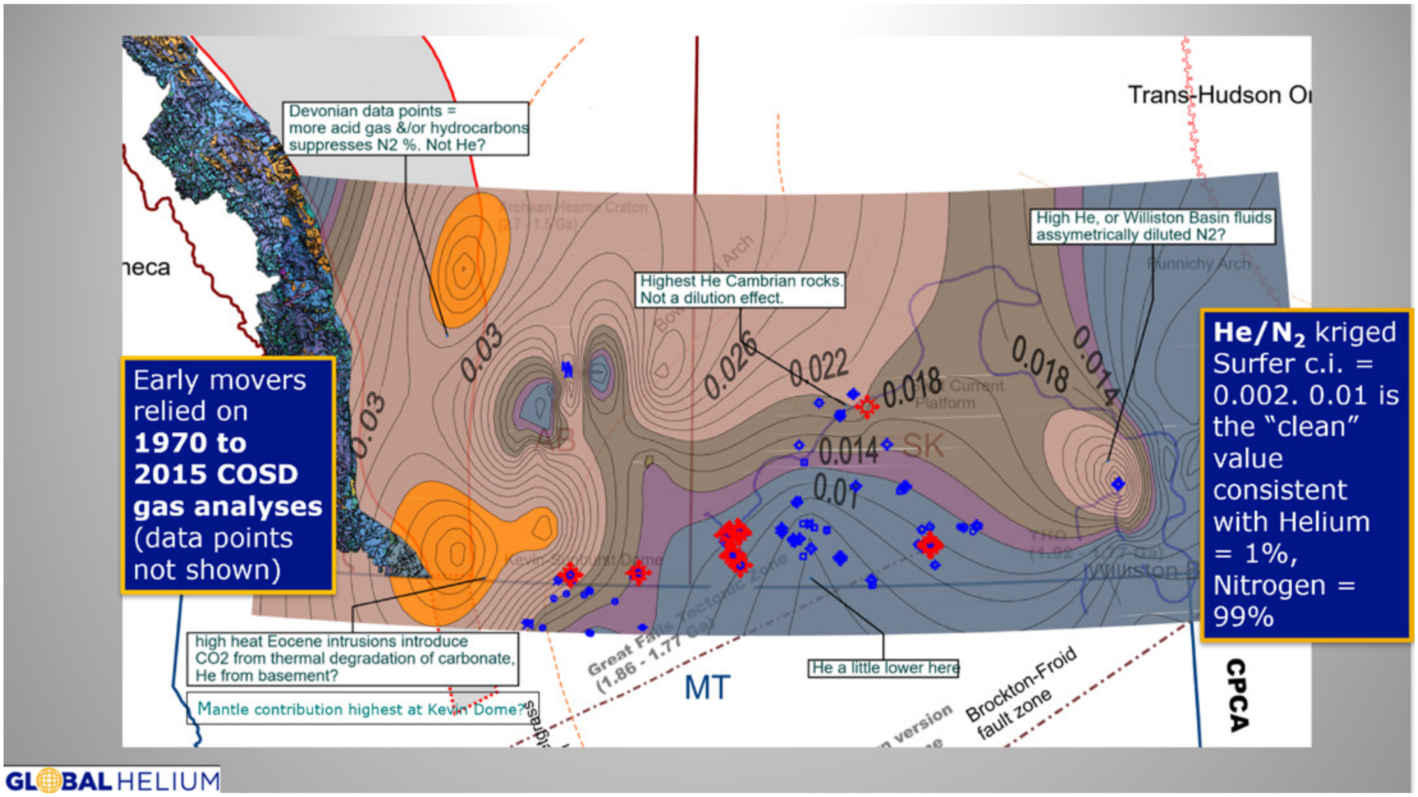

Figure 11. Helium to nitrogen ratio, mol% gas composition analyses 1970 – 2015.

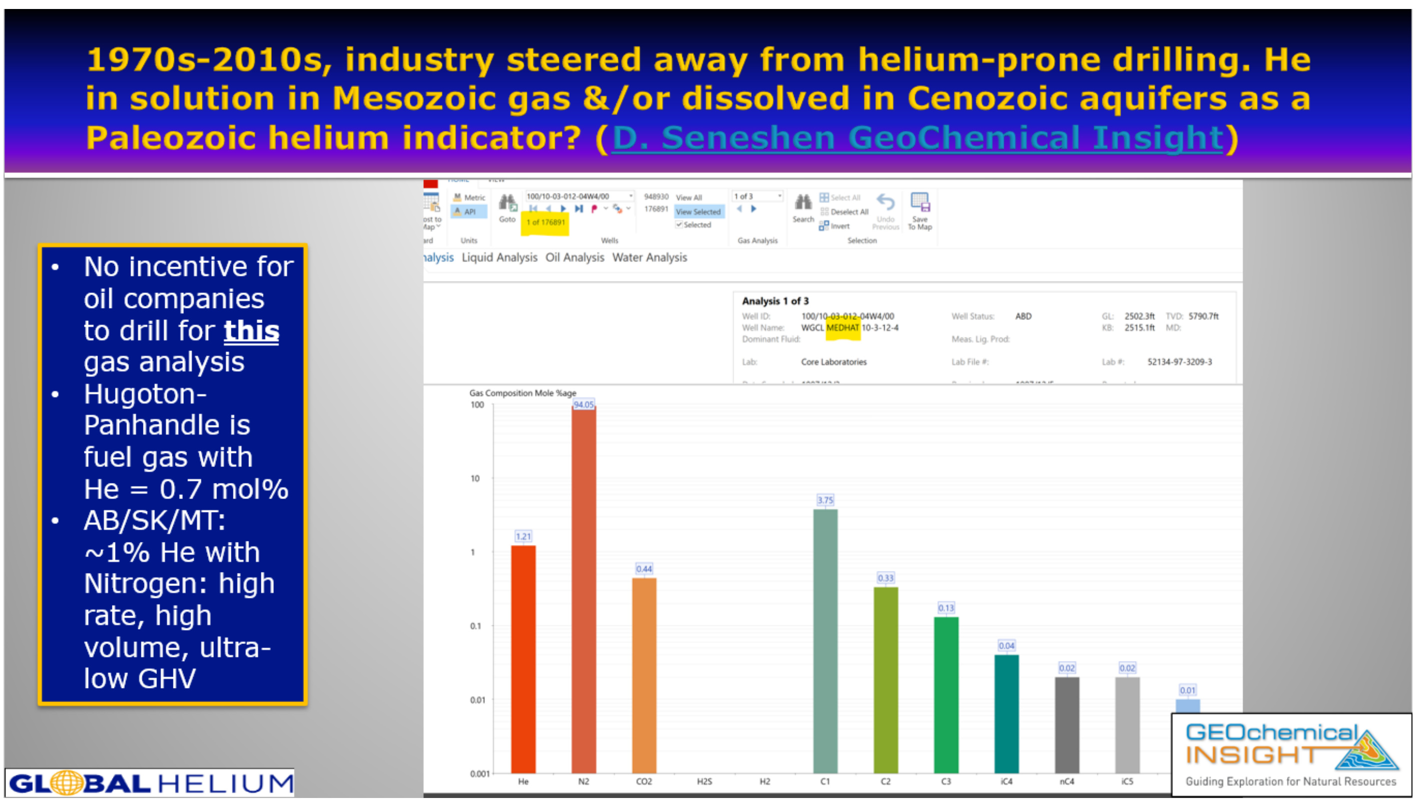

Figure 12. Representative gas composition analysis, Devonian Souris River formation (Givetian - Frasnian), southeastern Alberta 1997.

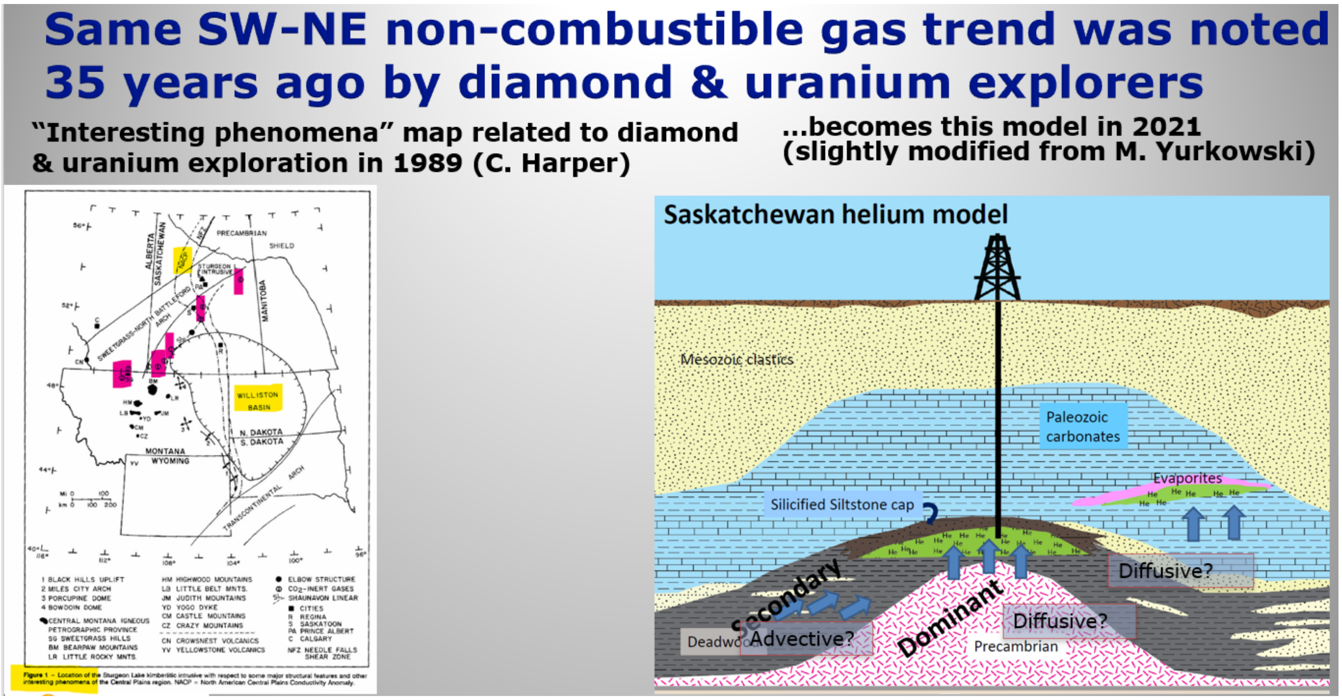

Figure 13. Unexplained Paleozoic southwest to northeast non-combustible gas trend Saskatchewan observed in 1980s, and 2020s helium accumulation model.

end of 2023. For the moment, high purity helium gas is trucked to the US mid-continent; loads are around 4000 m3 (140 mcf).

Production is dominated by heterogenous Cambrian basal clastics directly superposing or close to the Precambrian unconformity. There are dual completions with and limited stand-alone production from late Givetian-early Frasnian (Devonian) Souris River formation calcareous dolomite. Global Helium expects regional growth in Souris River production, which may change drilling and exploitation strategies.

OPERATORS

In 2023, North American Helium dominates Saskatchewan production, with minor additional volume from Canadian Helium Inc. Second quarter 2023 production is up to 4.3 million m3 (150 million cubic feet) annualized. Royal Helium and Helium Evolution have completed wells awaiting evaluation and/or tie-in. In Alberta, Thor Resources is producing helium mostly from Cambrian basal clastic reservoir at Knappen, Alberta, in the boundary township, adjacent to Toole County, Montana. Royal Helium drilled and completed Devonian Souris River wells 200 km (125 mi) north of Thor's wells at the international boundary. Weil Resources appears to be installing production equipment for a completed well, and Global Helium has a drilled and cased well awaiting completion (September 2023): both are near Dunmore, Alberta, on the Manyberries helium trend. Alberta second quarter 2023 production is unlikely to exceed one third of Saskatchewan volumes. This may reflect, in part, the Province of Saskatchewan's first mover advantage in stimulating the helium industry with exploration permits, awarded on a first-come-first-serve basis. Helium exploration permits resemble mining industry claims, with a work commitment: the Saskatchewan government's focus on helium may arise from its status as the only regional jurisdiction with meaningful legacy helium production.

Montana awaits first helium production. Global Helium, Avanti, and Thor Resources operate drilled and cased wells in Montana, all within three townships of the Alberta boundary; just south of 49°N, west of longitude 110°W. While Montana has less than ten modern helium wells awaiting surface facilities, this handful of wells shows commercially prospective helium in tall three of the Cambrian, Ordovician, and Devonian systems.

INSPIRING FUTURE GEOSCIENCE

Helium exploration is both a re-evaluation of past work, in mining as well as oil and gas, and an inspiration for exploration innovation. Thirty-five years ago, C. Harper (Harper, 1989) and M. Gent (Gent, 1989) noted a non-combustible gas trend, now identifiable as sub-parallel to the GFTZ. Their observations were helium exploration, inverted: they observed the southwest-northeast non-combustible gas trend, including helium, as an indicator of diamondiferous kimberlites with non-combustible gas inclusions. Gent proposed a link between kimberlites and alkaline intrusives more generally, and major and NW and NNE- to NE basement fault trends and craton border structures. Diamondiferous kimberlites have been found at the north end of the trend, at Fort à la Corne and Sturgeon Lake, near the City of Prince Albert, and near the intersection of the North American Central Plains Conductivity Anomaly and the Sweetgrass-North Battleford Arch at its north-eastern limit (Harper, 1989). The general case is that "intrusives…tend to occur along oblique transfer structures which in turn are usually old basement shears or faults and may extend into the basement." (White, 1995). Eocene alkalic intrusives outcrop in southeastern Alberta and adjacent Montana (Marvin et al., 1980, Gent, 1989), at the southwest end of the trend. They are plausibly present in the subsurface, on trend at Lake Diefenbaker, 110 m (70 mi) south of Saskatoon (Gent, 1989): Harper cites the Williams kimberlite, Little Rocky Mountains. Evidence for these intrusives includes igneous rocks encountered by the drill bit, structural anomalies in Phanerozoic strata identified by stratigraphic mapping, and aeromag, gravity, and seismic surveys; as well as tectonic and intrusive structures. Harper's 1989 map locating the Sturgeon Lake kimberlitic intrusive and many of the GFTZ-area non-combustible gas shows then available has turned out to be useful to helium explorationists.

Regional water well dissolved helium gas surveys and lake bottom sediment analyses were also undertaken in the 1970s as reconnaissance for uranium exploration. In Saskatchewan, elevated helium in lake bottom sediment analyses from Key Lake, north of the GFTZ, appeared to correlate with the then recently discovered uranium deposit (Dyck and Dunn, 1976, 1978, and Dunn, 1980): see also Phoenix deposits, southeastern Athabasca Basin (Dudek and Hattori, 2015). Global Helium completed a second field season of regional water well and associated pressure tanks dissolved gas surveys in southwest and south-central Saskatchewan in 2023. Results from the 2022 field season, as well as 742 soil gas samples, were presented at RMAG North American Helium Conference, 2023 (Seneshen and MacKenzie 2023).

New work inspired by helium exploration on the GMTZ trend includes the Saskatchewan Ministry of Energy and Resources and the Saskatchewan Geological Survey creating the first three-dimensional model of the architecture of Laurentia; that is, the Archean-cored cratons in Saskatchewan and neighboring jurisdictions (Bosman et al., 2021). Dr. Andrei Ichaso (Ichaso et al., 2022). has studied the impact of early Phanerozoic bioturbation – the Cambrian agronomic revolution - on reservoirs that had been little studied, due to depth and lack of a hydrocarbon system (Fig. 14). As of August 2023, the Alberta Energy Regulator and Geologic Survey are processing 106535 line km (66584 linear mi) of magnetic data that were flown in 2023 Q1, between the international (Montana) boundary and latitude 51°N, covering Alberta's portion of the GFTZ (Alberta Geologic Survey High Quality Regional Airborne Geophysical Surveys, 2021-2023, In Progress). Thousands of hours to date have been committed to the creation of a new Atlas of the Western Canadian Sedimentary Basin. The helium exploration boom has been one impetus to the creation of this new Atlas, a replacement for the highly-regarded 1994 version (Mossop and Shetsen, 1994). The 2027 steering committee aims to make the 2027 Atlas of the Western Canadian Sedimentary Basin (Haynes et al., forthcoming, 2027) the most comprehensive one-stop survey of any basin in the world, as well as one of the most extensive geological treatises ever published. While its focus is north of the 49th parallel, it is certain to shed significant light on areas of Montana and North Dakota adjacent to the 49th parallel. These are just four examples of the way the revival of helium exploration after 50 years' inactivity is inspiring new consideration of the geology of the southern portion of the Western Canadian Sedimentary Basin, including adjacent U.S. counties. Hydrocarbon development of recent years has tended in the direction of maximal exploitation of geologically and geographically focused targets, generally in Mississippian and younger reservoirs. Exploration for helium requires consideration of the structure, stratigraphy, and geochemistry of the entire Phanerozoic, the Precambrian basement, as well as the architecture and interrelationships

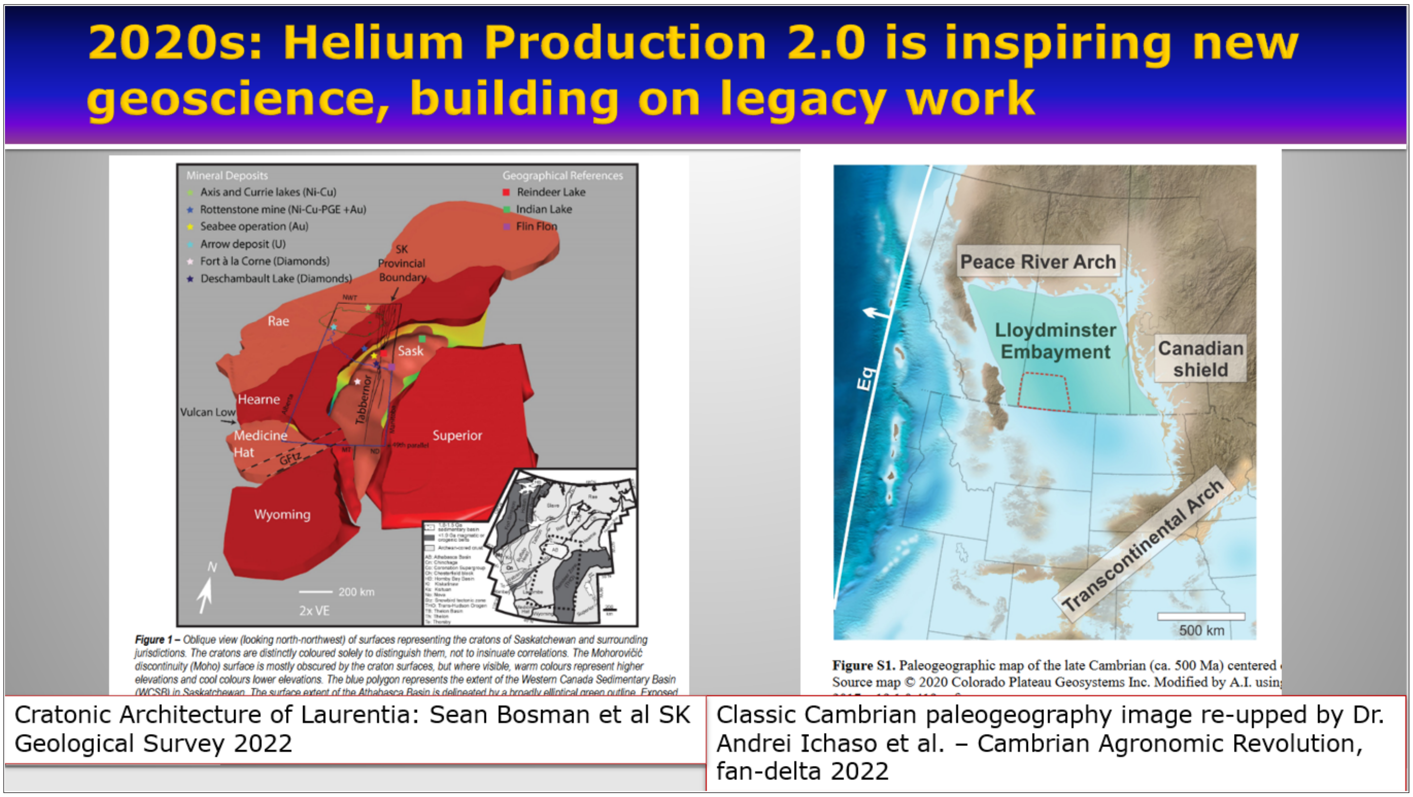

Figure 14. 2020s helium and non-combustibles-driven remodeling of Cratonic architecture and re-evaluation of lowermost Phanerozoic strata: Saskatchewan, Alberta, and adjacent Montana and North Dakota.

of the regional Archean-cored cratons. Even if done with modern technology, albeit without the resources of the mid-century petroleum majors, this is an undertaking unlike any since the first decades of Devonian-focused petroleum exploration in the area during and after the Second World War.

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THE AUTHOR

DUNCAN MACKENZIE

Duncan MacKenzie has spent 23 years as a geologist working in oil & gas exploration and development, mining reagents, and since 2015 non-combustible gases. Duncan is co-founder of Global Helium, and has seen the company grow from an LLC to one of Saskatchewan's largest publicly traded Helium Exploration Permit holders, as well as land and a producible well in Alberta and Montana. Duncan's interest in helium and non-combustible gases extends to presenting at RMAG's North American Helium Conference, and Associate Editor of the 2023 SEG-AAPG Interpretation Special Session on Helium.

Duncan's oil & gas career was been spent growing production and reserves with Calgary-based oil and gas producers such as Zargon Oil & Gas Ltd., and Montane Resources. He has also worked as a consultant on oil and gas projects in Colombia and the Gulf of Guinea. During oil & gas downturns and while working to fund Global Helium, Duncan worked supplying mining reagents from North Africa and West Asia to non-ferrous metals and chemical producers in North America and South America. Duncan studied geology at McGill University, Montreal and the University of Alberta, Edmonton, and obtained his BSc Specialization Geology from the University of Alberta. He is a professional member of the Association of Professional Engineers and Geoscientists of Alberta, and the *Ordre des géologues du Québec*.

Exploration for Helium in The Phanerozoic[1]

PAUL LAFLEUR[2]

1. Manuscript received May 22, 2023; Accepted August 24, 2023.
2. North American Helium Conference, Rocky Mountain Association of Geologists, March 22-23, 2023

ABSTRACT

Almost all the helium discovered worldwide has been found by chance in the drilling for hydrocarbons. Targets were usually anticlinal structures located by seismic surveys. The association of helium and natural gas in reservoirs is purely coincidental because the source rocks for each are different—natural gas is mainly produced from diagenesis of carbon rich shale whereas Helium- 4 is derived mainly from the decay of uranium/thorium in the crust.

A new geochemical exploration system for helium in the Phanerozoic is considered highly desirable by industry. The current exploration system in the Phanerozoic uses a modified petroleum system concept that has been used successfully for decades to high-grade plays and de-risk oil and gas prospects. Like a petroleum system, the helium system is identified by its source rock, reservoir, trap, seal, and migration pathways. However, this approach is expensive taking years to complete and can be a limiting factor for countries/provinces/states to develop their resources.

As a precursor to ground helium/hydrogen surveys for exploration in the Phanerozoic, hyperspectral (satellite) surveys assess huge areas for their helium potential as well as any associated hydrocarbons. These areas may be even devoid of any previous exploration for hydrocarbons. This is followed with geochemical soil gas surveys of the more prospective trends to locate drilling locations. Both methods ascertain whether helium anomalies, which represent helium reservoirs at depth, are associated with hydrocarbons or nitrogen. Helium reservoirs associated with nitrogen are higher in helium content but are deeper, close to the basement.

Hyperspectral and geochemical soil gas surveys are also applicable for projects that begin with helium analysis of old wells followed by seismic and drilling. Typically, exploration companies lease vast areas surrounding the legacy well, but their initial focus is on seismic in the area around the legacy well to determine the size and configuration of the helium reservoir and trap penetrated by the well and this is followed by drilling. It is not known at this point whether this reservoir is the best prospect because the helium discovered is usually associated with hydrocarbon (HC), not with nitrogen with much higher helium concentration in the lower Phanerozoic. Rarely do legacy wells penetrate deep enough to this level.

Any cost-effective exploration program for helium is best accomplished by hyperspectral and follow-up geochemical soil gas surveys.

HELIUM EXPLORATION IN THE PHANEROZOIC

Almost all the helium discovered worldwide has been found by chance in the drilling for hydrocarbons (Sears, 2015; Tedesco, 2022). Targets were usually anticlinal structures found by seismic surveys. The association of helium and natural gas in reservoirs is purely coincidental because the source rocks for each are different. Natural gas is produced from the diagenesis of carbon-rich shales whereas Helium[4] is derived mainly from the decay of uranium/thorium in the crust. The current exploration system in the Phanerozoic uses a modified petroleum system concept that has been used successfully for decades to high-grade plays and de-risk oil and gas prospects. However, this approach is expensive taking years to complete and can be a limiting factor for countries/provinces/states to develop their resources. A new geochemical exploration system for helium in the Phanerozoic is considered highly desirable by industry. This new system is described in this paper.

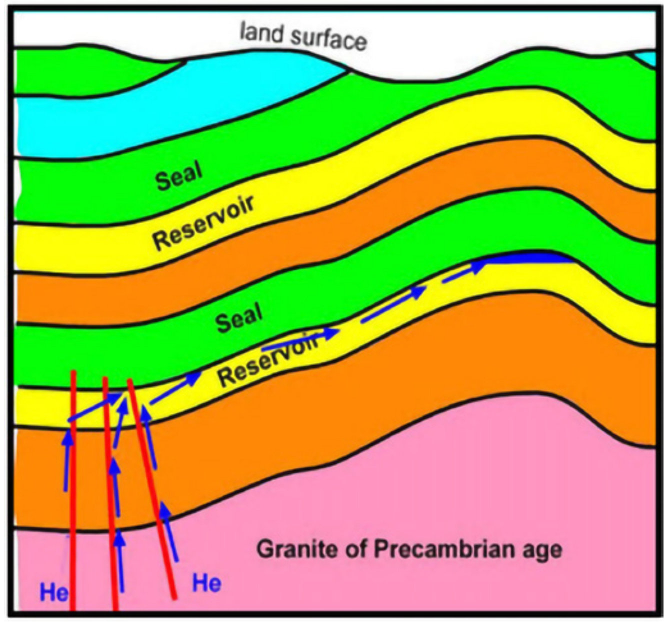

Figure 1. Helium migrates up fractures/faults into the Phanerozoic where it accumulates with nitrogen, CO_2, and HC in traps.

GENESIS OF HELIUM RESERVOIRS

Helium is derived from the alpha decay of uranium/thorium in basement rock; alpha particles convert to helium with pickup of two electrons. Helium migrates up fractures/faults into the Phanerozoic where it accumulates with nitrogen, CO_2, and HC in traps (Figure 1). The association of helium and natural gas in reservoirs is purely coincidental because the source rocks for each are different—natural gas is mainly produced from diagenesis of carbon rich shale whereas Helium- 4 is derived from the decay of uranium/thorium in the crust. Helium in the Phanerozoic is ancient helium produced over billions of years exceeding the age of sedimentary rocks. Accumulation of helium in crustal rocks over billions of years is released by comparatively recent tectonic and magmatic events (Figure 2). This new evidence has refocused exploration for helium. It should be noted that hydrogen produced by radiolysis of water by uranium radiation can be an important pathfinder for uranium deposits. Hydrogen, which is being produced constantly, can penetrate impervious formations more easily than helium because the atomic weight is half, and does not take years to accumulate like helium.

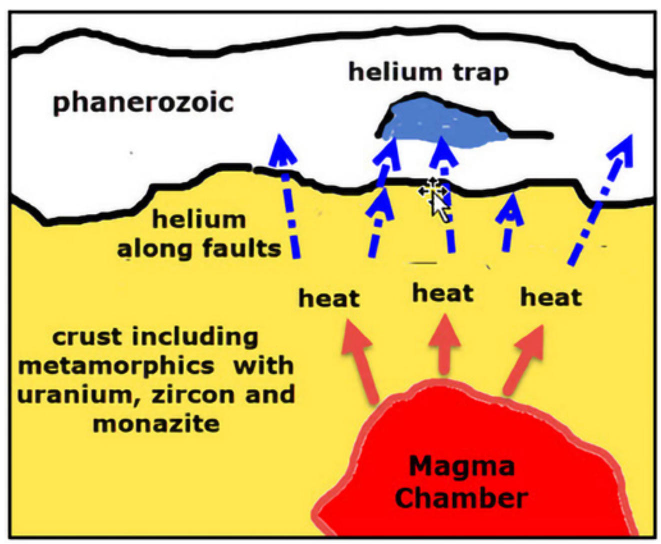

Figure 2. Accumulations of helium in crustal rocks over billions of years is released by comparatively recent tectonic and magmatic events.

DETECTION OF HELIUM RESERVOIRS AT SURFACE

Helium reservoirs can be detected at the surface by two methods: hyperspectral (satellite) and follow-up geochemical soil gas surveys. Helium and associated gases trapped by impervious caps can escape to the surface if the reservoir is cut by fractures/faults. A coincidence of helium and HC anomalies can show whether helium is associated with HC or nitrogen. Helium associated with nitrogen is usually of higher concentration than if associated with HC. Such reservoirs are found close to basement rocks such as in the Cambrian in Saskatchewan and Alberta (Figure 3).

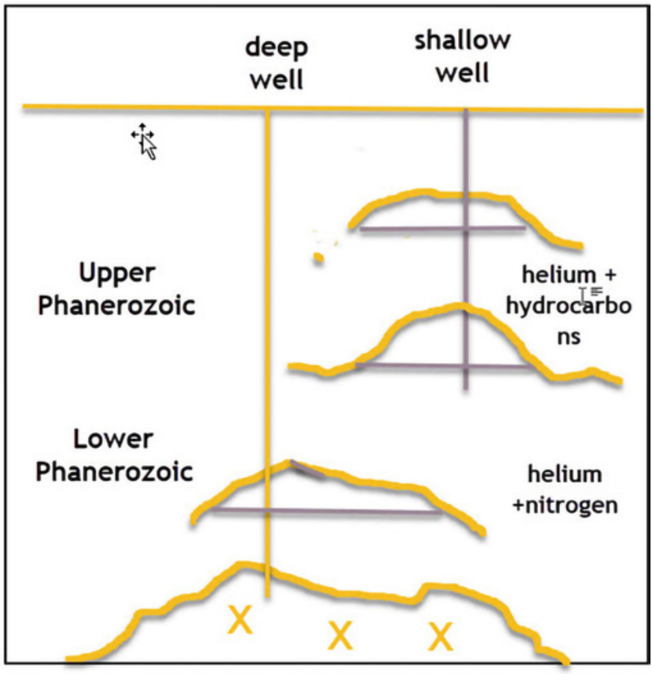

Figure 3. Association of helium and nitrogen with hydrocarbons.

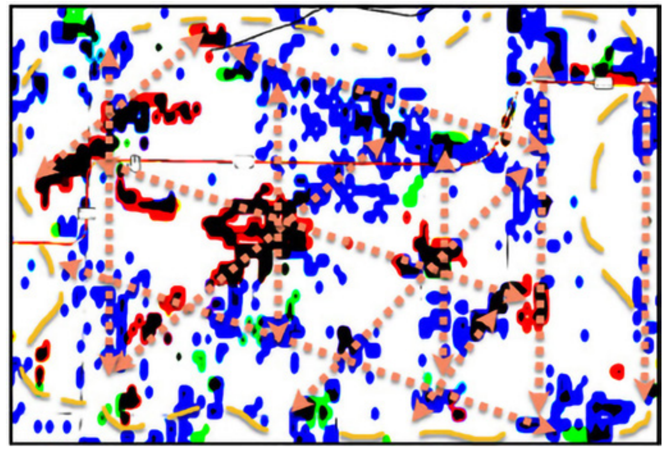

Figure 4. Hyperspectral survey over unknown area to determine the presence of hydrogen and helium.

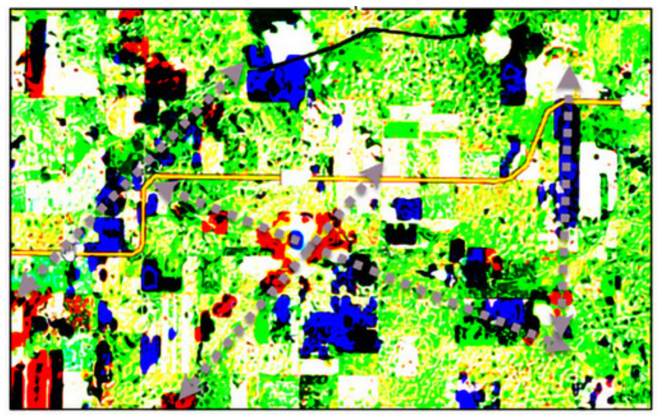

Figure 5. Helium and ethane survey over the same area in Figure 4 to further define anomalous areas.

COINCIDENCE OF HYPERSPECTRAL HELIUM AND HC ANOMALIES

As a precursor to ground helium/hydrogen surveys for exploration in the Phanerozoic, hyperspectral (satellite) surveys are employed to assess both medium-sized and huge areas for the presence of helium and hydrogen. Helium anomalies are usually associated with fault systems that have cut the helium reservoirs (dotted lines in Figure 4). If the hyperspectral survey shows coincident ethane and helium anomalies the helium reservoir the helium anomaly represents is likely to be associated with HC (Figure 5).

FOLLOW-UP GEOCHEMICAL SOIL GAS SURVEYS – FRONTIER AND MATURE FIELDS

Given the discovery by hyperspectral surveys of helium anomalies and their association with either hydrocarbons or nitrogen, companies must decide what next steps to pursue: geochemical soil gas surveys, seismic surveys or even drilling. Geochemical soil gas surveys can define the borders and configurations of the anomaly, locate sweet spots, define the fracture/fault systems, and determine which type of hydrocarbons are associated with the helium. From the economics and gas processing point of view the explorer will want to know before drilling whether the associated gas is condensate, wet gas, dry gas, or nitrogen. Should one drill deep nitrogen reservoirs with high helium content but high drilling cost or drill shallow hydrocarbon reservoirs with lower helium content but lower drilling cost? Size of reservoir would be an important factor. Are hydrocarbons a co-product of helium production and if so, do the hydrocarbons need to be flared because of lack of pipelines? In some areas of the U.S. flaring is not permitted.

TYPES OF GEOCHEMICAL SOIL GAS SURVEYS

The two types of geochemical surveys are grid and non-grid. Grid surveys are conducted in three stages: reconnaissance, high-density and very high density (Figure 6). If sample stations are too far apart concentration data is depicted by bubble maps rather than by contours. Non-grid surveys are conducted in rough terrain and heavy bush, usually along logging roads, paths, and roads (Figure 7). In non-grid surveys concentrations can be contoured if traverses are less than 500 meters apart.

START OF GEOCHEMICAL SOIL GAS SURVEYS—EVACUATION SYSTEM

Vials are evacuated to 5 Torr so there is no contamination of sample from ambient air (Figure 8). Vials are inserted into holes in Styrofoam then inserted in boxes for shipment to field and back (Figure 9). Glass vials with chlorobutyl rubber septa impervious to leakage for up to 5 weeks have been tested. Metal and smaller vials are used for special purposes. Glass vials are reused but caps with septa are replaced for each survey.

Direct Sampling – Dry Soils

Sampling by probe takes 7-10 minutes. A probe is driven into ground by an 18V cordless drill (Figure 10). The inner volume of the probe is first purged by syringe extraction through a port (Figure 11). A sample is taken by syringe and injected through a septum of a pre-evacuated vial. The vial is inserted back into the Styrofoam box for shipment to the lab. Coordinates are recorded by GPS and in a notebook as backup.

A passive system has been developed for wet sediments such as muskeg. Probes are left in the ground for 24 hours before a sample is taken. There is no purging. Any helium above 5.6 ppm enters the probe by diffusion.

GAS CHROMATOGRAPHS FOR ANALYSIS OF HYDROCARBONS/CO_2 AND HELIUM/HYDROGEN

The GC with autosampler analyzes for Alkanes (C_1 to C_5), alkenes (C_2 to C_4) and CO_2 (Figure 12). This determines the type of reservoir fluid the helium is associated with, whether oil, condensate, wet gas, or dry gas. The micro-GC analyzes for helium, hydrogen, and neon (Figure 13).

ANOMALY MAPS AND INTERPRETATION—TYPICAL HIGH-GRADE HELIUM ANOMALY

Significant anomalous helium concentrations in soil gas can range from 7.0 to 22 ppm (5.4 ppm is background). Helium is likely to be associated with nitrogen if a helium anomaly does not correspond with an HC anomaly. A helium reservoir associated with nitrogen is likely to be at depth close to the basement (Figure 14 shows a typical high-grade anomaly).

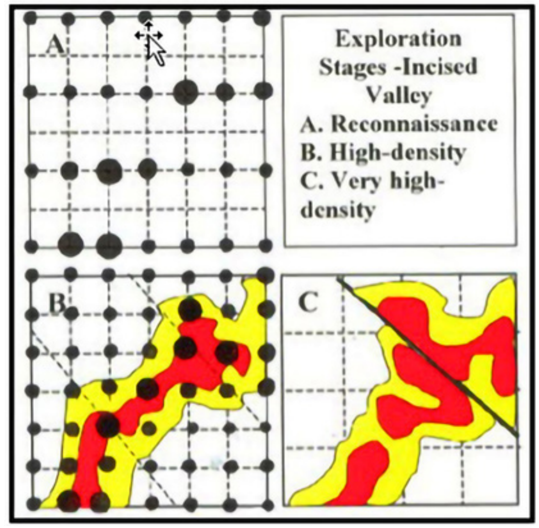

Figure 6. Grid surveys are conducted in three stages: reconnaissance, high-density and very high density.

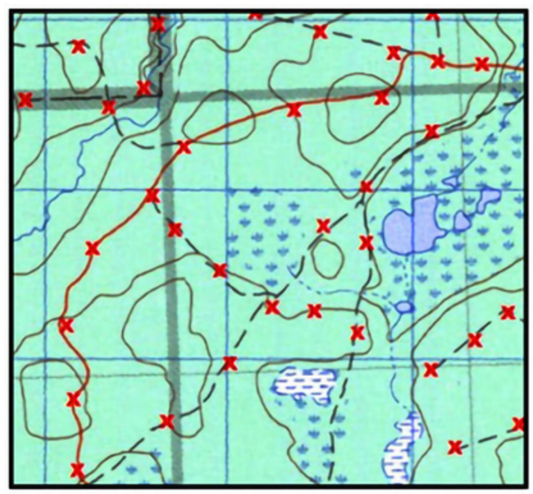

Figure 7. Non-grid surveys are conducted in rough terrain and heavy bush, usually along logging roads, paths, and roads.

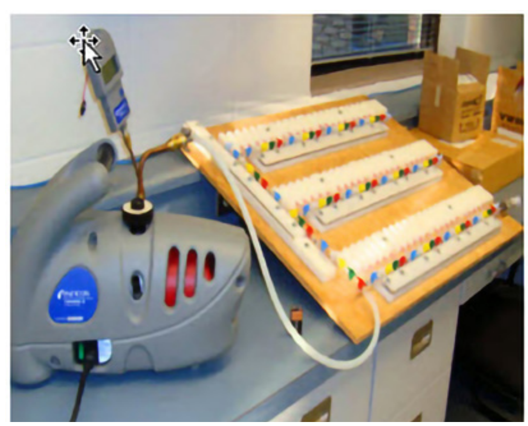

Figure 8. Vials are evacuated of all atmosphere so there is no contamination of sample from ambient air.

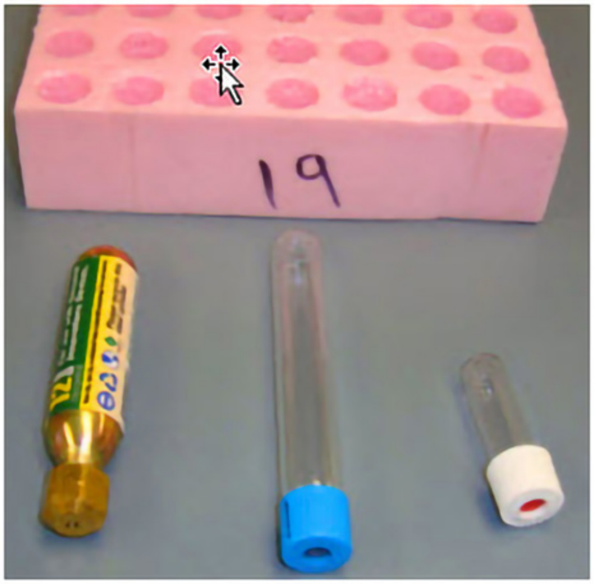

Figure 9. Vials are inserted into holes in Styrofoam then inserted in boxes for shipment to field and back.

Figure 10. A probe being drilled into the ground in order to collect soil gas sample.

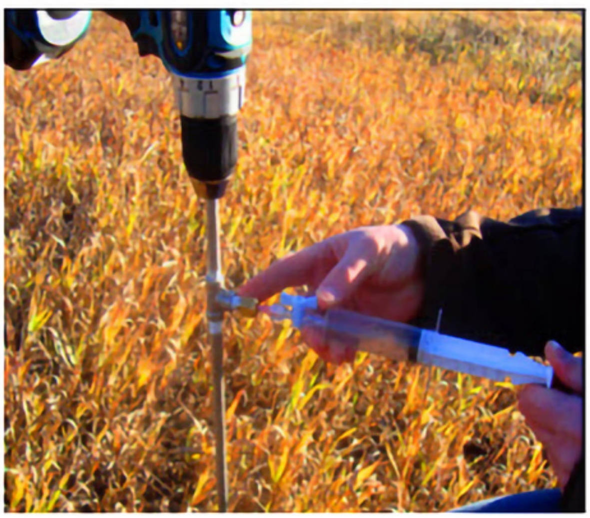

Figure 11. Collecting a sample of soil gas in the field to analyze for helium, hydrocarbons, hydrogen and neon.

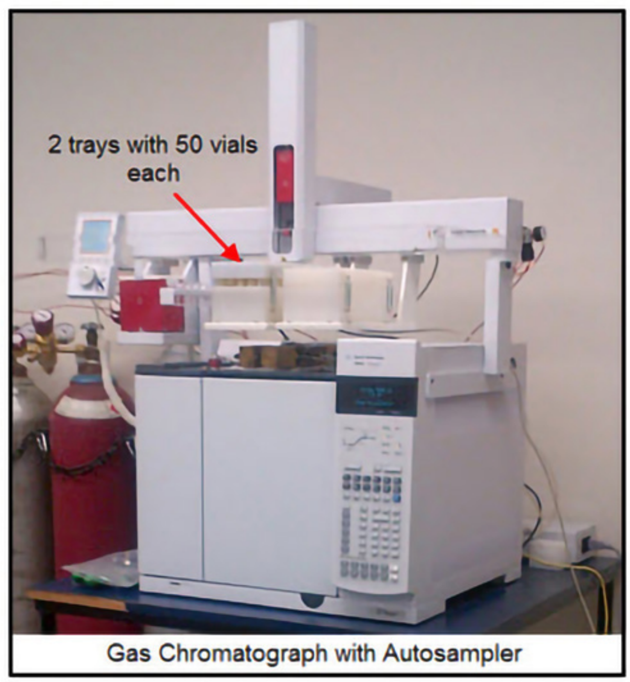

Figure 12. Gas Chromatograph with autosampler that analyzes for Alkanes (C1 to C5), alkenes (C_2 to C_4) and CO_2.

HELIUM EXPLORATION IN OLD/NEW GAS FIELDS BY GEOCHEMICAL SOIL GAS SURVEY

Hyperspectral and geochemical soil gas surveys are also applicable for projects that begin with helium analysis of old gas wells. Typically, exploration companies lease vast areas surrounding the legacy well, but initial focus is on seismic to determine the size and configuration of the helium reservoir or trap the well has tapped. It is not known at this point whether the reservoir tapped is the best prospect because the helium discovered is usually associated with HC, not with nitrogen with much higher helium concentration in the lower Phanerozoic. However, rarely do legacy wells penetrate the lower stratigraphic levels. The best approach is to first conduct hyperspectral surveys for helium as well as hydrogen, methane, and ethane. This is followed by a comparison of helium and HC anomalies as well as soil gas surveys in the more prospective areas. Figure 15 is an example of helium exploration in a mature oil and gas field.

FOR A PROJECT AREA PLOTS OF HELIUM VERSUS METHANE AND HYDROGEN ARE ALSO USED IN COINCIDENCE ANALYSIS

Statistical analysis is another tool to determine the association of helium with either nitrogen or type of hydrocarbon reservoir. Plots of helium versus methane and hydrogen are usually used for this purpose (Figure 16).

SOME ELEMENTS OF A COST-EFFECTIVE EXPLORATION SYSTEM FOR HELIUM IN THE PHANEROZOIC

The basic approach to a helium exploration program is to use methods that provide the maximum information at the lowest cost possible. Ideally in a four-step process, a hyperspectral survey is employed even before the accumulation of properties, followed by geochemical soil gas surveys, seismic and drilling. Once helium anomalies are discovered by hyperspectral surveys, they are compared with HC and hydrogen anomalies to determine whether the helium in reservoirs is associated with HC or nitrogen. Direct geochemical soil gas surveys by probe are necessary to define borders of a helium reservoir, locate sweet spots, define fault/fracture systems, and determine the type of associated gas. Soil gas survey equipment and analytical systems must be leak-proof because of the volatility of helium, hydrogen, and light hydrocarbons. A soil sampling drill must be hand portable to allow access to forests, environmental areas, populated regions, fields in crop, and fenced areas. Seismic becomes more focussed and less costly with this approach.

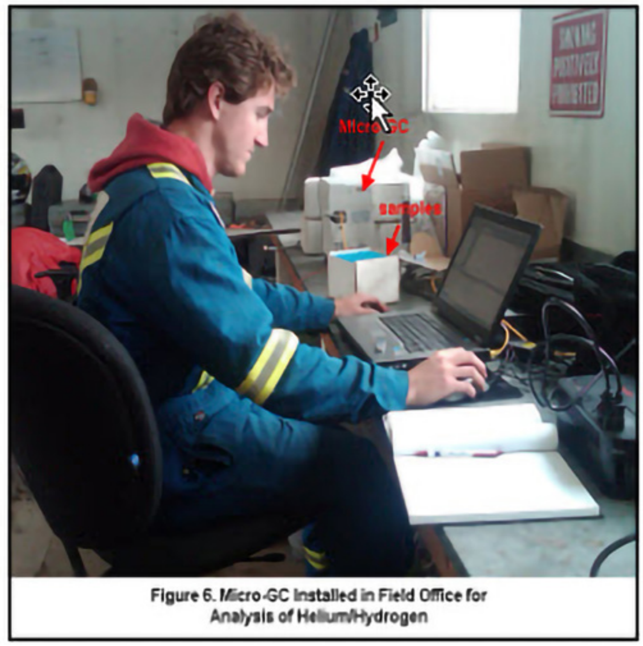

Figure 13. Gas Chromatograph operator analyzing and interpretating helium, hydrogen and neon data.

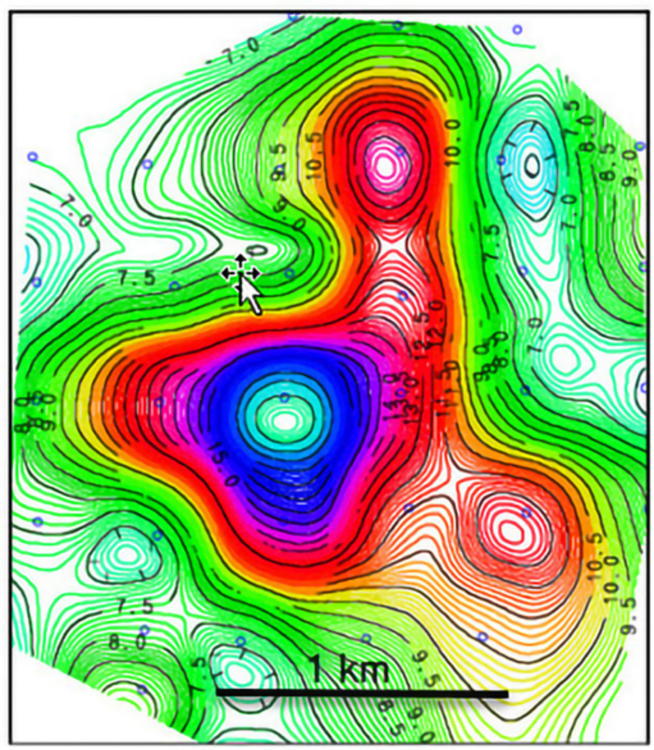

Figure 14. A typical high grade helium anomaly.

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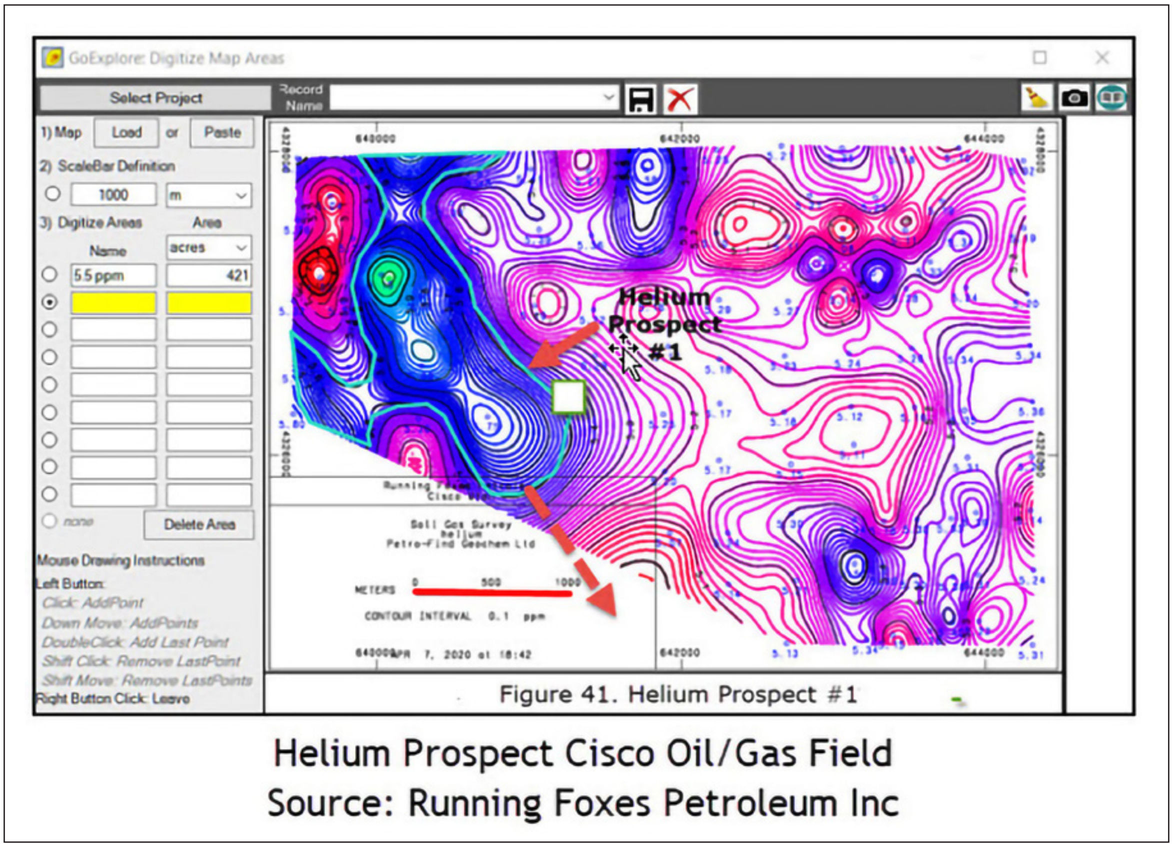


Figure 15. Helium survey at an area in the Cisco Springs, Grand County, Utah (printed with permission of Running Foxes Petroleum Inc.).

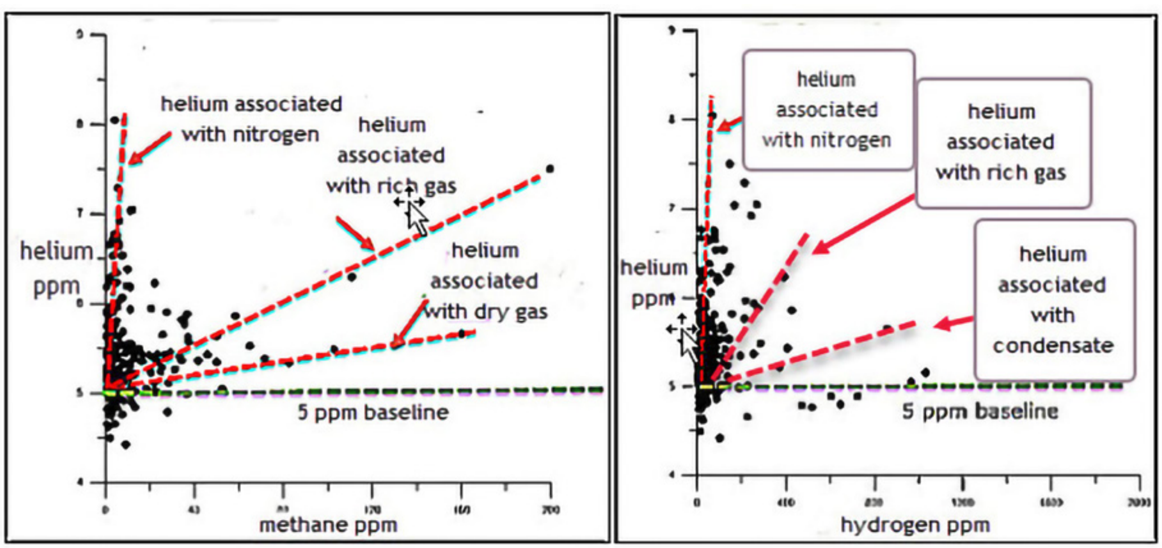
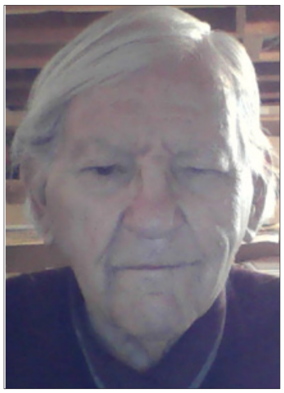


Figure 16. Helium versus methane and hydrogen used in coincidence analysis.

THE AUTHOR

Paul Lafleur



Paul Lafleur is owner and President of Petro-Find Geochemical Ltd located in Canada. A graduate of the Colorado School of Mines in engineering and geology, he is a Professional Engineer in Saskatchewan and is qualified to conduct geochemical soil gas surveys in the exploration for hydrocarbons, helium, and uranium.

Over 20 years Paul Lafleur developed unique technologies, methods, techniques, and systems that achieved superior performance in geochemical soil gas prospecting for hydrocarbons in structural, stratigraphic and reef trap settings. In the last ten years he has conducted geochemical soil gas surveys in the exploration for uranium using helium and hydrogen as pathfinders. This technology in combination with hyperspectral surveys has been applied in the exploration for helium in the Phanerozoic.

An Oil And Gas Play Turns Into A Prime Helium Prospect[1]

BRUCE A. BLACK[2]

1. Manuscript received July 6, 2023; Accepted October 21, 2023.
2. Black Exploration, LLC 206 W. 38th Street Farmington, New Mexico 87401, koko16@earthlink.net

ABSTRACT

Black Exploration, LLC drilled a wildcat oil and gas test on a large structure on the Zia Pueblo in early 2023. The primary objectives were oil and gas. However, helium potential was also recognized as a possible secondary objective. This large structure sits adjacent to some of the largest reported air corrected mantle, He and CO2 degassing carbonic and geothermal springs in the Rocky Mountain region. The prospect overlies a classic Synthetic Overlapping Transfer Zone between the northern Albuquerque Basin and the southern Espanola Basin in the Rio Grande rift in Northern New Mexico. Recognition of possible deep crustal and upper mantel faulting as well as surface geologic mapping, gravity, seismic and geo-microbial techniques helped delineated the prospect. A possible explanation for why high mantle derived helium is concentrated in this area is the intersection of the ancient Jemez Lineament and the more recent Rio Grande rift. This wildcat has now discovered helium and white hydrogen in the Abo formation. If economically productive the well will be the first helium discovery in the Rio Grande Rift. This could open the rift and its sub basins into a large, new oil, gas and helium and hydrogen producing province.

INTRODUCTION

In July 2012 Black Exploration, LLC (Black) took a Resource Assessment and Lease Option Agreement with the Zia Pueblo in Sandoval County, New Mexico. This wildcat play was initially an oil and gas play and set up by the knowledge of extensive Cretaceous oil and gas shows in two wells drilled by Shell Oil Co. in 1972 and 1976. These old wells are six to ten miles south and downdip of the Zia Pueblo and are over a mile structurally lower than the Pueblo acreage. Drilled with today's technology the Shell wells would probably have been productive.

There are no obvious surface indications of hydrocarbons on the Zia Pueblo in the rift. However, Helium with a high He3/He4 ratio is reported in the published literature on and surrounding the Pueblo. Helium is actively issuing from springs along the deep seated, easterly dipping major faults on the west side of the rift. These faults separate the downthrown Rio Grande Rift from the uplifted Colorado Plateau. The presence of Helium has become an important factor in the future drilling plans on the Pueblo.

SEISMIC AND STRATIGRAPHY

Two years after extensive surface field work and literature research, Black purchased, reprocessed, and interpreted six lines of old 2D Shell and Vastar seismic lines that had been shot on the Pueblo in the early 1970s and 1980s. The quality of the modern reprocessed seismic lines turned

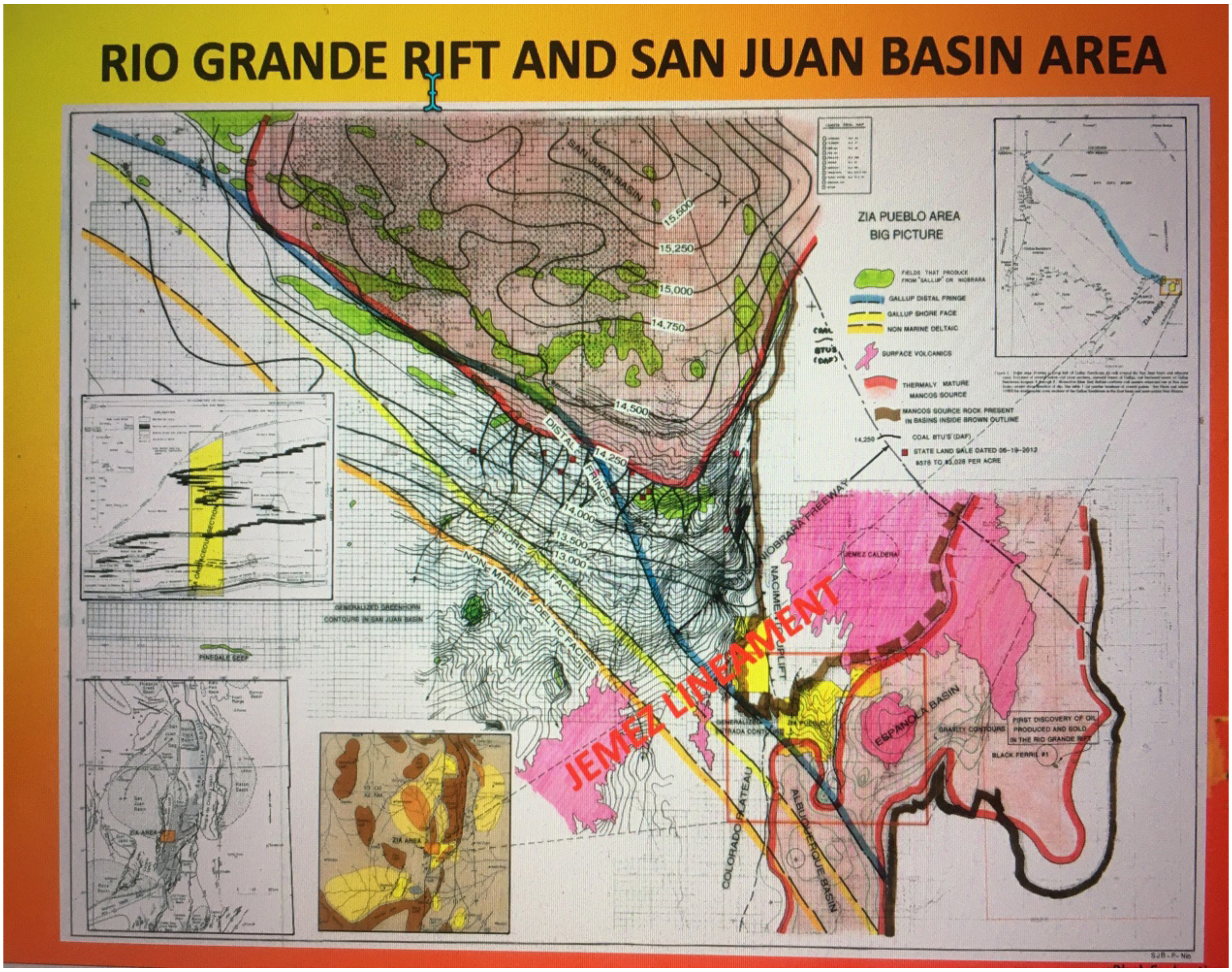


Figure 1. Location slide showing Zia lease area between the San Juan Basin and the Rio Grande Rift. Zia reservation is shown in yellow.

out to be outstanding. Working with the seismic sections, several things were immediately established.

First, the reprocessed seismic confirmed that we are structurally dealing with a classic rift system, one with virtually all the structural features seen in similar rifts around the world. Second, we are dealing with the same Pre-Tertiary Mesozoic and Paleozoic section that is so well documented by over 30,000 oil and gas wells in the nearby San Juan Basin. However, this identical pre-rift geologic section has been dropped thousands, to tens of thousands of feet into the spreading Rio Grande Rift and is now almost entirely hidden beneath Tertiary sediments. Only four miles of the narrow southerly plunge of the Laramide Nacimiento Mountains separates the San Juan Basin and its ultimate half billion barrels of oil and 70 trillion cubic feet of gas production, from the identical stratigraphy now underlying the Zia Pueblo. No wells had ever been drilled on the Pueblo in the rift.

Outstanding seismic reflections from formations like the Entrada-Todilto contact and the basement and others are easily followed and correlated. The same stratigraphy in the cratonic sag of the San Juan Basin is present. However, these rocks with the same source, reservoirs and potential oil and gas production, are now deep in the structural rift basin, buried and hidden by hundreds to thousands of feet of sand and gravel. When the earlier oil and gas producers were expanding production in the San Juan Basin easterly, they ran into the 9,800' Nacimiento uplift. It's understandable why the play stopped at the foot of the West facing Nacimiento Mountains.

PETROLEUM SYSTEM

After Black purchased all the available seismic, had it reprocessed and interpreted, a method was needed to try to establish that a live hydrocarbon system was present and active on the lease. The Black father/son team took surface soil samples every 600 feet over four of the six seismic line locations to look for possible indications of C4 geo-microbial surface leakage anomalies.

Positive results from these soil samples indicated a live petroleum system was present, and Black exercised its option and took a large acreage oil and gas lease. The lease was eventually reduced to its present size of 33,840 acres to encompasses the high, synthetic overlapping transition zone under the Pueblo that lies between the northern part of the Albuquerque Basin and the southwestern part of the Espanola Basin in the greater Rift.

SEISMIC IMPLICATIONS

Anomalously high C4's in the soil samples were found to directly overlay or are closely associated with structural highs and obvious potential angular unconformity traps that can be seen on the seismic lines. Although in some cases, the six 2D seismic lines are separated by several miles, it's obvious where the large, east-dipping, down to the east north-south faults are located on and under the Pueblo. These faults can be traced for miles on the surface and on the generally east-west oriented seismic lines. The large bounding faults on the west side of the acreage can be traced on the surface and confidently connected in the sub surface. Some associated conjugate shears are also recognized beneath the Tertiary basin fill on the seismic lines.

The northerly-trending, large scale faulting defines the northern trend of the Rio Grande rift on the Pueblo. Miocene to Present east-west rift separation and continuing expansion of the rift has long been documented by previous workers. However, the rift faulting is not well exposed on the surface as it moves north of the Zia Pueblo area. The faulting runs into and is covered to the north by extensive pyroclastic and volcanic ash flow tuffs from the 1.2 ma Jemez Caldera. Under the Pueblo, the rift is offset to the east into the Espanola basin by the overlapping synthetic transfer zone.

Coincidently, the older Jemez lineament, that is possibly an early Meso-Protozoic suture trend of the early continental crust, now marked on the surface by late Quaternary surface volcanics, runs north-easterly from central Arizona to the Jemez Caldera. Here the lineament runs into and is also covered by the Jemez Caldera volcanics. It is intersected and apparently offset by the younger Miocene Rio Grande Rift in the immediate vicinity of the Jemez Caldera.

The modern seismic reprocessing done in 2013 turned out to be spectacularly successful, and reflections are generally easy to follow and correlate. The seismic sections reveal both late Jurassic uplift and faulting in some blocks, and later Laramide uplift and early Tertiary onlap of the larger Laramide and pre-rift structures. The concurrence of C4 anomalies above the top of the structural highs indicated the there is an active petroleum system in place. It doesn't mean the area has an economic accumulation but does show there are hydrocarbons present and migrating through the system. To attempt to get a better handle on the structural configuration, Black then looked in detail at the available regional gravity and magnetic data.

GRAVITY IMPLICATIONS

Here Black ran into what was at first thought to be a problem. Like the available seismic, the gravity data was relatively old, and the gravity stations were sometimes far apart. More important however, was what appeared to be an obvious mismatch between what the gravity data was telling them and what the seismic was showing. This manifested itself as what appeared to be a paradoxical low above what Black expected to be a gravity high. Most granite basement highs are gravity highs. The old gravity data indicated there was a gravity low even though the seismic basement feature, with its non-salt sedimentary section overlying the granite basement high (Figure 2). Black searched the sparce well control for any indication of low-density materials in the stratigraphic section. There is no salt in the section in this immediate part of New Mexico. Likewise, there is no other significant thickness of low-density materials in the stratigraphic section in this part of New Mexico. Only a relatively few feet of anhydrite are present in some formations and not the multiple hundreds of feet necessary to account for the large, indicated gravity low. Black concluded the gravity was so widely scattered that it could not see the obvious basement high that the seismic lines showed was there, and where excellent correlations on three of the seismic lines crossed in the middle of the gravity low.

To resolve the question, in the summer of 2014 Black hired Gaurang Patel an independent consulting geophysist out of Oklahoma City. Using a modern CG-5 Autograv gravity meter with high resolution Black had Patel run a new 48 station gravity survey over what was thought to be the anomalous gravity low area. Several weeks later Patal reported back that indeed the original gravity was correct! There is a large gravity low where the seismic shows us an obvious structural granitic basement high with a full section of overlying folded sediments.

The day Black received the results back they were initially puzzled. Buz Black posed the question "Since there is no salt in the section could there possibly be so much gas and oil in the sediments on the structure that it's replacing the water and giving us a negative gravity?" It was initially hard to believe that was what was happening. Later that evening, Buz called his dad and said he had been researching the internet and had found several examples around the world where there are obvious gravity lows over shallow and sometimes very large oil and gas fields with high granite basements. In these fields, the oil and gas are so abundant that there is a gravity low produced over the basement high.

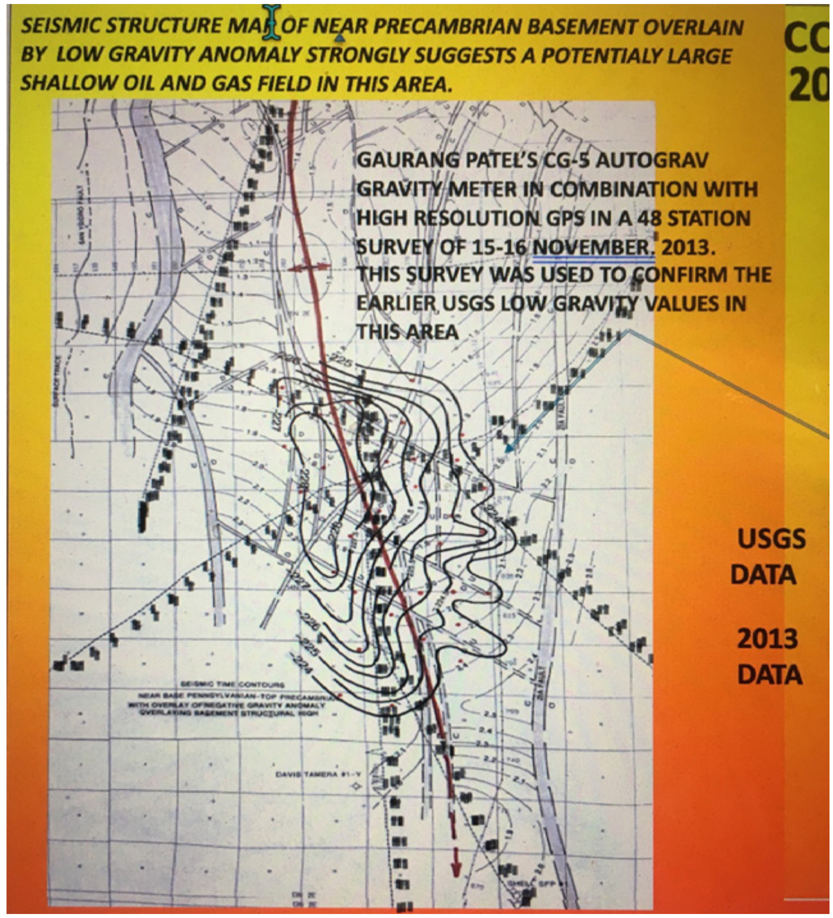


Figure 2. Slide showing the low gravity contours (dark) overlaying the structural map on the near basement contours (light).

The only field Bruce Black was personally aware of was the Ventura Avenue multi-billion-barrel oil field in the Ventura Basin in California. Black had worked on that field as a Senior Staff Geologist with Shell Oil in California in the late 1960's. Wow! Maybe that was in fact the answer! If so, the Blacks realized they may be chasing a giant oil and gas field.

Black will find out when they test their large Ko-Wa-Me prospect in the summer of 2023. If this is a large gas or oil accumulation, it could turn out to be a major gas and oil field with the bonus of a possible commercial helium component in the gas. Helium has now been proven to be in the Abo Formation on Black's present Cerrito Negro test. The larger Ko-Wa-Me structure also overlies the same source of the helium at the Cerrito Negro well and has an excellent chance for containing a significant helium content like the Cerrito Negro prospect presently being completed. Both the Abo Formation and the shallower, anhydrite-capped Entrada Sandstone are now considered two prime objective formations for helium and oil and gas reservoirs across the entire 33,840-acre lease.

HELIUM

While researching the literature for geologic information about the area under the Black's lease, the authors had previously found several important articles on thermal and carbonic springs in the western United States. Particularly important, and well documented is the 2014 article "Mantle He3 and CO2 degassing in carbonic and geothermal springs of Colorado and implications for neotectonics of the Rocky Mountains" by Karl Karlstrom and Laura Causey of the University of New Mexico, and others. Their article shows the location of the highest He3/He4 ratios in carbonate and hot springs in the western United States. Some of these springs are on the Pueblo lands and

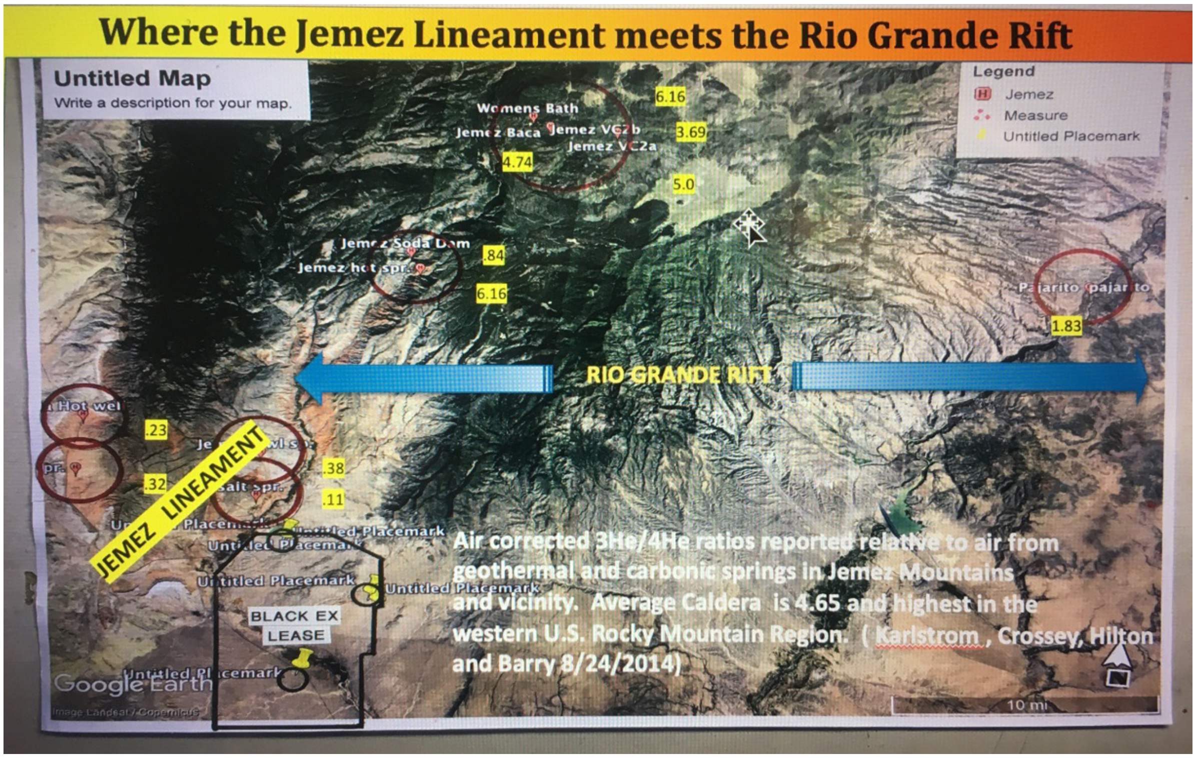


Figure 3. Google earth image with H3/H4 ratios in and near the Jemez Caldera.

bound the western side of Black Explorations Zia lease. (Figure 3).

Knowledge of the high ratios of He3/He4 helium along with the knowledge that the deep rift faults are dipping easterly under folded potential reservoir rocks and anticlinal structures on the high transition zone suggested these rift faults are providing pathways for migration of both the crustal He4 and the mantel He3. The helium from two different sources can then merge while moving up the faults into the overlying sediments and can be concentrated on the structures and in possible fractured basement granite. This "two source" model was instrumental in Black's inclusion of Helium and CO2 in the initial lease terms.

It was coincidental that Black was drilling their first wildcat well on the Zia lease at the time of the first Denver Helium Conference in March 2023. Black began to see helium in random grab samples that had been taken by Buz Black from the possum belly mud stream while drilling through the Permian Abo and the Pennsylvanian Madera sections of the well. Three of the five Abo grab samples were analyzed by Gas Analysis Services of Farmington, New Mexico. The samples were analyzed and showed helium, from 0.1654 to 0.2324% and one sample as high as 0.5840 Mole%. All 5 samples had a 99 +% nitrogen content in addition to the helium or other minor amounts of gases. This was obviously encouraging. In Black's recent completion work Black ran all the gas returns through a mass spectrometer on location. Helium from subsequent samples taken to Gas Analysis Services ran from 0% to a high of 0.9778 Mole% The mass spectrometer recorded helium as high as 10,576 ppm and white hydrogen up to 11%.

Black now believes there is a concurrence of two separate sources of helium. One, He3 from the deep-seated mantel, and the other, He4 from the radiogenic decay in the shallower crustal granite basement. This coincidence may be combining with favorable Laramide tectonics, and later rift structural folding to produce trapping structures. The presence of the Abo stratigraphy with its fluvial reservoir sands encased and isolated by thick Abo clay shales to act as seals, and the Entrada sandstone overlain by anhydrite to act as an excellent seal, are just two of several obvious objectives on the lease.

Additionally, the area has a history of a recent volcanic heat source that may have helped to mobilize, concentrate, and move the migrating helium atoms enough to provide an economic target for helium accumulations. The presence of the recent heat source in the nearby Jemez Caldera volcanics and the deep-seated faulting that may be tapping into the lower crust and upper mantel is important. This along with the intersection of the deep faulting in the Jemez Lineament and the Rio Grande rift and the presence of overlaying structures with excellent reservoir seals, may also be combining with favorable ground water transportation to assist moving the helium to available traps.

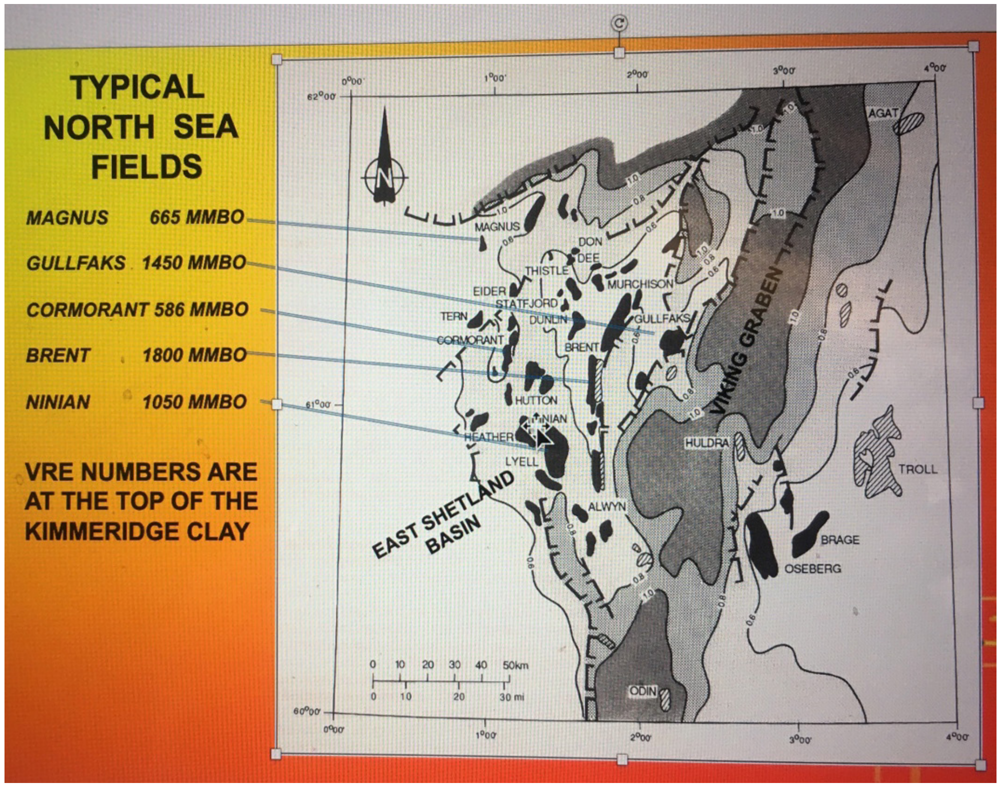


Figure 4. Slide of the North Sea area showing oil and gas fields and the Viking Graben. The Gullfaks field is the analog for the Zia Play. Figure annotated from Beaumont and Foster 1990 AAPG Atlas of Oil and Gas Fields, Structural Traps II, P. 33. AAPG 1990, reprinted by permission of the AAPG whose permission is required for further use.

ANALOG

After reviewing the literature for possible analog fields in our original search for oil and gas, we used the Gullfaks Field in the North Sea (Figure 4) for both shape comparison and for a surprising number of many other structural characteristics that are present in the Zia Prospect. One of the most striking is the similar size and its structural location on the flank of the rift, and its relative similar position on the high transition zone between major sub basins of the rift. Figure 5 is an overlay of part of the Rio Grande rift and the Zia prospect on the Viking graben and the Gullfaks Field at the same scale. While there are many similarities, like the presents of a central graben structure on the crestal areas of both structures, there are also obvious dissimilarities. The source rock richness in the North Sea is considerably greater than the TOC richness of the Mancos shale at the Zia structure. However, the greater Mancos thickness offsets this difference by its much thicker section and its proven ability to generate major amounts of hydrocarbons. At the time of this writing Black is attempting the completion of a 20' marine sand in the Pennsylvanian Madera Formation that had significant hydrocarbon shows.

Analogs in the search for helium alone should be different than those for oil and gas. However, areas of basement disturbance rifts like the East African Rifts and the Rio Grande Rift may be appropriate for both.

LESSONS LEARNED

Exploration companies should not underestimate the potential for economic Helium production in the Rio Grande rift area. What may originate as an oil and gas play or a helium play may evolve into both.

The large majority of the 33,840 acres of the Zia lease has the favorable Abo formation present and it is in a structurally high position. It is underlain by the deep penetrating east- dipping faults of the Rio Grande Rift. These are probably conduits for both He3 and He4 migration up to the areas of overlying favorable trap configurations. Because the Abo sands are fluvial non- marine channel sands, they may also serve as stratigraphic traps over much of the area.

The intersection of the Rio Grande Rift and the Jemez Lineament is producing a crustal weak spot where primal He3 can be released from the mantle and He4 can be released from the weakened and heated crust. Both Helium sources can use the deep-seated faulting of the Rift for a migrating pathway up and into overlaying favorable trapping stratigraphy. The entire high overlapping synthetic transition zone should be an excellent target for both hydrocarbon and Helium production.

Helium held in solution in formation waters below a free gas cap may be present and detectable with a Mass Spectrometer but may not be producible in economic quantities. Because Helium is present in solution does not necessarily mean you can produce it economically. Structurally high trapping positions are probably very important to successful exploration for Helium in commercial quantities.

In plays where there is potential for both oil and gas as well as helium, it is important to understanding both the similar aspects of the two objectives and the distinct differences in sources and in paths of migration. What may be an excellent reservoir for helium may not be a viable reservoir for oil and gas. The physical characteristics of both objectives such as molecular size and chemical attractions are very different, and what is good for one may not be good for the other.

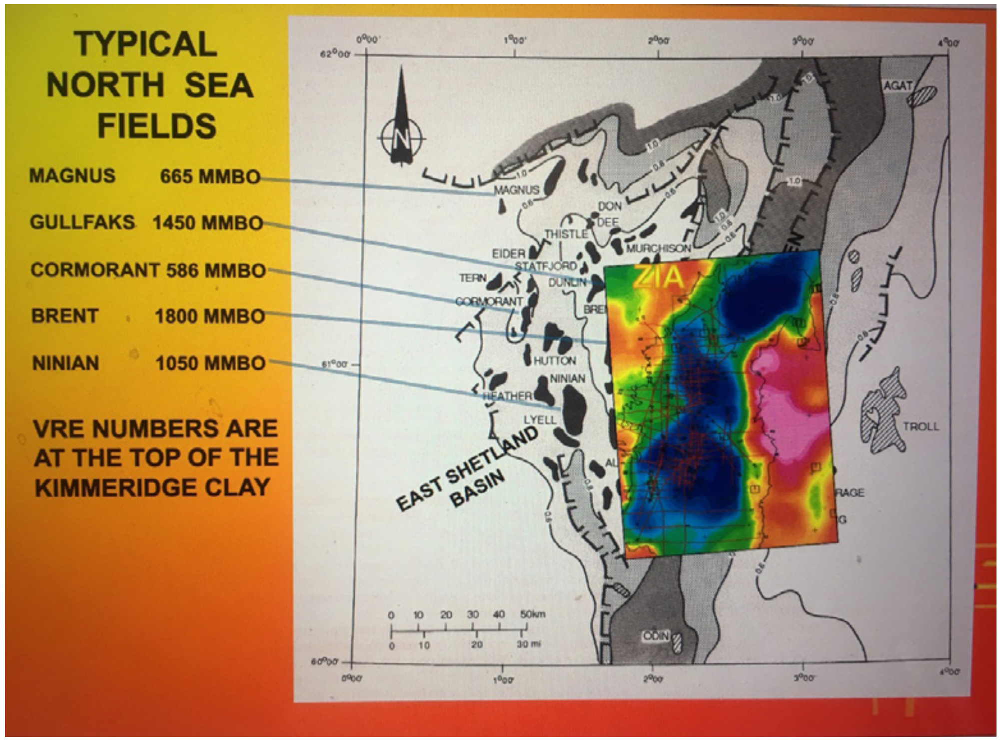


Figure 5. Slide of the North Sea area and its fields with the gravity map of the Rio Grande Rift superimposed on the Viking Graben at the same scale. Figure annotated from Beaumont and Foster 1990 AAPG Atlas of Oil and Gas Fields, Structural Traps II, P. 33. AAPG 1990, reprinted by permission of the AAPG whose permission is required for further use.

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THE AUTHOR

Bruce Allen Black PhD.

Bruce is a native New Mexican born in Albuquerque in 1936. He graduated from Highland High School in1954. He entered the University of New Mexico in 1955 and joined the Navy Reserve the same year as a Seaman Recruit. He transferred in 1956 to Texas Western College on a Football scholarship, and graduated in 1959 with a BS Degree in Geology. After graduation he went on active duty with the U.S. Navy going through the Navy's Officer Candid School, and was commissioned an Ensign in 1959. He married his wife Marjorie (of 64 years) after graduation. He served 4 years on active duty as the Intelligence officer for VP-50, a Navy sea plane squadron in Iwakuni, Japan, and later as an Intelligence instructor at the Pacific Fleet Intelligence Training Center in Alameda, California. After active duty Bruce stayed in the Naval Reserve and returned to the University of New Mexico where he received his Master Degree in Geology in 1964. He then joined Shell Oil Company where he served as Shell's District Geologist in Ventura California, then as Assistant to the Vice President of Exploration in Los Angeles and eventually as Senior Staff Geologist in Farmington, New Mexico. Bruce left Shell in 1970 to form his own exploration companies. He received his PhD in geology from the University of New Mexico in 1974. Bruce has explored the Rio Grande Rift for over 52 years. In 1985 he found, produced and sold the first oil sold out of the rift. His civilian and Navy careers continued to intertwine as he served on and off of active duty with the Navy for over 41 years. In 1992 he was promoted to Rear Admiral and retired from the United States Navy as the Commander of the Naval Reserve Intelligence Command in 1996. Today he is President of Black Exploration, LLC and consults as a frontier explorationist. He is currently active in rift exploration in the Rio Grande Rift including exploration for Helium on the Zia Pueblo in the rift.

Fly Me to the Moon[1]

TIM RYNOTT

1. Manuscript received August 15, 2023; Accepted November 20, 2023.

On August 16th, 1960, sitting in an open-air gondola at 103,000' carefully suspended by a 200' tall helium balloon, U.S. Air Force Captain Joe Kittinger peers upon cobalt blue skies and the blackest of black (Figure 1). The avant-garde astronaut gets word from the ground crew, "*Jump*!", triggering a free fall from 103,000' and setting the record for the highest skydive ever by any living being (Kittinger, 1961; Kindy, 2023). Captain Joe blazed the trail for the likes of Sheppard, Grissom, and Glenn, testing the limits of the human body.

A mere nine years later helium – a relative newcomer to the Periodic table - again flexed its muscle by aiding the propulsion system for Apollo 11's moon expedition.

Jettisoning to 2022, a whopping 180 space launches occurred worldwide, and this number is expected to double in less than seven years. Space tourism leads the pack with an average orbital joyride costing ~$100K of helium to achieve lift-off (NASA/SpaceEx). During his lonely and ubiquitous ascent into the heavens in 1960, could Captain Kittinger have envisioned the oncoming explosion of helium uses? Could anyone have imagined?

Figure 1. U.S. Air Force Captain Joe Kittinger jumping from an open-air gondola at 103,000 feet on August 16th, 1960 (Kittinger, 1961).

HELIUM'S MAGIC

Besides rocket propulsion, Helium's unique qualities make it indispensable in MRI machines, semi-conductors, fiber optics, welding, leak detection, and specialized laboratories (Figure 2).

Topping the list is the use of helium in MRI machines. As an example: In August of 2022, a senior Vice-President with the American Hospital Association, representing 270,000 physicians and 2 million nurses/caregivers, wrote to the Director of the Bureau of Land Management owners of the (Federal Helium

Reserve), stating their concerns regarding adequate helium supplies for their magnetic resonance imaging

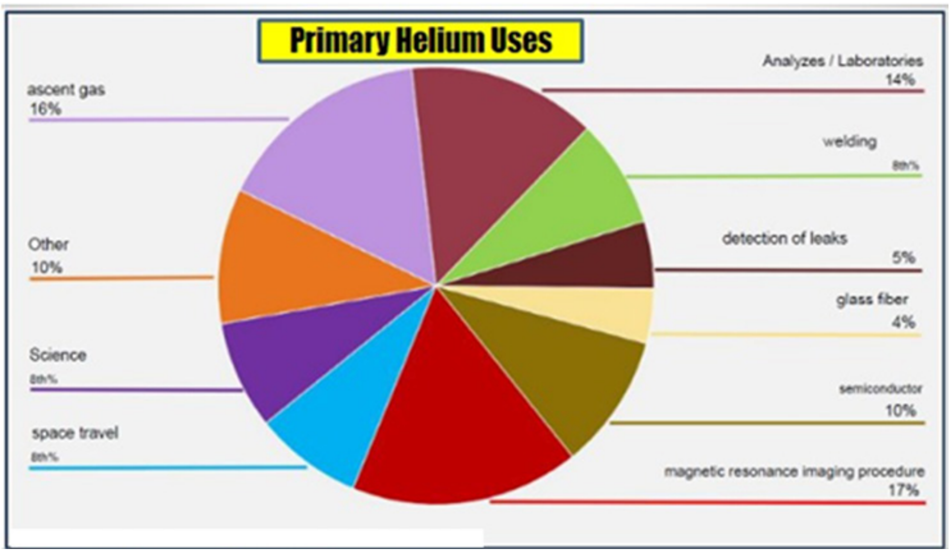

Figure 2. The primary uses of helium (BLM, Intelligas, Shene Capital)

(MRI) machines. Can't blame them. In 2021, approximately 38 million critical MRI examinations were performed in the United States (Source: OECD).

Not to be outdone, the growth in the semiconductor industry is staggering. Chip fabricators such as Intel, Micron, Texas Instruments, GlobalFoundries, and others have announced projects totaling $90Bn in the western states alone, aided by the recently passed US CHIPS Act contributing $52Bn to this shaky supply chain. Could you survive without your phone, car, or home computer?

FEDERAL HELIUM RESERVE

The first and only major helium storage facility in the world might not have been built, if not for Helium filled blimps becoming an important tactical weapon during WWI (Figure 3). The Federal Helium Reserve (FHR) located ~12 miles northwest of Amarillo, Texas was created in 1925. Before you could say supercalifragilisticexpialidocious, the United States Government expropriated all produced helium, filling the reserve to the gills.

At its peak in 1995, the reserve held 40+ BCF of helium that had been stripped from the giant Hugoton and Panhandle natural gas fields (Figure 4). This underground storage was also more than a billion dollars in debt at the time, pushing congress to pass the 1996 Helium Privatization act thus prompting the Federal Helium Reserve to sell off the stockpiled helium by 2005. Unfortunately, from 1996 to 2013, the BLM sold much of the helium at prices that were overly competitive with private producers, which temporarily made exploration for new helium resources uneconomical (Nuttall et al., 2012; Sears, 2015). In 2013 Congress recognized this and passed the Helium Stewardship Act, which directed the Federal Helium Reserve to auction the rest of the stockpiled helium to the highest bidder, and to sell all government-owned helium assets and equipment by September 30, 2021. After multiple delays, the next bid date is presently scheduled for January of 2024. The FHR currently supplies ~30% of Americas helium needs but is nearly 90% depleted. Due to the complexity of the reservoir, it's a matter of debate whether the Reserve is depleted in a matter of 3-5 years, or lasts into the mid-2030's. The former prediction causes great consternation since overall exploration efforts have been less than 'stellar'. Figure 5 depicts daily production from the FHR (Edge Global Innovation Inc, 7/2020). Starting in late 2019 to present, between maintenance and field operations, there has been minimal static production, therefore the time period from mid-2018 to Fall of 2019 affords the most representative example of the FHR production decline. With an estimated 200 MMCF of YOY decline, and only 200- 225 MMCF/yr of new supplies after ~11 years and over 25 helium explorers, should the alarm bells be sounding?

CRAWL BEFORE YOU CAN WALK

Oil and gas exploration has been around for over 160 years - helium exploration – a scant 9 years. (The 1st US well was drilled in 2014 by Praxair in NW New Mexico).

Figure 3. The flying aircraft carrier USS Macon above New York City in 1933.

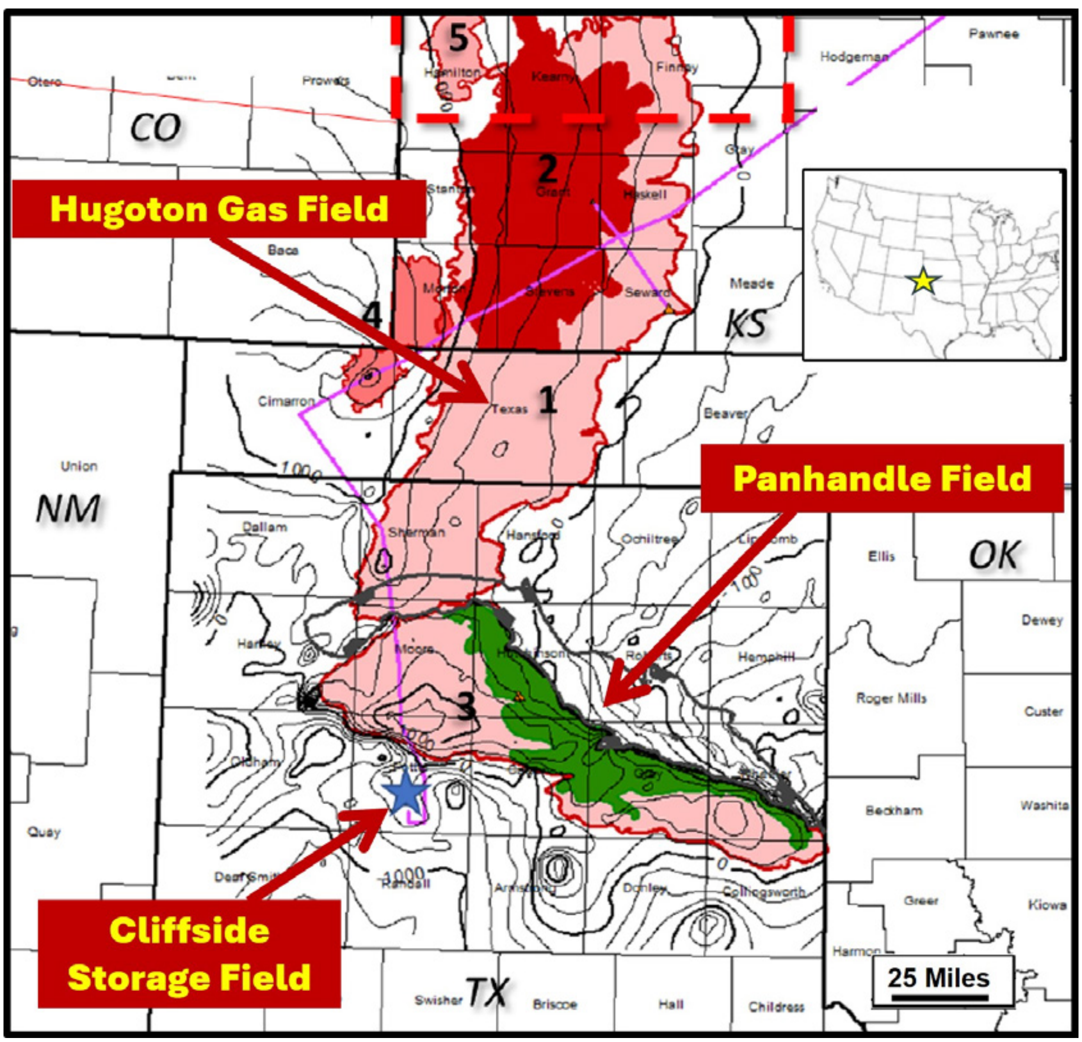

Figure 4. The Hugoton and Panhandle Fields: Contoured on the Chase Group; 250' contour interval. Combined production of over 27 TCF of gas, comprised of ~70% methane and .25 to 2.5% helium (Geoconvention 2023, Calgary, Ca).

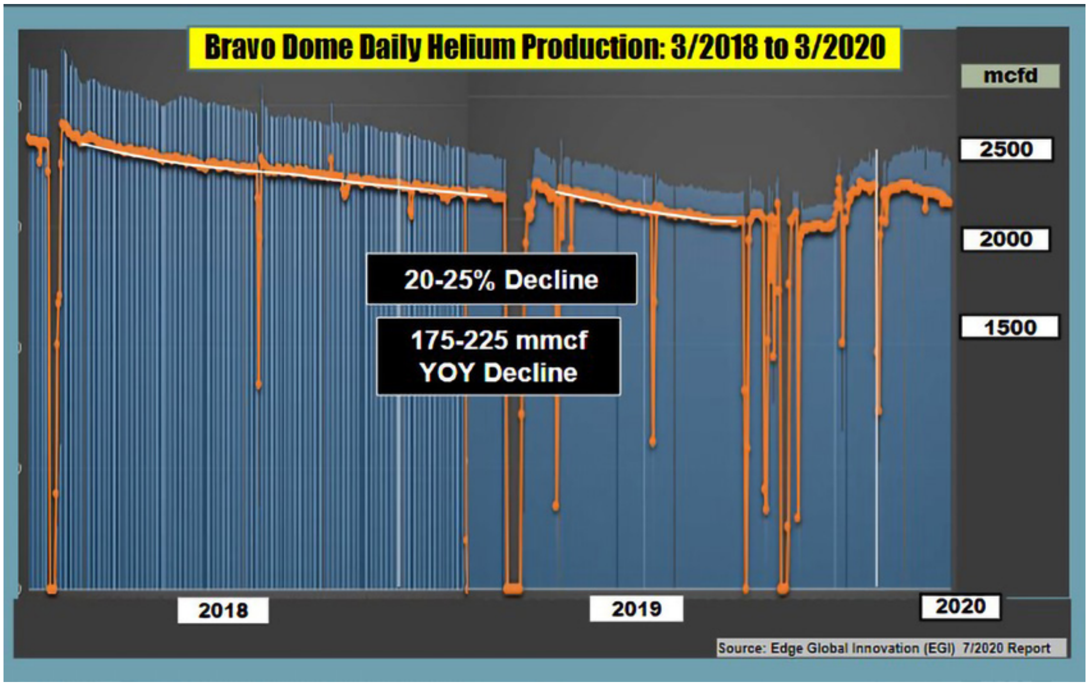

Figure 5. Estimation of the Federal Helium Reserve daily decline rate (daily production data derived from Edge Global Innovation).

Historically, most of the known helium accumulations were found serendipitously while in search of hydrocarbons. Therefore, explicit helium prospecting is still in its infancy. Fortunately, many of the same exploration methods used in oil and gas exploration are utilized in helium exploration. Although, source and seal play higher priorities in the risk-analysis game.

A large percentage of new helium exploration has been geared towards chasing non-hydrocarbon gas reservoirs – despite many prospective reservoirs containing large volumes of CO2 and occasionally H2S – both corrosive and problematic to safety and midstream processing. Ideally, fields with high percentages of nitrogen offer the best economics, since nitrogen can be safely vented.

GEOLOGY MATTERS

Modern helium exploration can be subdivided into two broad categories: 1) Drilling host rock overlain by salt/evaporitic seals; and 2) drilling host rock with tight clastic and carbonates seals. There is nothing in the subsurface that can trap helium – but certain formations slow it down better than others – tight evaporites being the best. Over millions of years, basins associated with the Ancestral and modern Rockies developed the thickest and most laterally contiguous salt layers, in association with thorium/uranium rich fractured granites. Top subsalt players include ExxonMobil (LaBarge, southwest Wyoming); Kinder Morgan, Air Products, and PetroSun, Inc (SW Colorado and Eastern Utah); Grand Gulf Energy (Red Helium Project, SE Utah); Blue Spruce (LaBarge); and Wesco (Three Mile Unit, SE Utah) (Figure 6).

All of the sub-salt helium accumulations above are associated with Mississippian-aged carbonates. Through early porosity enhancement via the diagenetic conversion of limestone to dolomite, and further porosity enhancement by localized hydrothermal dolomitization, these reservoirs possess world class porosities and permeabilities. In cases like southwest Wyoming (LaBarge) and southeast Utah, (Red Helium project), basement-rooted structures can cover areas in the 10's of square miles.

With the momentous announcement that Blue Spruces Dry Piney project will be funded by Japex (U.S.) Corp, a subsidiary of Japan Petroleum Exploration Co., Ltd, it's possible the combined (unrisked) reserve potential of Blue Spruce and sub-salt explorer Grand Gulf could represent 20-25% of the world's future helium needs, on par with

Exxon's current 20% share of the current global helium market.

Non-subsalt fields (Figure 7) can have exceptional economics when helium is trapped at anomalously shallow depths (800-1200') with concentrations ranging from 5-8%. The best example is the prolific Pinta Dome and Navajo Springs accumulations located on the northeastern edge of Arizona's east-central Holbrook Basin. The 700 MMCF of produced helium from these two geologically conjoined fields could be demanding to repeat, but PetroSun, Total Helium, and the Navajo Nation Oil and gas Company (NNOGC) are up to the challenge. Detailed geomorphology and high definition aeromagnetics - followed by state-of-the-art 2D/3D seismic can provide a blueprint to profits.

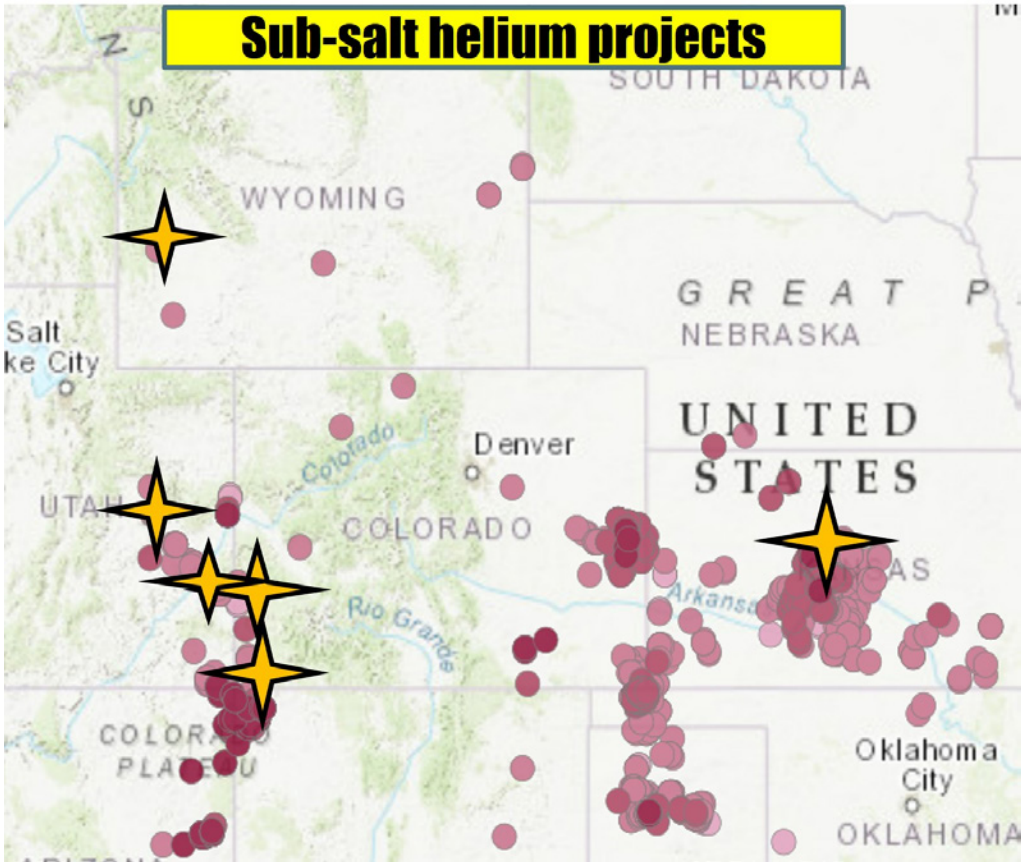

Figure 6. Location map of sub-salt helium projects in the US and Canada. Dots represent wells with gas compositions greater than 1% mole helium.

New production in the US Four Corners Area has shown excellent recent success. German based NASCO has confirmed nine new completions in DBK and Hogback fields, but flow results are unknown to date. The Navajo Nation Oil and Gas Company (NNOGC) made an excellent Mississippian carbonate discovery in NE Arizona, and the Navajo Transitional Energy Company (NTEC) has been successfully exploiting Devonian helium rich sandstones in NW New Mexico. With helium concentrations reaching 6-7% in the aforementioned trends, the economics are outstanding, although plan on 2-to-4-year lead times from drafting table to drill bit.

In southeastern Colorado and western Kansas, chasing helium-bearing lower Pennsylvanian Morrow channel sands utilizing advanced seismic attributes shows promise, but minimal acoustic impedance contrasts create a relatively high-risk profile using existing 3D data sets. This could change with Pure Helium, LLC (a subsidiary of Aspect Holdings), shooting a multi-component high resolution 3D survey dedicated to circumventing AVO false positives.

Southwest Saskatchewan and southeast Alberta has seen significant helium activity from a plethora of Operators, with North American Helium (NAH) carrying the torch since 2013, and more recently successfully partnering with Helium Evolution. NAH has raised significant capital, built an enviable midstream, and has drilled ~80 wells to date. NAH's estimated current capacity of 155 MMCF/yr is commendable and augmented by highly pro-active and pro-helium governmental agencies.

Outside of Blue Spruce and Grand Gulf, the next most exciting devel-opment is Avanti Helium's Cambrian discovery in north-west Montana. Based upon a prolonged test, this 20% porosity sandstone had an open flow test of 20 MMCFGD with only 3% drawdown. This basement derived anticline, identified by 3D seismic, represents one of many similarly risked structures in the Greater Knappen area.

HELIUM PRICING

Good luck determining the present price of helium – it's as opaque as Captain Kittinger's view into deep space.

The helium playing field is dominated by a small number of companies that control a large portion of the supply chain, and these companies are not required to disclose detailed pricing information. Furthermore, many helium suppliers and consumers enter long-term contracts, which may include confidentiality clauses. Unfortunately, the helium market has historically been unregulated, with little oversight on pricing practices.

All of this creates significant price spreads. Producers with legacy contracts are living with contracts that can generally range from $200-250/MCF, while more recent contracts have been reaching nearly $800/MCF in certain areas (Figure 8). While the prices for refined helium (greater 99.997%) are fetching more than $1200/MCF. In the near term, high-rate subsalt discoveries could provide immediate relief to Helium Shortage 4.0. In the longer term, the addition of sustained organic growth in certain non-subsalt play areas could bode well for counterbalancing the depleting Federal Helium Reserve. With the Federal Helium Reserve declining faster than domestic replacement, helium pricing is thriving in a bull market. For those long in tooth, today's helium time stamp is reminiscent of the late 1970's in the oil and gas Industry.

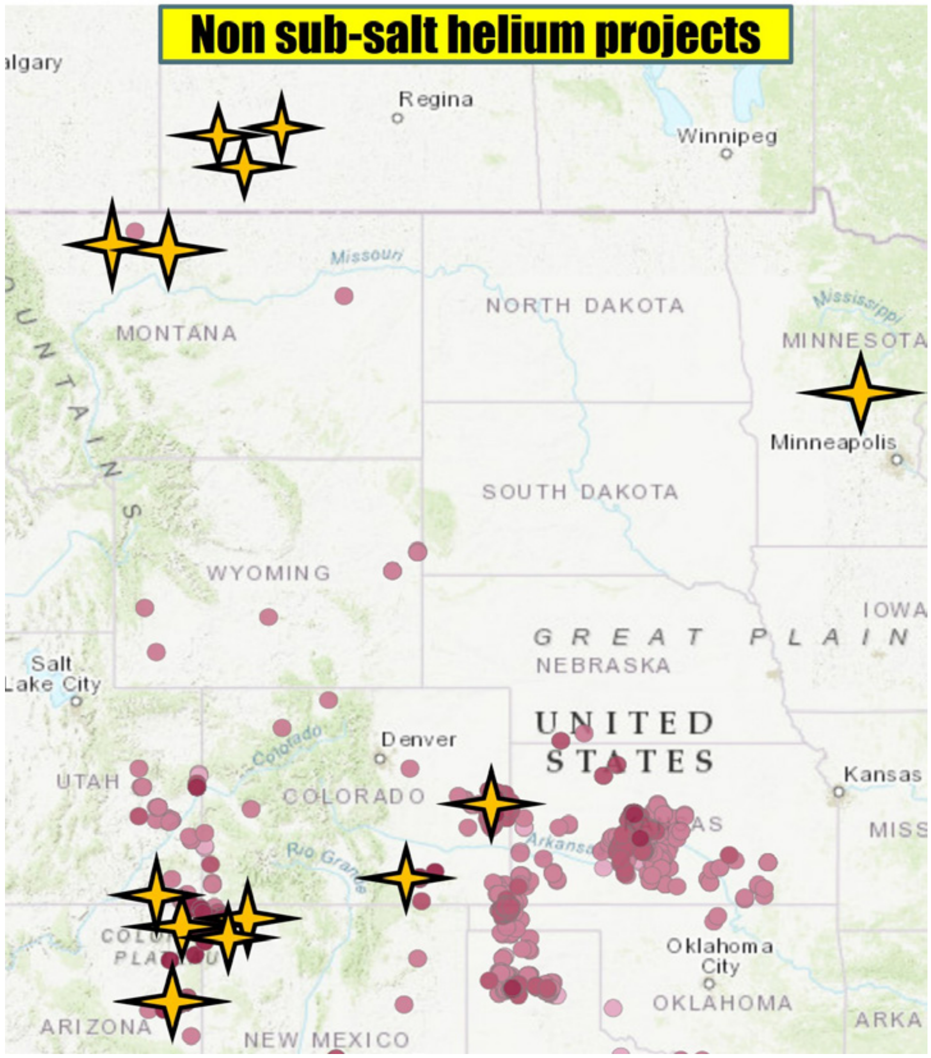

Figure 7. Location map of non-sub-salt helium projects in the US and Canada. Dots represent wells with gas compositions greater than 1% mole helium.

IS THERE A HELIUM CRISIS?

Domestically, the US supply trend for helium is foreboding (Figure 9). Consider last year when the FHR was down for ~6 months during extended maintenance. Combining that event with an explosion at a small helium plant in Haven, Kansas, sent shockwaves to many helium end users. Four of five major U.S. helium suppliers began rationing the element (Kornbluth, 2022 and 2023), and numerous force majeures were put in place. "Helium is on allocation for sure," said Donna Craft, a regional construction manager for Premier Inc. who contracts with helium suppliers for some 4,000 hospitals. Tier one Industrial Gas companies have become the Maytag men of years gone by, with endless hours of watching, waiting for the phone to ring from a helium supplier.

Capital constraints are problematic. Due to the nascent nature of helium exploration, and investors who

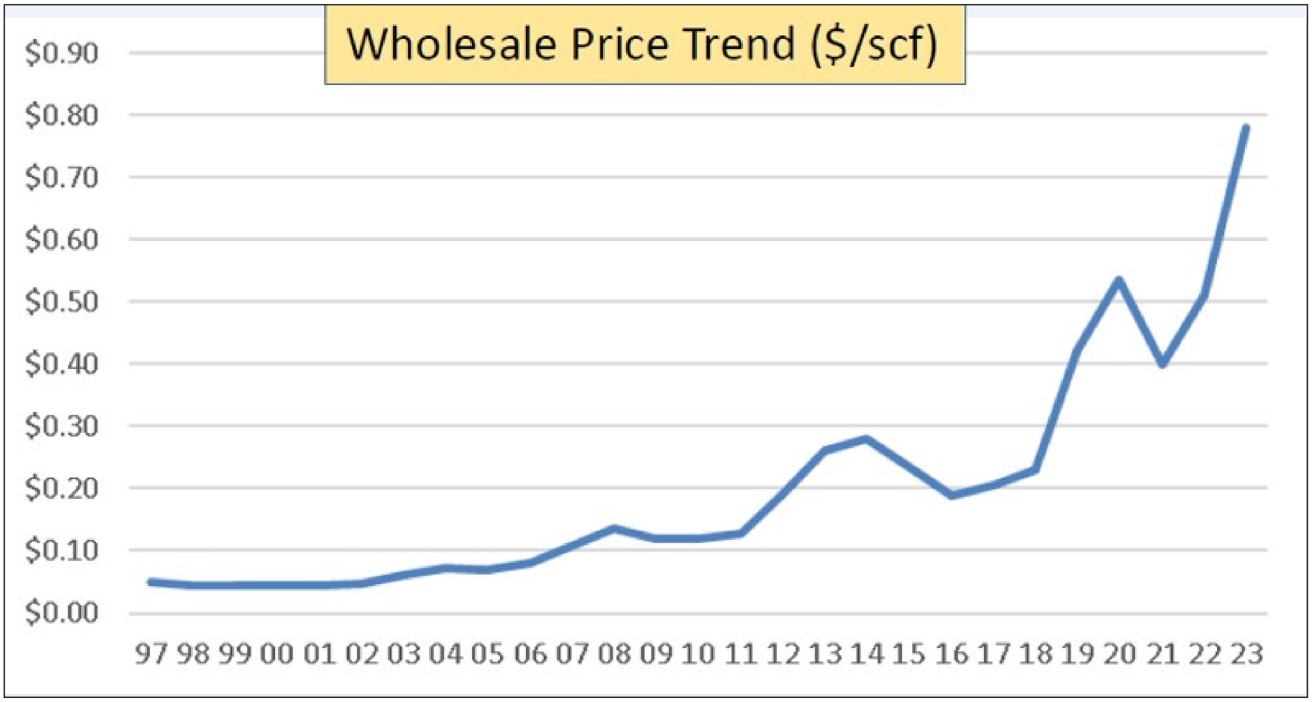

Figure 8. US Wholesale helium prices, sourced directly from offtake agreements (The Edelgas Group).

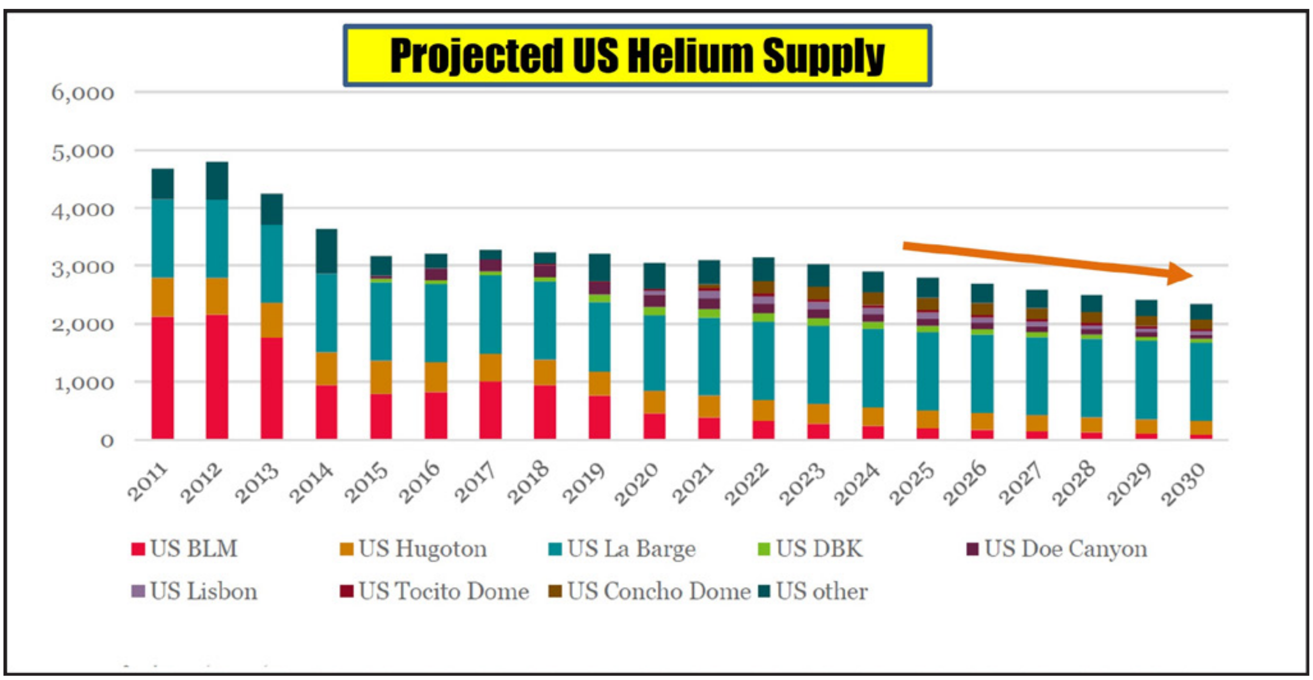

Figure 9. Projected US helium supply (USGS, Hannam & Partners).

maintain a proclivity for playing in a familiar sandbox, the headwinds are strong for raising much needed capital. The best estimate suggests $80-100MM USD could be required in the next 3-6 years for North America to be able to turn the helium corner. It's not easy to envision an origin for this sizable investment.

On the plus side, GNG Partners made the strategic move of purchasing the Lisbon Valley helium processing plant out of bankruptcy for $16 million and change. Located near Moab, Utah, the Lisbon plant is one of only 8 liquefaction units in North America and lies in the epicenter of the rapidly expanding semiconductor industry (13% CAGR assuming all projects come to fruition; Intelligas). Surrounded by intense helium activity, this 500 MCFD helium plant - augmented by carbon sequestration - has the makings of being one of the best investments of the year in the CO_2 and helium sectors.

Cars, computers, and rocket ships are one thing, but lacking access to a life sustaining MRI machine is another. Yes, MRI's have become more efficient, and price-induced softening of demand has helped, but it ultimately comes down to one's definition of a 'crises'.

GAZPROM

Move over Russian bear and make room for the 800# gorilla. Russia has helium. Lots of helium. Who consumes helium like no other? Uncle Sam. Gazprom, the largest oil and gas company in Russia, didn't spend $13Bn (USD) for helium exploration and infrastructure in lovely eastern Siberia for the fun of it.

As usual, it all comes down to money. North American explorers will find helium – but will their F&D be competitive with Gazprom – who would be willing to trade profit for margins? Consider this - before the Permian Basin exploded, there were no North American oil fields that could compete with most of the OPEC countries on a dollar-for-dollar basis, including transportation costs. Who's to say Russia doesn't become the OPEC of helium? Look no further than the EU, who became dependent on 40% of their natural gas supplies from Russia in a short period of time. How'd that turn out?

In February of 2022, US Senator John Barrasso and Senator Mike Lee sent a letter to Secretary of the Interior, Deb Haaland, stating: "As US production declines, Russia has made massive investments to take our place in the global helium market".

Gazprom's ambitious Amur helium processing plant is 1-2 years behind schedule, primarily related to a 2022 refinery explosion. Yes, Russia made a hullabaloo on September 11th (TASS) that helium is finally flowing at Amur, but let's take a reality check. The flow has been a trickle; the pipeline from Amur to the eastern seaport of Vladivostok is far from complete, there is a deficiency of skilled personnel due to the Ukrainian war, and Western sanctions are limiting the supply of critical 11,000-gallon ISO containers ('International Organization for Standardization'). No ISO's – no transport. With a fixed number of ISO's in the world, and a gruelingly slow supply chain (Kornbluth, 2023), the world would be ill-advised becoming overly enamored with the Amur plant as a white knight. The hard working and dedicated North American helium explorers cannot and must not take their foot off the upstream gas pedal.

BUCKLE UP

This colorless, odorless, non-flammable, non-toxic, minuscule element managed to go undetected until an 1868 solar eclipse. Not bad for the second most abundant element in the Universe.

Does the average Joe understand that helium's uber-low boiling point makes it indispensable to health services, space propulsion, and the semi-conductor industry? Barely.

Is their party balloon shortage awareness –YES – just ask Kim Kardashian.

In theory, the combination of soaring prices and hard-working creative entrepreneurs will lead us to a smooth non-Gazprom transition. It's no coincidence that the top performing helium companies are led by oil and gas industry veterans. This niche has been proving themselves for decades upon decades – *with little to no fanfare.* Can they come to the rescue again? Stay tuned.

Dedicated to the late, great Tony Bennet.

ACKNOWLEDGEMENTS

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THE AUTHOR

Tim Rynott

Mr. Rynott, founder of Four Corners Helium, LLC (FCH) and Ridge Resources, LLC has spent the majority of the past four decades successfully exploring for oil and gas in over twelve US Basins, including the Gulf of Mexico Deep Water. During his career he has generated/endorsed countless discoveries, and has been personally investing in oil and gas drilling projects since 1985.

The most recent 4 years has been an immersion in applying natural gas exploration techniques into successful helium endeavors. The newly formed Four Corners Helium technical team, comprised of five geoscientists, three geophysicists, and a top geochemist, has mapped almost ten million acres of the helium charged Colorado Plateau. Having also reviewed helium projects in eastern Colorado, Northern Montana, the Texas Panhandle, New Mexico, and Arizona, the team has gained appreciable insights for the geologic and geochemical challenges inherent in helium exploration.

Over the past 28 years, Mr. Rynott has served on the following Boards: AAPG Advisory Council, AAPG House of Delegates, AAPG Associate Technical Editor, Louisiana Oil & Gas Assoc, Gulf Coast Assoc of Geological Societies, and Gulf Coast Prospect Expo. In 2019 he was awarded the AAPG Distinguished Service Award. Mr Rynott is a Domestic and International speaker and author, providing technical presentations for multiple Oil and Gas Conferences, including AAPG, SEG, GCAGS, SIPES, and RMAG's recent North American Helium Conference.

He is presently serving as Rocky Mountain Section Counselor for the Division of Professional Affairs of the AAPG and is a member of good standing with the AAPG, DPA (Cert #5803), LOGA, HGS, LGS (Honorary Member), and FCGS.