PS The Helium System: A Modification of the Petroleum System for Inert Gases*

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Search and Discovery Article #42098 (2017)**
Posted June 26, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, United States, April 2-5, 2017

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Abstract

Helium is a naturally occurring inert gas commonly associated with oil and gas accumulations. Although it generally constitutes less than two percent of the total gas stream, its occurrence within specific stratigraphic intervals and geographic areas can shed light on gas migration pathways within a basin. Moreover, the recent rise in helium prices and contemporaneous drop in oil and gas commodities has piqued commercial interests where oil and gas infrastructure, insight, and expertise are readily available. Most petroleum explorationists are not familiar with helium exploration; however, a widespread and common method may be easily modified for our purposes: the petroleum system. The petroleum system concept has been used successfully for decades to high-grade plays and de-risk oil and gas prospects around the world. We propose a modification of the petroleum system approach to aid exploration for helium resources and other inert gases. In order to provide a proof-of-concept, a case study was undertaken in the Uinta basin of eastern Utah and Piceance basins of northwestern Colorado. These basins produce nearly three percent of the total natural gas in the United States and contribute appreciable amounts of helium from various geologic formations. Like a petroleum system, the helium system is identified by its source rock, reservoir, trap, seal, and migration pathway. Two helium systems are identified and tentatively called the Uncompahgre and Uinta systems; named after their interpreted source rock intervals. The helium gas, as well as nitrogen and carbon dioxide, are believed to migrate through basinal brine systems until trapped in conventional petroleum traps. These gases are found primarily in the Entrada, Morrison, Dakota, Frontier, and Prairie Canyon Member of the Mancos formations. The Mancos Shale provides a basin-wide seal for both helium systems and prevents significant leakage to the younger Mesaverde, Wasatch, and Green River gas-productive intervals. We used common risk segment (CRS) approach and mapped areas of low, moderate, or high risk for the occurrence of pools with significant helium content.

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Abstract

Helium is a naturally occurring inert gas commonly associated with oil and gas accumulations. Although it generally constitutes less than two percent of the total gas stream, its occurrence within specific stratigraphic intervals and geographic areas can shed light on gas migration pathways within a basin. Moreover, the recent rise in helium prices and contemporaneous drop in oil and gas commodities has piqued commercial interests where oil and gas infrastructure, insight, and expertise is readily available. Most petroleum explorationists are not familiar with helium exploration; however, a widespread and common method may be easily modified for our purposes: the petroleum system. The petroleum system concept has been used successfully for decades to highgrade plays and de-risk oil and gas prospects around the world. We propose a modification of the petroleum system approach to aid exploration for helium resources and other inert gases. In order to provide a proof-of-concept, a case study was undertaken in the Uinta basin of eastern Utah and Piceance basins of northwestern Colorado. These basins produce nearly three percent of the total natural gas in the United States and also contribute appreciable amounts of helium from various geologic formations.

Like a petroleum system, the helium system is identified by its source rock, reservoir, trap, seal, and migration pathway. Two helium systems are identified and tentatively called the Uncompahgre and Uinta systems. The helium gas, as well as nitrogen and carbon dioxide, are believed to migrate through basinal brine systems until trapped in conventional petroleum traps. These gases are found primarily in the Entrada, Morrison, Dakota, Frontier, and Prairie Canyon Member of the Mancos formations. The Mancos Shale provides a basin-wide seal for both helium systems and prevents significant leakage to the younger Mesaverde, Wasatch, and Green River gas-productive intervals. We used common risk segment (CRS) approach and mapped areas of low, moderate, or high risk for the occurrence of pools with significant helium content.

Executive Summary

Inert gases, such as carbon dioxide, nitrogen, and helium, are a common occurrence within natural gas reservoirs in the Uinta and Piceance basins. These gases can be a nuisance or opportunity depending on field location, zone of interest, and relative concentration. Additionally, their prescence or absence may shed light on gas migration within a basin.

The U.S. Bureau of Mines began helium surveys in 1917 across the United States in an effort to produce commerical volumes for airships in World War I. World War I ended the next year; however, the surveys continued in anticipation for future military uses. By World War II, fixed-wing aircraft had become readily available and the use of helium had diminished, but the surveys continued until 2007. After ninety years of data collection, a large database of over 15,000 wellhead samples are now available to the public. These reports include a wealth of information from natural gas wells and pipelines, including hydrocarbon compositions, inert gas concentrations, heating values, and specific gravities. This dataset was digitized for Rio Blanco, Garfield, and Mesa counties in Colorado and Uinta and Grand counties in Utah and filtered to 479 wellhead samples based on good data and a contiguous area-of-interest.

The Piceance and Uinta basins are large natural gas provinces which constitute three percent of domestic natural gas production. These reservoirs produce a wide range of inert gas concentrations (0 to 99%) from a variety of plays, primarily structural traps, stratigraphic traps, and basin-centered gas accumulations. Detailed analysis of inert gas compositions shows distinct differences between stratigraphic intervals and geographic areas. Nitrogen and helium are correlated by multiple linear trends, suggesting nitrogen is the carrier gas for helium and multiple "source rocks" and/or migration pathways are present. Regional geology suggests the basement-cored Uncompahgre Uplift (south) provides the source material for helium creation through radiogenic decay. A northern source has not been identified. Vertical fractionation can be seen by differences between highly-charged Paleozoic rocks versus inert-free Tertiary reservoirs. In Mancos B (Prairie Canyon) gas fields, the presence of helium may indicate commingling between distinct petroleum systems; suggesting a more significant structural control (i.e., faulting) than previously recognized.

Integrating inert gas relationships and regional geology delineate areas of low and high concentrations, important parameters when exploring for new prospects or planning production facilities. Additionally, the recent rise in helium prices may create new opportunities where methane-rich wells are uneconomic under current market conditions. This study proposes inert gas relationships as a potential tool for natural gas exploration and risk analysis within the Colorado Plateau and other gas-rich provinces.

Research Questions

1) Can inert gases shed light on basin-scale gas migration?

2) Can the petroleum system concept be adapted for inert gases?

3) Can composite risk mapping be applied for inert gas systems?

How can we extract value?

Helium studies fall into main primary categories:
1) Field characteristics and field analogs
2) Gas source (i.e., isotope geochemistry)

What do we know about helium?
- Very small (i.e., highly mobile)
- Relatively rare
- Non-reactive (noble gas)
- Easily detectable and measureable

Maybe we can think of helium as a basin-scale tracer gas??

Gas	Mantle	Intrusions	Atmosphere	Diagenesis	Radiogenic Decay	Metamorphism	Chemical Dissolution	Bacterial Degradation
Helium	✓	✓	✓	-	✓	-	-	-
Nitrogen	✓	✓	✓	✓	✓	✓	-	✓
Carbon Dioxide	✓	✓	✓	✓	-	✓	✓	✓

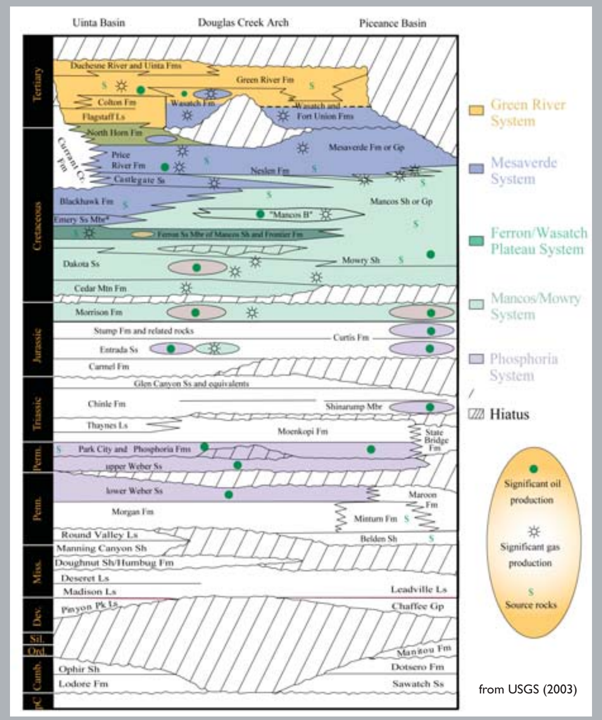
Gas	Mantle	Intrusions	Atmosphere	Diagenesis	Radiogenic Decay	Metamorphism	Chemical Dissolution	Bacterial Degradation
Helium					✓			
Nitrogen						✓		
Carbon Dioxide		✓				✓		

Gas sources compiled from Ginsburg-Karagitscheva (1933), Lang (1959), Picard (1962), Hunt (1979), Carothers & Kharaka (1980), James & Burns (1984), Smith et al. (1985), Whiticar & Faber (1986), Smith & Ehrenberg (1989), Clayton et al. (1990), James (1990), Kotarba (1990), Krooss et al. (1995), and Milkov (2010).

Gas Sources

Inert gases can come from a variety of sources. The table at top left outlines list of proposed sources for different formations and basins around the world. Radiogenic decay is cited as the primary source of helium, but must be confirmed by isotope geochemistry. ^4He is formed by radiogenic decay, whereas, ^3He is leftover from Earth's formation, referred to as "primordial" helium.

The interpreted sources of inert gases in the Uinta and Piceance basins can be seen at bottom left. Helium is believed to come from radiogenic decay of the Precambrian basement, likely alpha decay from potassium or uranium; however, isotope data is required to confirm this interpretation. Nitrogen is also thought to be sourced from the Precambrian basement due to its high correlation with helium. The source of nitrogen is ambiguous, but may be related to the metamorphism of micas. Carbon dioxide is thought to be related to igneous intrusions. Although the intrusions themselves can be a source of gas, we believe the majority of the gas comes from metamorphism of Paleozoic carbonates, specifically the Leadville Limestone. The Leadville has been demonstrated to be a major source of carbon dioxide in the Paradox Basin through similar metamorphic processes (Cappa & Rice, 1995).



from USGS (2003)

Petroleum Systems

A stratigraphic column from USGS (2003) can be seen at left. The Uinta and Piceance basins are composed of five primary petroleum systems. This study focused on the four petroleum systems that are located at the Uinta-Piceance transition: (1) Green River System, (2) the Mesaverde System, (3) the Mancos System, and (4) the Phosphoria System.

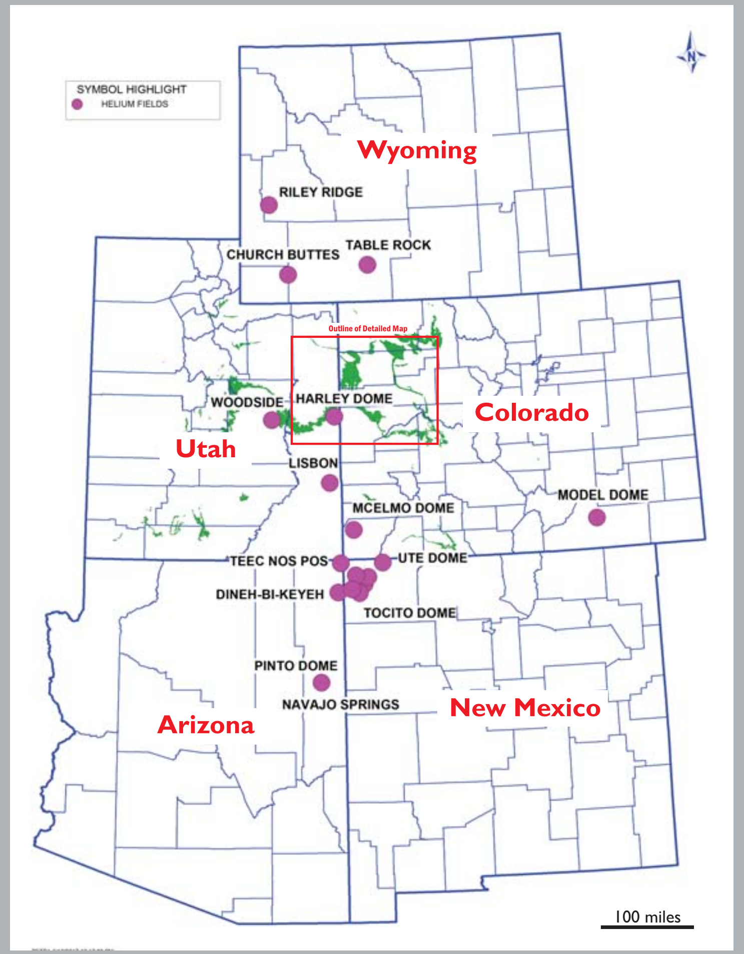
The Green River and Mesaverde systems are interpreted to be basin-centered gas accumulations created from thermal maturation of lacustrine and coaly source rocks, respectively. The Mancos Sytem contains a wide variety of plays including structural traps, stratigraphic traps, and continuous accumulations. This system is also gas-rich and interpreted to have sourced from organic-rich shales in the Mancos Group. The Phosphoria System produces primarily oil with some associated gas. This system is very limited in areal extent with the Rangely Anticline being the only major oil accumulation, a structural trap with a stratigraphic component.

Helium occurs most commonly in formations directly below the Mancos Shale including the Entrada Fm., Morrison Fm., Cedar Mtn. Fm., and Dakota Fm. in decreasing helium concentration. Formations above the Mancos Shale have little-to-no helium, suggesting the Mancos may be a basin-scale seal for vertical gas migration.

The Helium System

Magoon & Dow (1978) defined a petroleum system as "a natural system that encompasses a pod of active source rock and all related oil and gas and which includes all geologic elements and processes that are essential if a hydrocarbon accumulation is to exist." This definition can be thought of as a special case for organic-rich source rocks that produce hydrocarbons. This concept could be easily modified for helium (The Helium System) or other inert gases (The Inert Gas System); thus, we propose a formal definition for these cases.

Sensu Magoon & Dow (1978), an inert gas system is a natural system that encompasses a source rock and all related gas and which includes all geologic elements and processes that are essential if an helium accumulation is to exist. The elements of the inert gas system are identical to the petroleum system: source rock, reservoir rock, seal rock, and overburden rock. The inert gas system processes are also identical to the petroluem system: trap formation and generation-migration-accumulation. This generic definittion can be further refined for specific inert gases. For instance, the previous definition can be applied for *The Helium System*, except the overburden rock element. We do not believe overburden is necessary for helium gas creation; thus, this element would not be used.



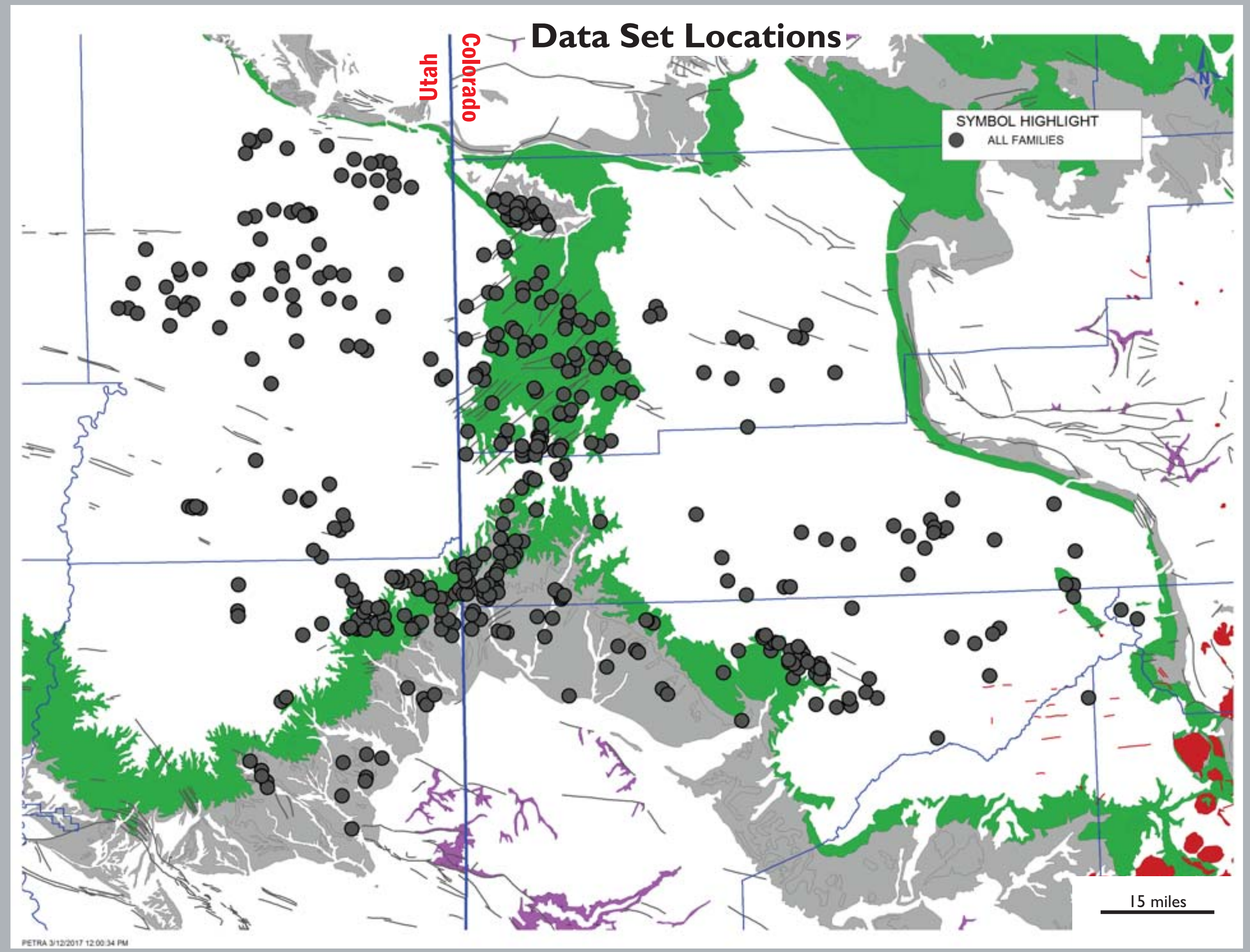
Case Study

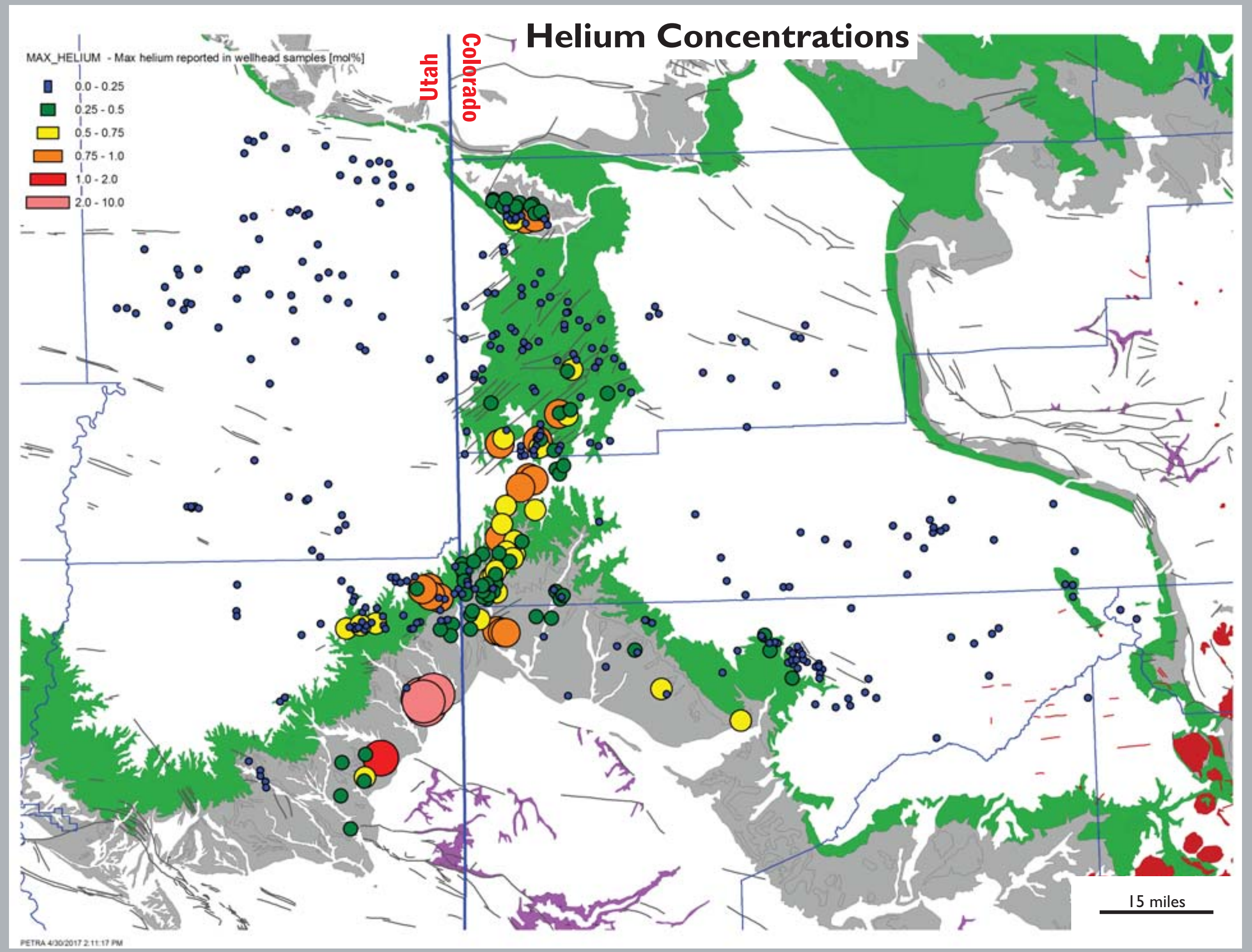
- Focus on western Piceance and eastern Uinta Basins
  - Large gas provinces
  - Well-documented geology
  - Very good well control (subsurface control)

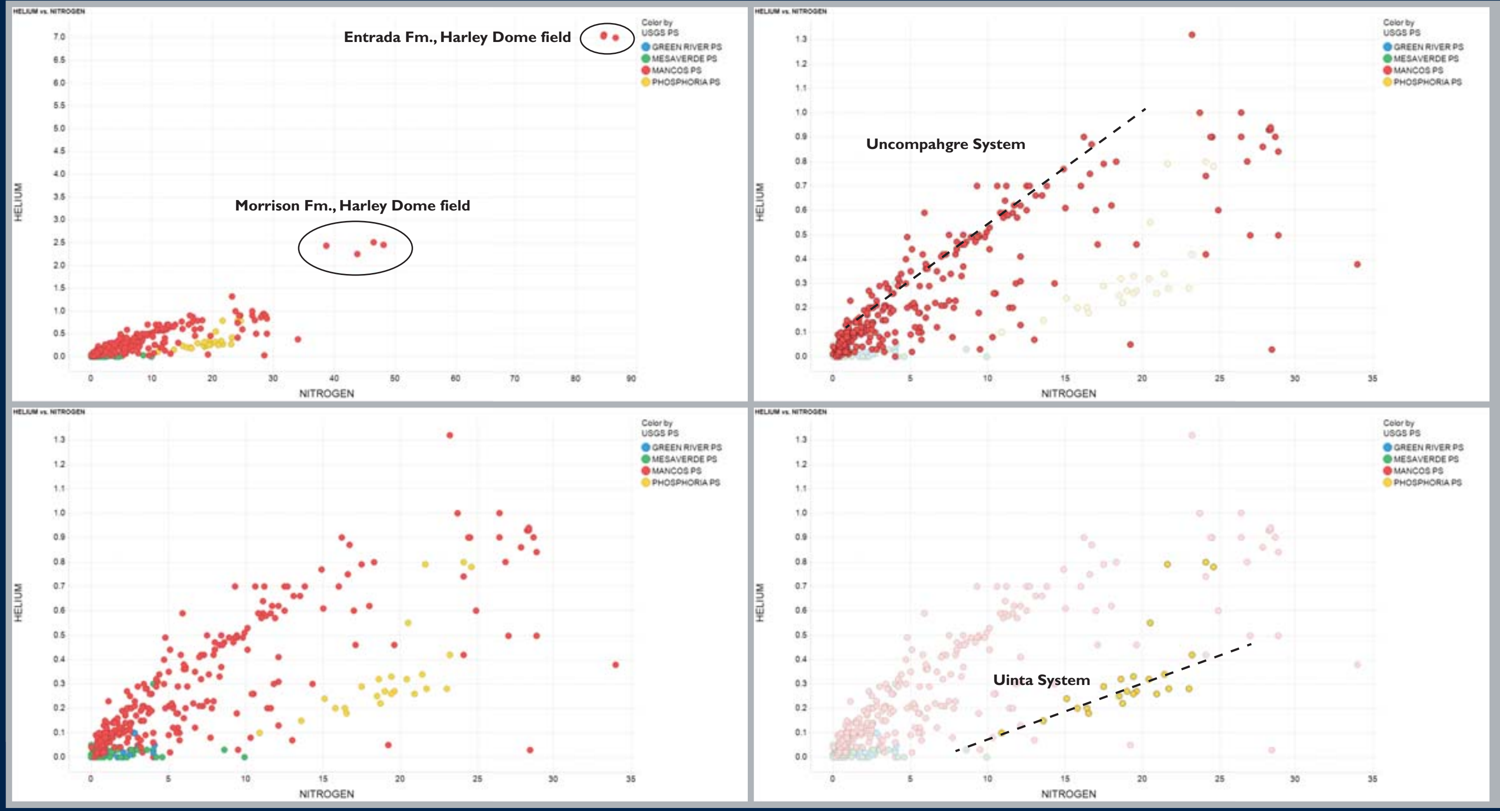
The map at left shows the location of significant helium fields in the southern Rocky Mountains. An outline of the Piceance and Uinta basins can be seen in green (outcrop of the Mesaverde Group. The location of helium fields was compiled from Broadhead & Gillard (2004), Cappa & Rice (1995), Clair & Bradish (1956), Hamak (2013), Morgan & Chidsey (1991), Rauzi (2003), and Roth (2003).

The map at right shows the location of the data set (479 wellhead samples) used in this study. Mesaverde outcrop is outlined in green, Mancos/Niobrara Shale is outlined in grey, Precambrian basement is shown in purple, intrusions are shown in red, surface faults are shown as grey lines, counties are outlined in blue, and the location of wellhead samples are shown in dark grey circles. Note: the vertical line in the middle of the figure is the Utah-Colorado state line.

A map of maximum helium concentrations per wellbore can be seen on the far right. Helium concentrations are denoted by color and the size of the circle. All other colors are identical to the data set map. Notice helium concentrations are highest along the Douglas Creek Arch, a basin-scale structure that trends North-South along the state line, and within the Rangely Anticline (northern cluster of data points).







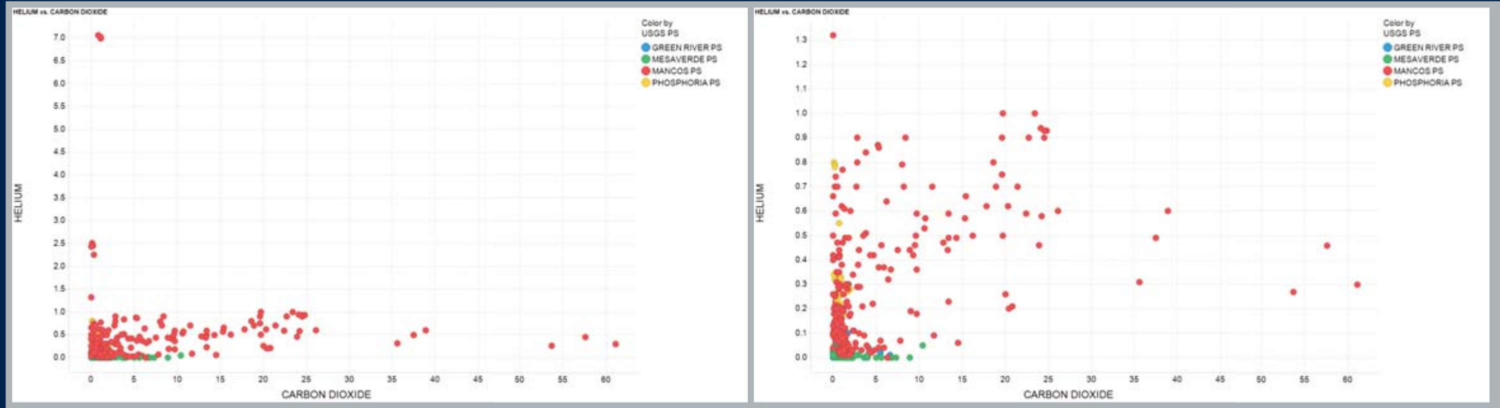
Helium vs. Nitrogen

Scatter plots of Helium vs. Nitrogen Concentration can be seen on the left. Data points are colored by the petroleum system defined by USGS (2003) to help distinguish groups of reservoirs.

The top left figure highlights the highly-enriched Harley Dome field. The two groups of points is caused by gas samples from two reservoir intervals: the lower quality Morrison Formation and higher quality Entrada Formation. In all areas, the Entrada Formation appears to have the highest inert gas concentration which decreases with younger stratigraphy.

A closer look at the data can be seen in the bottom left once the Harley Dome points are removed. This view reveals two apparent trendlines in the Mancos and Phosphoria petroleum systems. These trendlines are annotated in the top right and bottom right figures, respectively. These trendlines are interpreted to: (1) illustrate a distinct helium-nitrogen ratio for different inert gas systems and (2) approximate inert gas sequestration with increasing distance from the source (or area with highest recorded concentration).

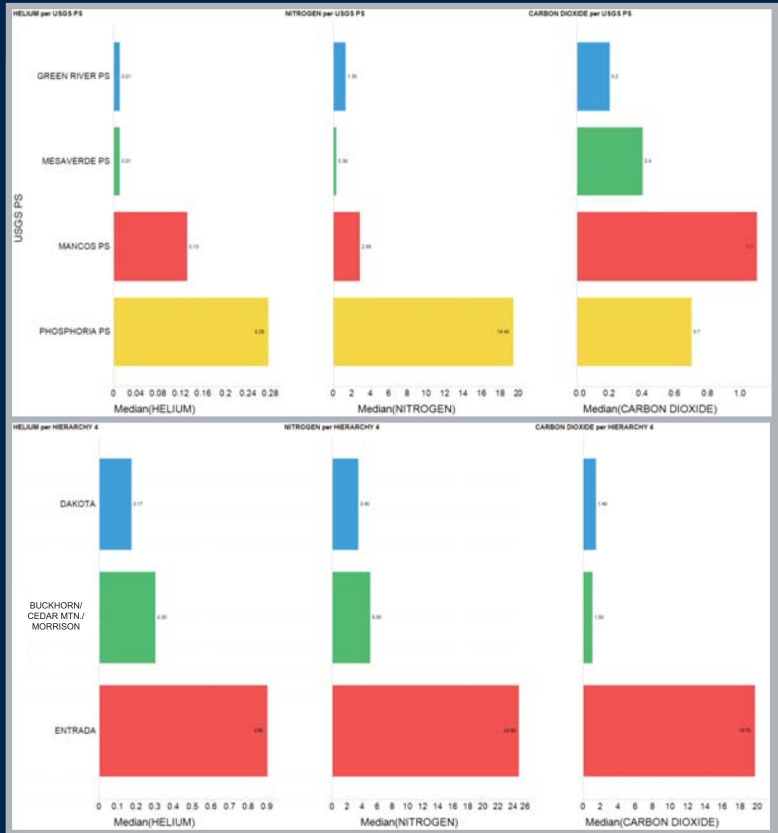
Scatter around the intepreted trendlines is caused primarily by varying amounts of carbon dioxide and/or hydrocarbon gases. Although helium and nitrogen have a demonstrable correlation, this correlation does not exist when compared to other gases common in these reservoirs. This suggests the helium-nitrogen charge are related to each other, but separate from hydrocarbon and carbon dioxide charges which may have been introduced earlier or later.



Helium vs. Carbon Dioxide

Helium and carbon dioxide concentrations do not appear to be related, even when Harley Dome data points are removed. This suggests helium and carbon dioxide enrichment are decoupled even though they share the same reservoirs and petroleum system. Based on inert gas reservoirs in the Paradox Basin, carbon dioxide was likely introduced by metamorphism of the Leadville Limestone by Tertiary intrusions.

We believe the co-occurrence of helium/carbon dioxide and lack of correlation may indicate a shared carrier bed, but not a shared source. Carbon dioxide may have been introduced into the system later and filled any space remaining in structural traps formed during the Laramide Orogeny.

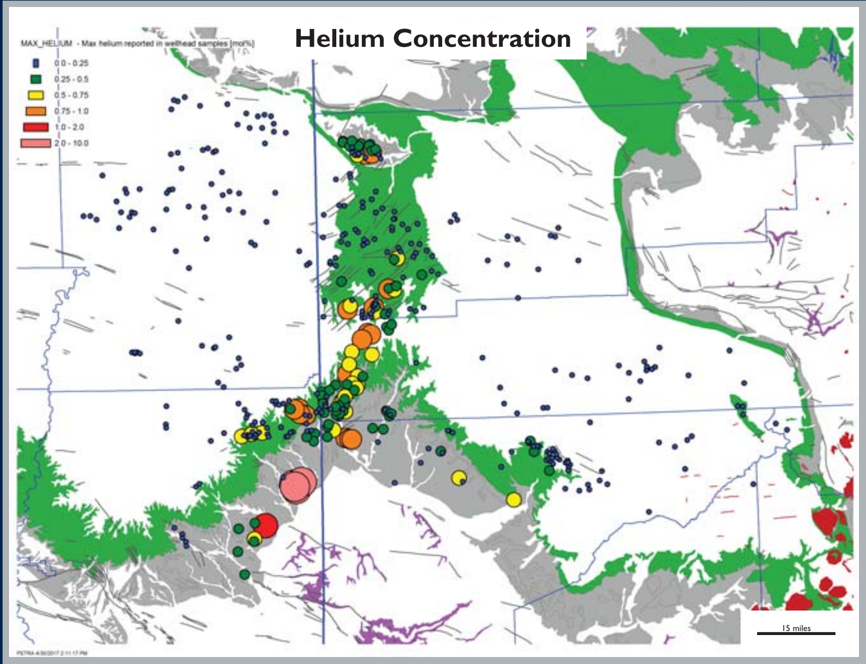


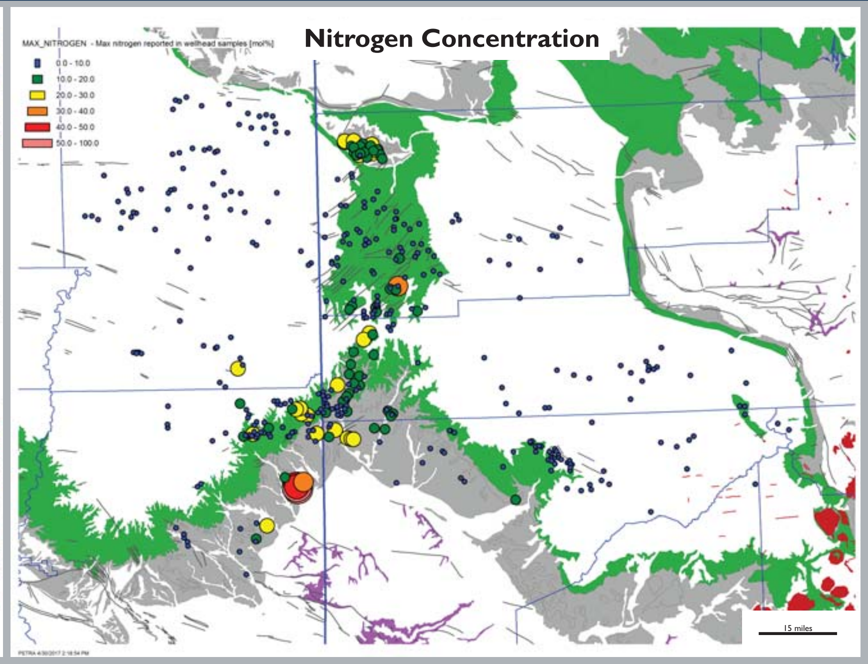
Bar Charts

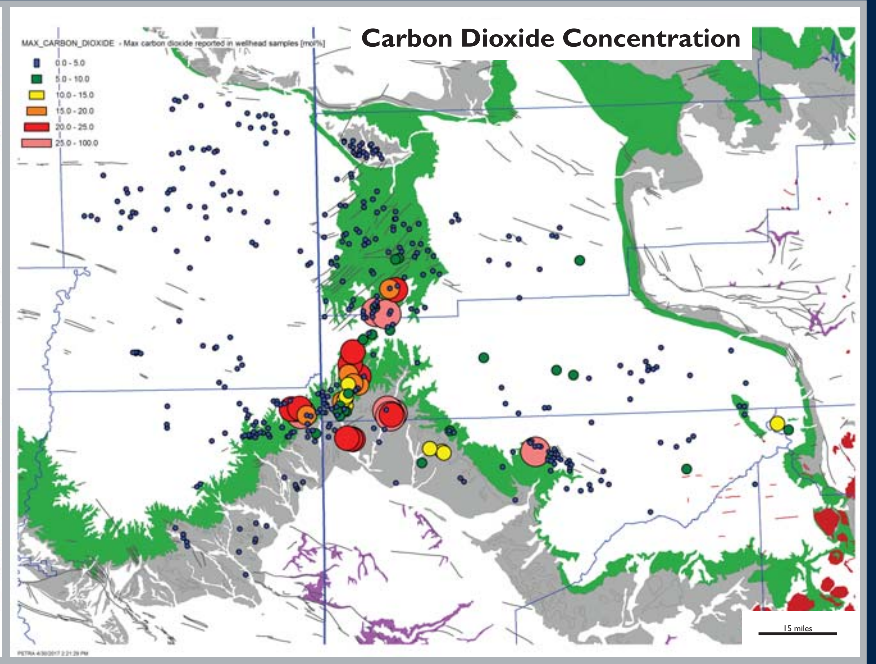
The median gas concentrations for helium, nitrogen, and carbon dioxide in the four primary petroleum systems can be seen in the top left bar chart. One can easily see gases occurring in the Mancos and Phosphoria petroleum systems have a much higher inert gas concentration than the Mesaverde or Green River systems. This is likely due to the Mancos Shale which forms a regional seal across the basin and separates the older petroleum systems from the younger petroleum systems.

Notice both helium and nitrogen are most abundant in the oldest petroleum systems and decrease similarly in younger rocks. This relationship is not true for carbon dioxide; again, further evidence that carbon dioxide is decoupled from the helium-nitrogen charge that is seen across the basin.

We can further subdivide the Mancos Petroleum System into the Dakota, Buckhorn/Cedar Mountain/Morrison, and Entrada formations. Although the Buckhorn, Cedar Moutain, and Morrison are distinct formations, they have been lumped in this case due to their common low net-to-gross sand content and difficulty in distinguishing the formations using purely subsurface data. The bottom left figure shows a distinct change in gas composition between the Entrada Formation and younger stratigraphic intervals for all three inert gases.







Maps of helium, nitrogen, and carbon dioxide concentrations can be seen at top left, top middle, and top right, respectively.

Helium and nitrogen show similar enrichment trends as the scatter plots and bar charts. Both gases show high enrichment in the far south with decreasing concentration towards the north. This enrichment fairway parallels the Douglas Creek Arch, a major structural high that separate the Uinta and Piceance basins. The Douglas Creek Arch can be seen here as the broad Mesaverde outcrop (green outline) that trends north-south along the Utah-Colorado state line.

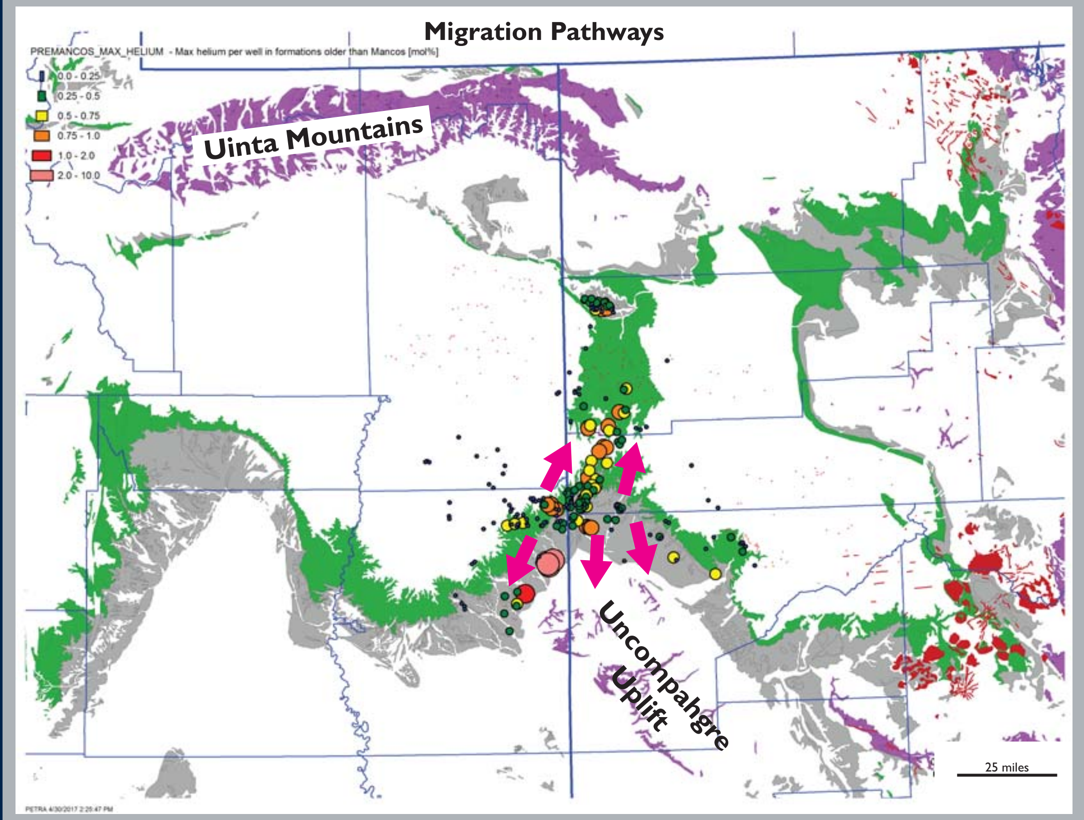
This southern cluster of enriched gases appears to die out midway along the Douglas Creek Arch and reappears at a localized area farther north. This northern cluster of enriched data points is the Rangely Anticline, a large double-plunging anticline that traps Paleozoic oils in the eolian Weber Sandstone.

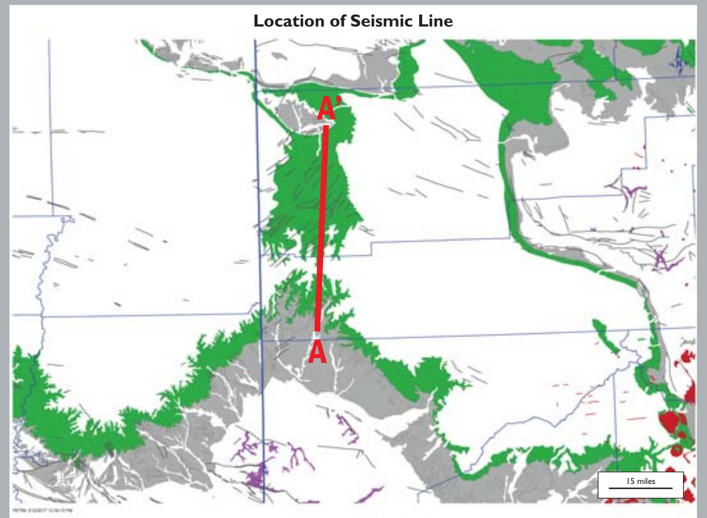
Helium and nitrogen enrichment also appears to decrease very rapidly east or west of the Douglas Creek Arch. This is primarily a function of the basin geometry and hydrocarbon productivity. Very few wells penetrate or produce from strata below the Mancos Shale east or west of the Douglas Creek Arch. These fields produce almost exclusively from the Green River or Mesaverde petroleum sytems. Both of which are interpreted to be basin-centered gas accumulations and separated by Paleozoic (and Precambrian basement) by up to two thousand feet of marine Mancos Shale.

At first glance, carbon dioxide appears to display similar enrichment trends; however, two distinct differences are present. The Rangely Anticline and the northwestern tip of the Uncompahgre Uplift do not display high concentrations of carbon dioxide unlike helium and nitrogen. Carbon dioxide enrichment appears to be more localized and focuses around the Garmesa Fault Zone which can be seen in the cross section below.

Also unlike helium or nitrogen, higher concentrations of carbon dioxide can be seen off the Douglas Creek Arch axis in the deeper Piceance Basin. Most of these points occur within reservoirs in the Mesaverde Group and are interpreted to be carbon dioxide created during thermal maturation of coals, the primary source rock for the Mesaverde Petroleum Sytem in the Piceance Basin. Curiously, this deep basin enrichment is not seen in the Uinta Basin.

Interpreted migration pathways can be seen on the map below. Southern helium is believed to source from the Uncompahgre Uplift. Northern helium may be sourced from the nearby Uinta Mountains or migrated with Phosphoria oils from Idaho.

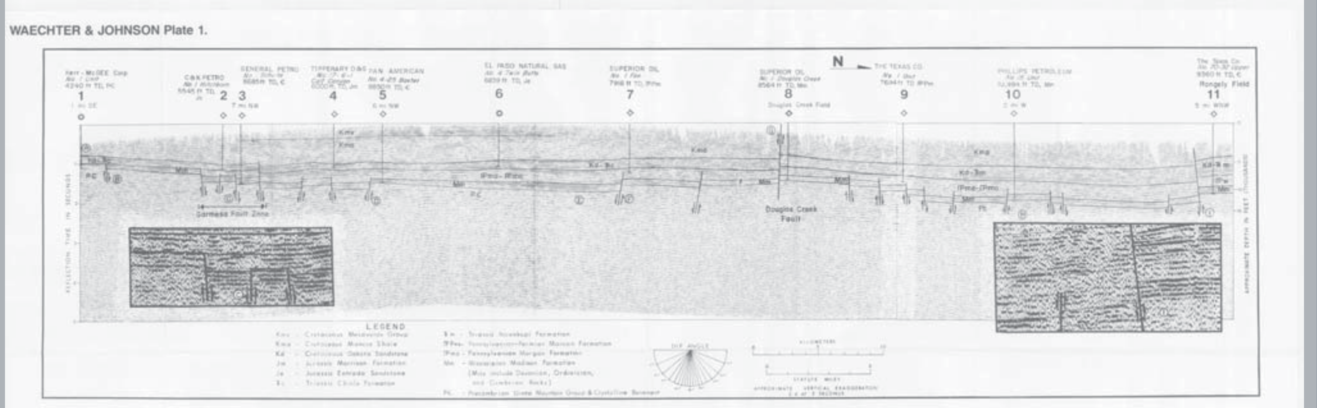




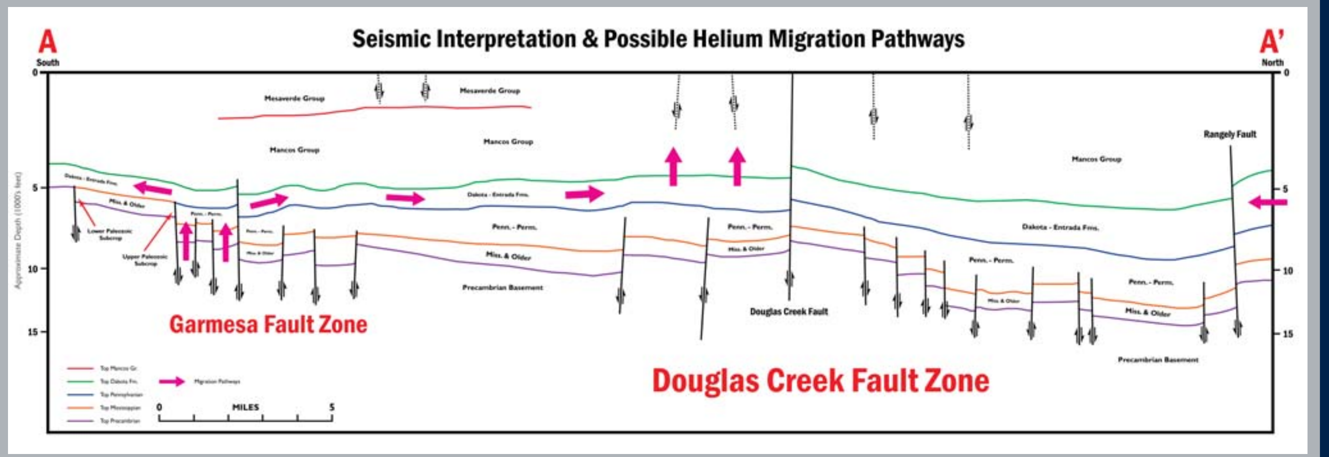
The index map (above) shows the location of a seismic line interpreted by Waechter & Johnson (1986) (seen at top right). Bader (2009) added additional faults in the Mesaverde Group and Mancos Group to highlight a series of normal faults associated with Prairie Canyon (Mancos B) gas production on the Douglas Creek Arch. A modified version of the Bader (2009) cross section can be seen at bottom right.

Helium is interpreted to migrate vertically from basement through a series of normal faults in the Garmesa Fault Zone. After its primary vertical migration, the helium likely migrates laterally through the Entrada Fm., a highly permeable eolian sandstone, by structural relief provided by the Uncompahgre Uplift (south) and Douglas Creek Arch (north). Local-scale vertical migration from the Entrada Formation would allow helium, nitrogen, and carbon dioxide to charge the overlying Dakota and Morrison Fm. reservoirs.

Lateral migration is interpreted to stop at the Douglas Creek Fault, a major normal fault on the Douglas Creek Arch. Interestingly, overlying Prairie Canyon reservoirs are slightly enriched in helium and nitrogen. This suggests modest vertical migration through the Mancos Group, perhaps through normal faults that commonly bound productive fields. These fields have previously been attributed stratigraphic traps; thus, helium enrichment may suggest a larger structural control on gas migration.



From Waechter & Johnson (1986)



Common Risk Segment Mapping

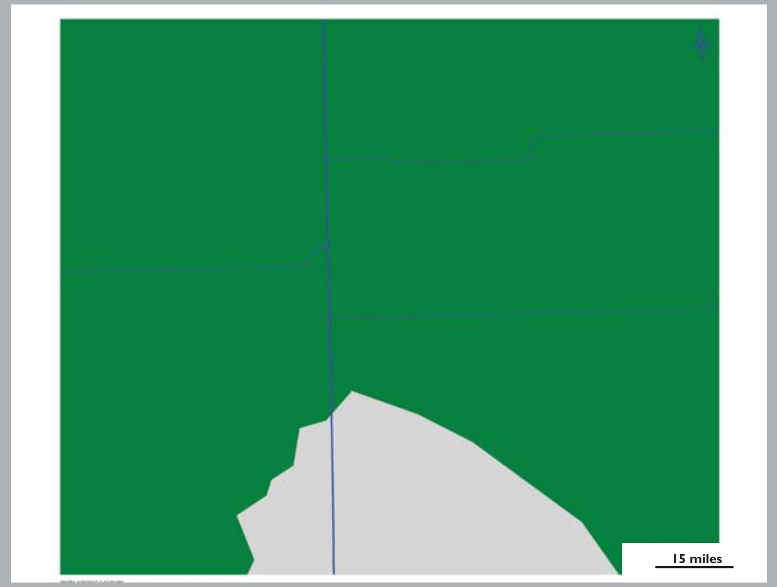
Common risk segment (CRS) mapping was undertaken to test the helium system concept and highlight potential areas for future exploration. The Entrada Formation was used as a test case due to its high helium content and remaining exploration potential.

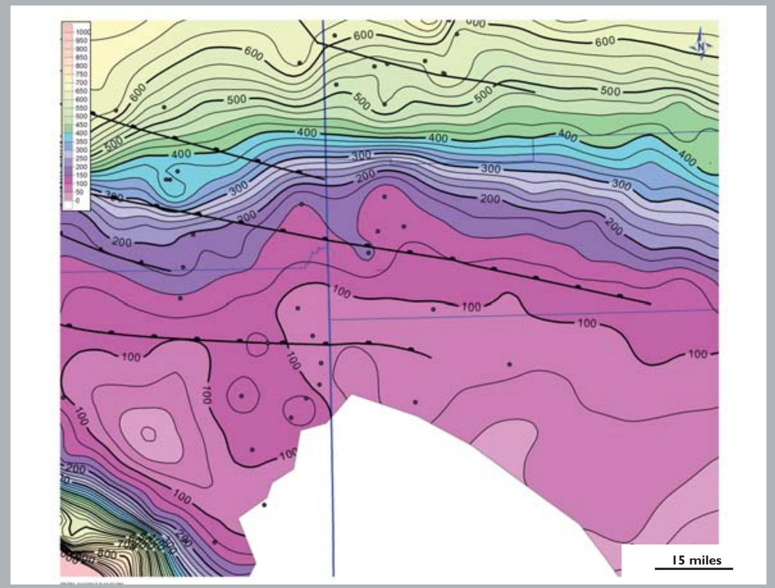
Maps were created using the helium system elements and processes defined here and based on the workflow from Grant et al. (1996) and Fraser (2010). Areas of high risk are highlighted in red, areas of medium risk are highlighted in yellow, and areas of low risk are highlighted in green. After a risk map is created for each helium system element/process, the colors are overlaid to create a composite CRS map and determine the maximum risk for a given area. Areas of higher risk trump areas of lower risk; thus, green areas on the composite CRS are considered low risk on all CRS maps.

Source Rock CRS Map

The source rock for helium is assumed to be potassium-rich Precambrian basement; however, we are unable to prove this without helium isotope.

Due to the lack of isotope data and lack of detailed basement rock maps, we assume the entire area of interest has low risk for a source rock.

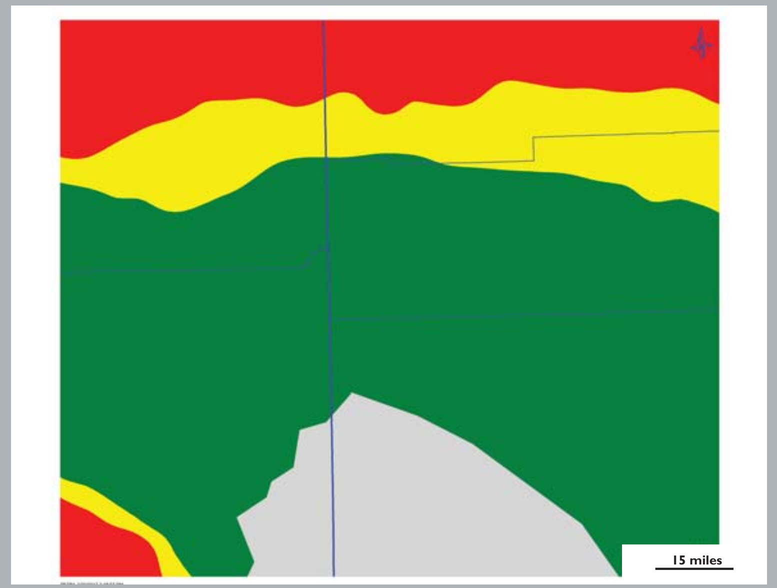


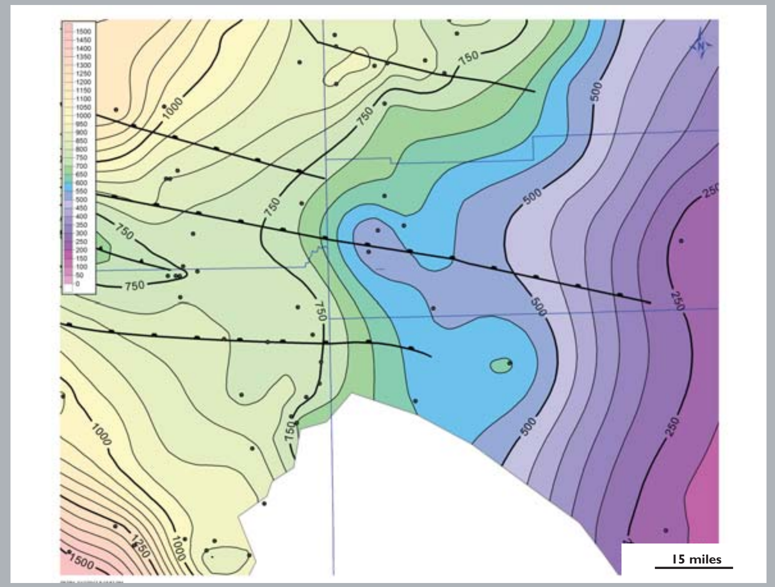


Vertical Migration CRS Map

Triassic (and older) sediments are thought to be a baffle and/or seal to vertical migration of helium; thus, we use the thickness of the Triassic section (Chinle Fm., Moenkopi Fm.) as a proxy for vertical migration. An isopach map of the Triassic can be seen at left. Contour interval = 25 feet.

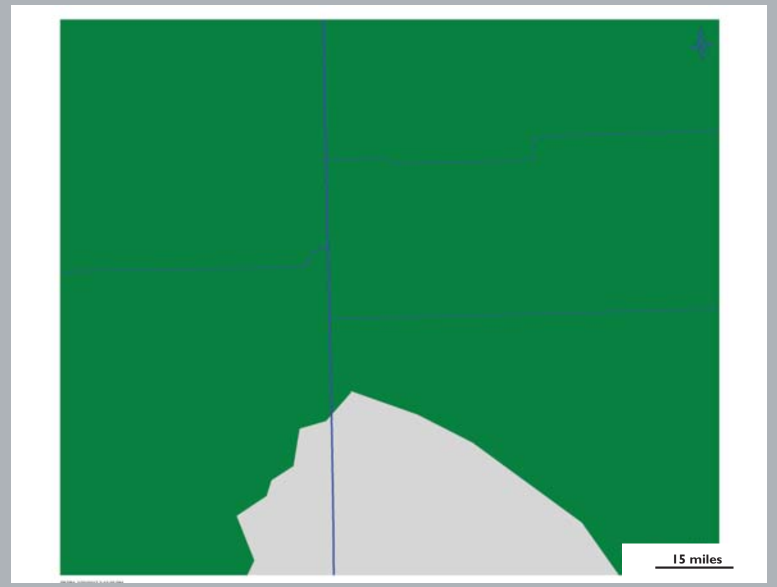
The Vertical Migration CRS map is colored green for thicknesses less than 200 feet, yellow for thickness between 200 and 500 feet, and red for thicknesses greater than 500 feet. These cutoffs were based on enrichment in the Entrada Formation as well as the Morrison and Dakota formations.

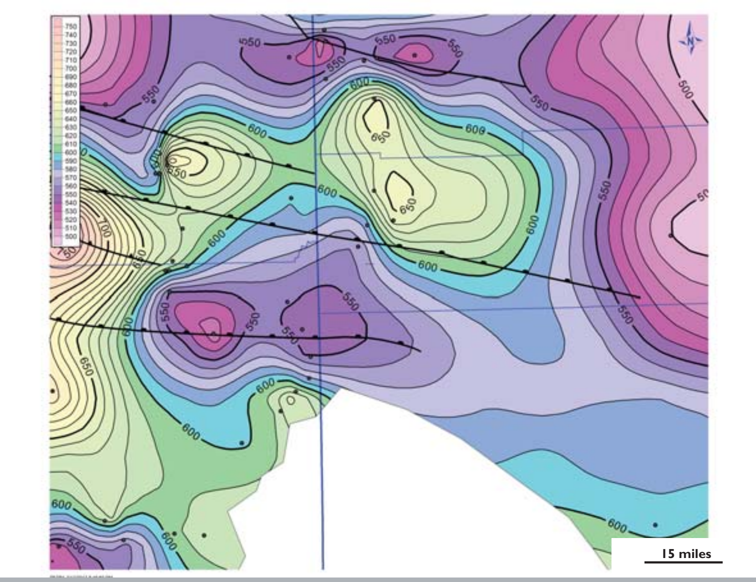




Reservoir CRS Map

The Entrada Formation is present through the area of interest and hundreds of feet thick; thus, we assign a low risk for the entire area. The Entrada Formation is a member of the larger Glen Canyon Group, a group of formations consisting primarily eolian sandstones. These formations are difficult to distinguish using well logs; thus, an isopach map of the Glen Canyon Group can be seen at left. Contour interval = 50 feet.

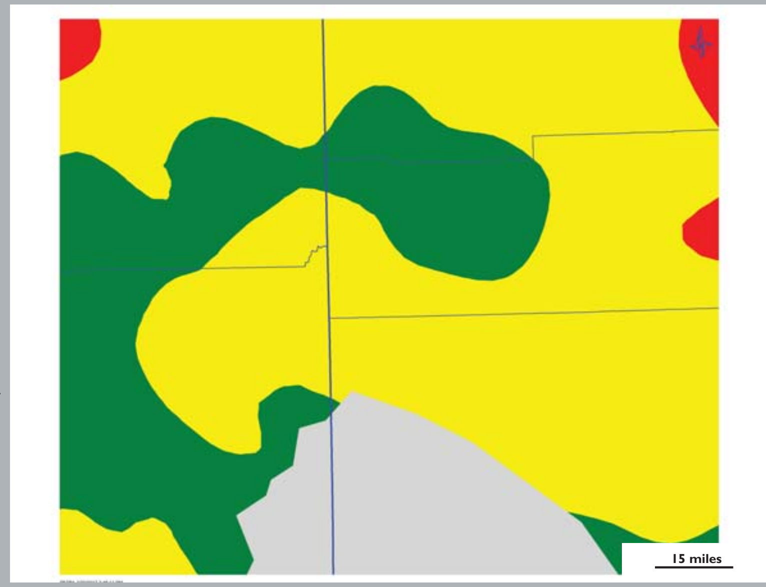


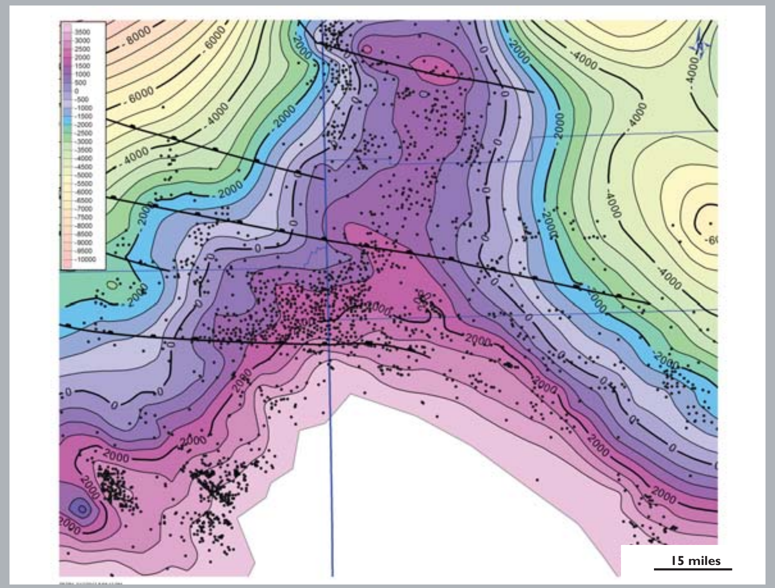


Top Seal CRS Map

Although the overlying Morrison Formation is considered a reservoir interval, the low net-to-gross sandstone appears to act as a baffle for vertical migration and a top seal for the Entrada Formation. The Cedar Mountain Formation (above the Morrison Fm., below the Dakota Fm.) can also be composed of low net-to-gross section and likely helps the Morrison trap helium in the Entrada Fm. In order to map the quality of the top seal, the Cedar Mountain Fm. and Morrison Fm. were lumped together and mapped. An isopach map (seen at left) of the combined Cedar Mountain and Morrison intervals was created as a proxy for the top seal risk. Contour interval = 10 feet.

The Top Seal CRS map (seen at right) is colored green for thicknesses greater than 600 feet, yellow for thickness between 50 and 600 feet, and red for thicknesses less than 50 feet. These cutoffs were arbitrary picks based on gas enrichment maps and subject to change.

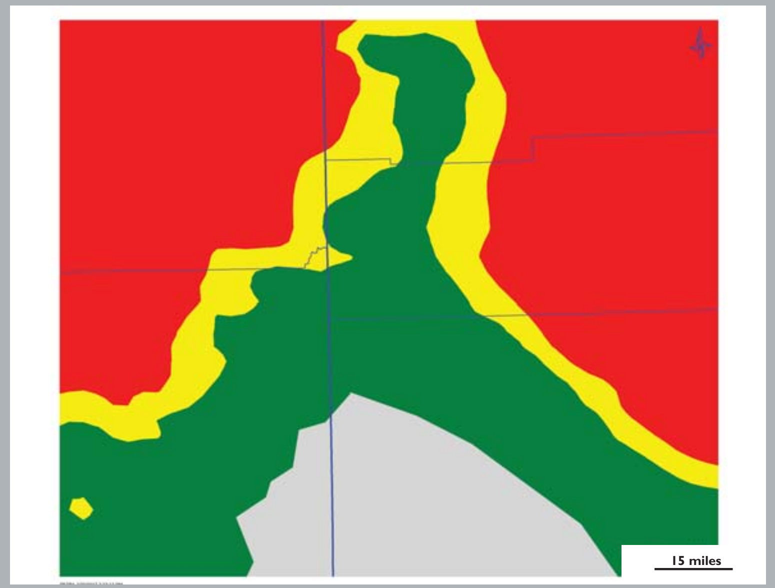


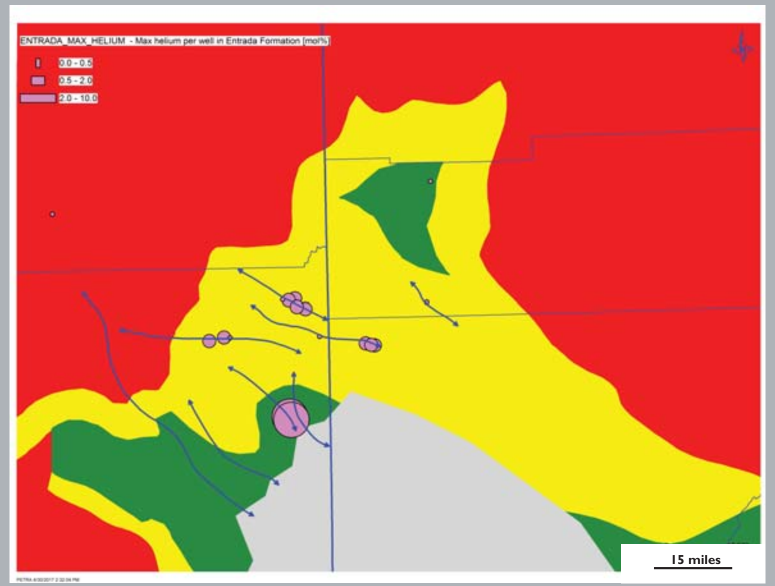


Lateral Migration CRS Map

Helium enrichment appears to be strongly correlated with basin-scale structural contours as seen in maps on the previous poster panel. In order to account for structural control, a structural contour map was created from the top of the Dakota Formation using tops from IHS (2016). The top of the Entrada was not used due to a lack of subsurface penetrations. The structural contour map can be seen at left. Contour interval = 500 feet.

The Lateral Migration CRS map (seen at right) is colored green for elevations greater than 1000 ft above sea level, yellow for elevations between sea level and 1000 ft above sea level, and red for elevations below sea level. These cutoffs were based on helium trends along the Douglas Creek Arch.





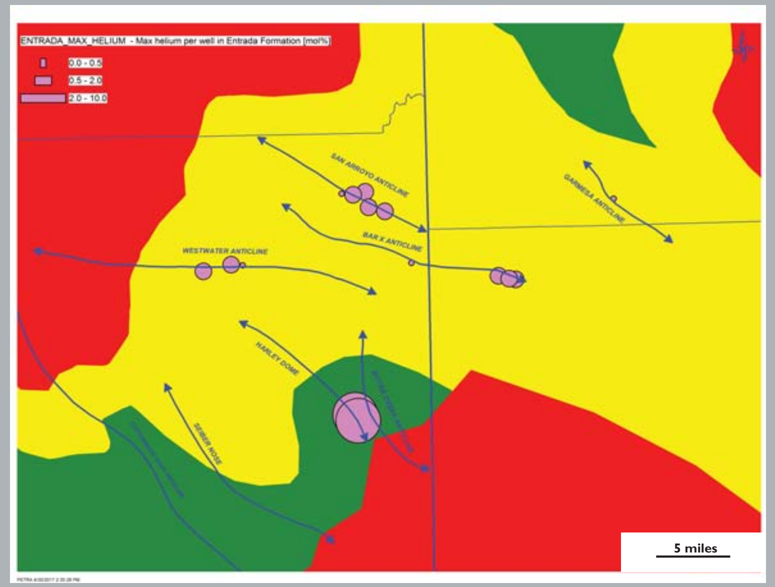
Composite CRS Map

The previous CRS maps were combined to create a Composite CRS map seen at left. A closer look at the composite map may be seen at right. Helium data and major anticlines were added in order to compare the data sets.

Using the criteria previously mentioned, most of the study area is considered high risk. This is especially true east and west of the Douglas Creek Arch basinal high.

Three distinct areas of low risk (green) can be seen. The southwest green area matches very well with previous data. These bubbles are the most helium-rich gases in the basins and belong to Harley Dome. The green area to the north has only one gas sample which does contain significant amounts of helium; however, this sample was a formation test which may explain the lack of correlation. Another green area is shown to the southeast. This area has not been tested previously and contains no data to prove or disprove the interpretation.

Most samples fall within the yellow area. These data points appear to be enriched in helium, but less so than the Harley Dome area in green. This indicates the yellow (medium risk) areas may still be a viable exploration target depending on economic factors.



Conclusions

The Uinta and Piceance basins provide a unique look at the distribution of inert gases in multiple petroleum systems. Inert gas concentrations appear to be dependent on startigraphic age and proximity to the northern Uncompahgre Uplift and Rangely Anticline. These trends can be identified on Helium vs. Nitrogren scatter plots and have been named the Uncompahgre and Uinta helium systems, respectively.

Helium and nitrogen are interpreted to source from Precambrian basement, migrate vertically to the Entrada Formation, and migrate laterally towards basinal highs until being trapped in conventional stratigraphic and structural traps. The Morrison and Cedar Mountain formations form imperfect top seals; thus, allow some inert gases to migrate into younger formations.

Additionally, the inert gas system concept (more specifically the helium system concept) was defined to formalize an exploration strategy modified from the well-established petroleum system methodology. Common segment risk mapping was then undertaken to test the applicability of these concepts for helium exploration. The resulting maps create a realistic interpretation of the data and highlight areas that may be potential targets for future exploration.

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