[PS]Formation of High Helium Gases: A Guide for Explorationists*

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Abstract

Economic helium (He) accumulations, like hydrocarbon accumulations, result from predictable processes of generation and migration. He-rich gas forms as a two step process: (1) generation/accumulation of He in pore water, and (2) interaction of pore water with gas. Radioactive decay of U and Th forms He, which then diffuses to pore water. He concentration in pore water increases with increasing U and Th concentration, increasing age, and decreasing porosity.

He is concentrated into economic gas accumulations where pore water rich in dissolved He interacts with a gas phase. Most He quickly partitions into the gas. High He concentration in the gas is favored by high He concentration in the pore water, low gas volume interacting with water, and low pore pressure where the gas interacts with the water. Once He is entrained in the gas, it migrates with the gas to traps just like other gas accumulations.

Old (Paleozoic) sediments can act as efficient He source rocks and have sufficient He generation potential to account for known economic He accumulations. He generated in the deep crust is not likely to form economic accumulations. Deeply generated He cannot migrate to traps in overlying strata unless some fluid carries it out of the basement. Most basement is devolatilized, so there are few settings where fluid is available for He transport.

The following guidelines are proposed to aid exploration for high He gases. (1) Old siliciclastic sediment, not deep basement, is the most probable source rock for economic He accumulations. Old fractured shales, arkoses, granite wash, and shallow fractured basement are good potential source rocks. (2) The pore water must be old prior to gas interaction, preferably 100 My or more. (3) Gas and water should interact at shallow depths to maximize He extraction from the water. (4) The total volume of gas that interacts with the pore water should be relatively small to avoid He dilution by later gas charge. Explore in petroleum systems with marginal hydrocarbon gas generation or near the updip limits to supercharged petroleum systems. Less gas is available in these settings, so He concentrations will not be diluted. The validity of these controls are demonstrated by geochemical interaction models and correlations of regional- and field-scale He concentrations in the southwest US.

FORMATION OF HIGH HELIUM GASES: A GUIDE FOR EXPLORATIONISTS

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SHEET 1: THEORY

ABSTRACT

Economic helium (He) accumulations, like hydrocarbon accumulations, result from predictable processes of generation and migration. He-rich gas forms as a two step process: (1) generation/accumulation of He in pore water and (2) interaction of pore water with gas.

Helium forms by radioactive decay of U and Th and diffuses to pore water. He concentration in pore water increases with increasing U and Th concentration, increasing age, and decreasing porosity.

Helium is concentrated into economic gas accumulations where pore water rich in dissolved helium interacts with a gas phase. Most helium quickly partitions into the gas. High helium concentration in the gas is favored by high helium concentration in the pore water, low gas volume interacting with water, and low pore pressure where the gas interacts with the water. Once helium is entrained in the gas, it migrates with the gas to traps just like other gas accumulations.

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The validity of these controls are demonstrated by geochemical interaction models and correlations of regional- and field-scale helium concentrations in the southwest US.

OBJECTIVES

- Review models for origin and migration of helium in natural gas accumulations.
- Model helium behavior during interaction of gas and water.
- Determine where He in economic accumulations is sourced by analysis of regional gas compositional data:
  - deep basement?
  - shallow basement?
  - sedimentary section?
- Develop predictive helium exploration models.
- Test exploration models and concepts using distribution of high-helium gases in the SW USA as reported in the USBM gas database.

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PREVIOUS INTERPRETATIONS

- Most helium in petroleum gases is generated by uranium and thorium radioactive decay (eg. Ruedemann and Oles 1929).
- Helium source rock:
  - Ruedemann and Oles (1929) favor shallow pegmatites and granite for He in Panhandle gases and radioactive minerals in sedimentary rocks for He in Kansas gases. Hydrocarbons have a source different from that of helium. Nitrogen is from air.
  - Pierce et al (1964) reluctantly favor a sedimentary source, due to insufficient basement volume.
  - Katz (1969) favored a sedimentary source. He proposes that N_2 is also derived from sediment by alpha bombardment of ammonia-bearing minerals and organic matter.
  - Nikonov (1973) favors crust source, cogenetic with argon.
  - Gold and Held (1987) conclude basement origin cogenetic with basement hydrocarbon sources.
  - Ballentine and Sherwood-Lollar (2002) interpret shallow crust origin for He and high-maturity source of nitrogen.
  - Broadhead (2005) and Maione (2004) favor basement source.
  - Mantle He contribution to some gases (many: e.g., Ballentine and Sherwood-Lollar 2002).
- Migration/localization:
  - Helium migrates upwards by diffusion and by advection with crust fluids (e.g. Ballentine and Burnard 2002). It is trapped where helium flux is focused and high and where effective seals (especially evaporites) are present.
  - Transport by groundwater, demonstrated by Ne, Ar isotopes for Panhandle/Hugoton field (Ballentine and Sherwood-Lollar 2002).
  - Basement faults and fractures localize vertical He migration (e.g. Nikonov 1973, Gold and Held 1987, Broadhead 2005).

Exploration strategy suggested by Previous Interpretations

- Explore in reservoirs near major basement faults cutting old, granitic basement rocks. Traps with evaporite seals and active aquifers.

INTRODUCTION

Distribution of helium-rich gas accumulations is controlled by the same types of processes that control distribution of conventional oil and gas accumulations: generation, migration, and trapping. The interaction of gas and water has a much greater influence on helium accumulation than accumulation of conventional gas. Therefore, so concepts have to be utilized for helium exploration that may be unfamiliar to some explorationists.

The purpose of this poster is to review the processes that lead to high helium natural gases and to develop general concepts that can be used to guide helium exploration. These concepts will be tested against settings where high and low helium gases occur in the southwestern United States. Of special interest is the nature and generalized location of helium source rocks.

Summary Model (Figure, Right)

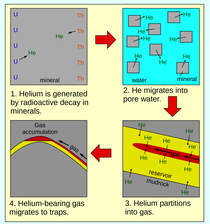
(1) Helium is generated from radioactive decay of uranium and thorium in mineral grains. Helium generation is a function of time and concentration of precursor elements (U, Th).

(2) Helium transfer from solid grains into pore water. Most helium accumulates in pore water. Old, stagnant water collects more helium than young, hydrodynamic water.

(3) Helium partitions into a gas phase as soon as the gas comes in contact with the water. This is the step that determines the helium concentration in the gas.

(4) Once helium is in the gas, it migrates with the gas to traps. This process is identical with conventional gas trapping, and the helium concentration is altered only by dilution or mixing.

Steps 3 and 4 may be reversed. See below.



GENERATION IN MINERALS

A small fraction of the helium in economic accumulations is primordial; most of the helium is generated by radioactive decay of uranium and thorium and their daughter products. Uranium and thorium occur predominantly in mineral grains, not pore water. Thus, helium is generated in minerals. Radioactive decay is independent from temperature and pressure. Uranium and thorium have such long half-lives that generation can be considered linear with time. The total helium generation can be estimated from the uranium and thorium concentration and time:

He (STP cc He/g rk) = (1.22E-13*ppm U + 0.292E-13*ppm Th)*T, y (STP = 0°C, 0.1 MPa) or

He (mcf/acre-ft) = (1.49E-5* ppm U + 3.57E-6* ppm Th) * T, My (assumes 2.65 g/cc density, no porosity, and STP = 60° F and 1 atm)

Typical Generation Rates (Figure Below)

Helium generation in typical (average) rocks are shown as a function of time of generation (below). Hot shales have by far the greatest generation potential, with a generation rate about 8 times higher than average shale. Typical sandstones and carbonates have less generation potential than average shales. Average shales have the generation potential of average granites. These calculations are approximate because they are based on average rock compositions and assumed bulk density.

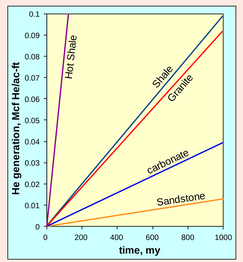
Rates of generation are low. It therefore takes significant geological time to generate significant helium per volume of rock. This means that (1) source rock volume must be large, and (2) there must be some concentration mechanism that allows dispersed helium generation to be concentrated.

Helium generation is trivial compared to gas generation. For example, a shale with minimum petroleum source rock potential (S_2^0 = 2 mg HC/g rk) generates approximately 377 scf of hydrocarbon gas per ac-ft, over three thousand times greater than helium generation in typical shales after a billion years. Any rock generating hydrocarbon gases would dilute helium to sub-economic levels. Petroleum source rocks are not helium source rocks.

Average Rock Concentrations, wt ppm

Rock	ppm U	ppm Th
granite	3	13
shale	3.7	12
sandstone	0.45	1.7
limestone	2.2	1.7
Hot Shale	50	12

Concentrations from Turekian and Wedepohl (1961), except for the hot shale, which is an unpublished Woodford analysis from spectral GR log.



Implications:

- Sedimentary rocks have similar source potential to basement rocks. Both are "lean" source rocks. A large rock volume and relatively long geological time is required to generate potentially economic amounts of helium.
- Thermally mature petroleum source rocks cannot be helium source rocks.

FROM MINERALS TO PORE WATER

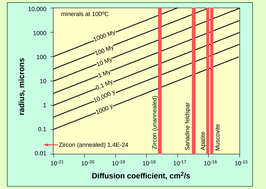
Mechanisms and Rates

Helium moves to pore water by mineral recrystallization and diffusion. Recrystallization/dissolution will release essentially all of the generated helium at the time of recrystallization. Diffusion is driven by equilibrium of helium chemical potential, so helium diffuses to pore water even where helium concentration in pore water is higher than that in the mineral. Diffusion rate is controlled by the diffusion coefficient divided by the diffusion length squared. The diffusion coefficient increases with temperature following an Arrhenius relationship.

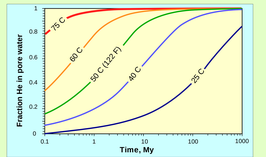
Helium diffuses through the unaltered mineral and along fission tracks. Diffusion coefficients of interest are those of uranium-bearing species: uraninite, apatite, zircon, etc. At 100°C, 90% of the helium is released from most minerals in less than 10 My (upper figure, right). This assumes no helium production as helium is lost. Where helium loss is considered concurrent with helium generation in apatite (middle figure, right), helium is released almost as fast as it is generated at diagenetic temperatures (>50°C).

Alpha particle fission tracks in most sedimentary minerals are zones of crystal damage with elevated diffusion coefficients. Such tracks are approximately 20 microns long in most sedimentary minerals (Ballentine and Burnard 2002). Essentially all fission tracks extend to the grain surface of medium silt to mud-sized grains. Such small grains are likely to lose helium relatively rapidly. The effect of fission tracks on diffusion is demonstrated by comparing zircon diffusion in annealed (undamaged) crystals to that in unannealed crystals (upper figure, right).

Implication: detrital minerals can lose helium to pore waters at diagenetic temperatures, either as they recrystallize or by diffusion.



Time needed to diffuse 90% of the helium from a mineral at 100 °C as a function of diffusion coefficient and grain radius. Figure modified from Ballentine and Burnard (2002). Zircon diffusion from Reiners (2005).



Helium generation from an authigenic apatite, assuming that generation and diffusion are simultaneous. Model conditions: 3 ppm U and 10 ppm Th, constant temperature, 50 micron grain radius, Wolf et al. (1996) apatite kinetics.

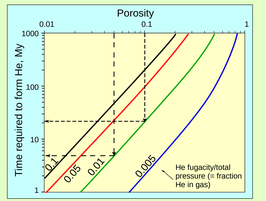
Porosity Controls on Helium Concentration

If essentially all helium is transferred from solid minerals to pore water, then it follows that the less volume of water per volume of mineral, the greater the concentration of the helium in the pore water. In other words, more helium is concentrated into less water where total porosity is low. This results in higher helium concentration in water and in any gas equilibrated with that water.

In the figure at right, the concentration of helium in pore water is plotted as a function of fractional porosity (horizontal axis) and time (vertical axis). The helium concentration in the water is plotted as helium fugacity divided by total pressure. This is equivalent to the mole fraction of helium in an infinitesimal volume of gas equilibrated with the water. For example, the time needed to form water with helium concentration sufficient to form a 1% He gas in a rock with 10% porosity is about 22 My. Where porosity is 5%, water with helium concentration sufficient to form 1% He gas would form in only 5 My.

This demonstrates that exceptionally high U and Th concentrations and long generation times are not needed to form high helium concentrations in gas. On the other hand, high-porosity He source rocks require exceptionally long times to generate sufficient helium to form a gas with high helium concentrations.

Porosity only affects the maximum concentration possible in a gas equilibrated with the water, not the total amount of helium generation. The total helium generation is not a function of porosity.



Model conditions: 3 ppm U, 10 ppm Th, 1 km burial (10 MPa, 50 °C), 4 molar NaCl brine, closed system, infinitesimal gas volume

Implications:

Helium concentration in water sufficient to generate high helium gas can form in a relatively short time (tens of millions of years) from rocks with U and Th concentrations similar to that of average shale. Low porosity in helium source rocks favor high helium concentrations in the gas.

GAS-WATER INTERACTION

Helium Partitioning Between Water and Gas

Helium dissolved in pore water stays dispersed in the water; it cannot concentrate to charge the trap. Helium becomes concentrated by interacting with a gas phase. The amount of helium in a gas coexisting with helium dissolved in water is described by Henry's law:

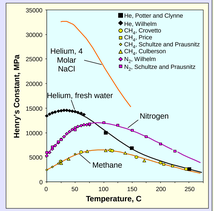
$$X_{He} = \lim_{f_{He} \to 0} \frac{f_{He}}{H_{He}}$$

Where f_{He} is the helium fugacity. Fugacity is approximately the partial pressure, the total pressure times mole fraction of helium in the gas. X_{He} is the mole fraction of He in water, and H_{He} is the Henry's constant for helium in water. The Henry's constant is a function of temperature and water salinity.

Henry's constant is always much greater than 1 (figure above right), so helium is naturally concentrated into the gas phase. The larger the Henry's constant the greater fraction of the total helium is in the gas phase.

Helium is less soluble (larger Henry's Constant) than N_2 and methane at diagenetic temperatures. At metamorphic temperatures, nitrogen is less soluble in water than helium.

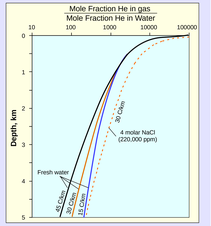
Lower curves are gas solubility in fresh water. The upper (orange) curve is Helium Henry's constant in high salinity water. Salinity decreases gas solubility (increases Henry's constant). Salinity decreases nitrogen and methane solubility about as much as it affects He solubility.



He Fractionation with Depth and Temperature

The Henrys constant, combined with temperature and pressure changes with depth, can be used to predict the ratio of the mole fraction of helium in a gas to that in water as a function of depth and thermal gradient:

- Pressure has a major effect on helium distribution. More He fractionates into the gas phase in shallow reservoirs than in deep reservoirs. Lower fluid pressure gradient (underpressure) favors more helium in gas.
- Thermal gradient has a minor effect on helium distribution. More helium is in the gas phase where thermal gradients are cooler than where they are hotter.
- More helium is in the gas phase where pore water has a high salinity.

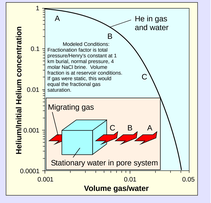


Dilution and Source Depletion During Gas Migration

Henrys law describes molar concentration equilibrium between two static phases. The concentrations equilibrate, so the actual mass of helium in each phase depends on the mass of each phase. Where gas has less mass than water, the concentration of helium in the gas in the water will be higher.

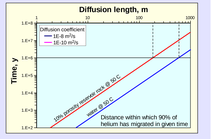
Where gas migrates through water, the situation is a bit more complex. The first bit of gas interacting with the water picks up most of the helium. The helium concentration in this gas will be greatest because it equilibrates to water with maximum helium concentration. The migrating gas removes helium from the system, so later gas migrating through the water-saturated reservoir will see lower concentrations of helium dissolved in the pore water. These gases will therefore pick up less gas and their concentration of helium will thereby decrease. This process continues as described by the figure at right.

Gas extracts helium from pore water not directly in contact with the gas. As dissolved helium is extracted from pore water, helium dissolved in pore water of adjacent rocks diffuses towards the migrating gas. Assuming diffusion time scale of 1 million years, 90% of helium dissolved in a rock thickness between 200 and 500 m above and below the migrating gas is extracted by the gas (lower right figure).



Implications:

- Most helium and nitrogen in pore water fractionates into migrating gas, even gases dissolved in pore waters of shales adjacent to the gas carrier beds. This process concentrates helium in the gas and causes the helium/nitrogen correlation in most high helium gases.
- High helium gases are more likely to form at shallow depth rather than deeper in the earth. Cool thermal gradients favor higher helium in gases.
- The less gas relative to water, the greater the helium concentration in the gas.



FORMATION OF HIGH HELIUM GASES: A GUIDE FOR EXPLORATIONISTS

SHEET 2: TESTS OF THEORY

PREDICTIONS FROM THEORY

- **HELIUM SOURCE DIFFERENT FROM HYDROCARBON SOURCE**. Helium-rich gases develop by the interaction of helium-rich water and gas. Co-generation of helium and with methane in even the leanest source rock would dilute helium concentration to uneconomic levels.
- **SEDIMENT OR BASEMENT SOURCE**. Sedimentary shales and granites have equal helium source potential. Either could be a source. Sediment is closer to traps, but basement has a larger source volume.
- **OLD WATER**. Generation time needed to form high helium gases is on the order of tens of millions of years. Hundreds of millions of years are needed to form the amounts of helium observed in some accumulations. This means that high helium gases are most likely to be associated with old pore water, on the order of hundreds of million years. The age of the water in the rock is more important than the age of the rock itself. The water ages are poorly known, so look for old reservoirs with saline pore water.
- **SHALLOW DEPTH**. High helium gas is most likely to form by gas interaction with water. More helium is partitioned from water into gas at low pressure, high salinity and cool temperature. These conditions are more likely to occur in shallow reservoirs than deep reservoirs.
- **LOW HC GENERATION**. High helium concentrations result from low gas to water ratio. This occurs in two settings. One setting is where total gas volume is small due to minor generation of hydrocarbon gas **or**
- **EDGES OF PROLIFIC PETROLEUM SYSTEMS**. The first gas strips most helium from pore water. This gas is the gas that migrates to the up-dip end of a migration chain. High helium gas is most likely to occur at the margins of prolific petroleum systems, either geographically or stratigraphically.

These concepts are tested on a regional scale in the this panel. The last panel will summarize exploration models and use field and area examples to test these models.

DATA

Basic exploration concepts are tested using the USBM helium resource assessment gas database as preserved in the USGS gas geochemistry dataset. These data are available online for download at http://energy.cr.usgs.gov/prov/og/data2.htm (as of October 2008). The downloaded gas compositional dataset was merged with location data set into a single file. These data are filtered to remove seep analyses, solution gases, and data that do not sum to close to 100%.

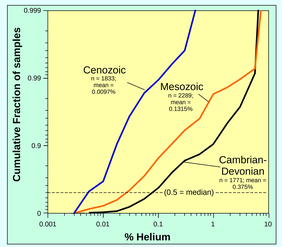
The USBM data were collected for helium resource assessment; as such, the dataset is biased towards areas and reservoir ages with higher helium concentrations, namely gases in the SW USA and gases from early Permian reservoirs. Permian and Pennsylvanian gases were therefore removed from regional assessement to avoid this bias.

This data set includes about 40% historic (pre mass spectrometer) analyses based in part on hydrocarbon combustion. Most of the rest of the USBM analyses are mass spectrometric measurements. Results are reported as mole percent. These older analyses do not report reliable concentrations of C2+ hydrocarbons. The older helium and nitrogen analyses are relatively reliable although not as precise as modern gas chromatographic analyses. As such, they are suitable for regional reconnaissance such as that done here.

AGE VS. HELIUM CONCENTRATION

Helium is present in gases of all ages. Most gas samples, regardless of age range, have low helium concentrations (Figure below). As reservoir age increases, the median and average helium concentration increases and the fraction of gases with high helium increases. The greatest helium concentration difference is between Cenozoic gases and older gases.

This effect could be the result of either the reservoir age or the age of the pore water with which the gases had equilibrated. Given that reservoirs typically have lower source potential than argillaceous rocks, it is more likely that this age effect is related to age of the pore water at the time of gas migration, not the reservoir age.



(above): Plot of cumulative frequency of gas samples of stated age range (vertical axis) against helium percentage (horizontal axis). The cumulative frequency is that of gases with helium less than the helium percentage. USA data only.

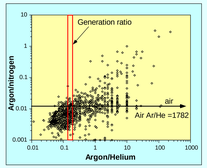
GAS COMPOSITION

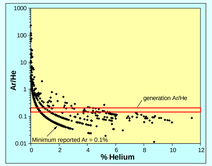
Another trace gas, argon (^{40}Ar), is a product of radioactive decay of potassium and comprises most Ar on earth. The ratio of ^{40}Ar to ^{4}He generation in granites and shales is about 0.14 to 0.2. Argon diffuses much slower than helium in minerals at diagenetic temperatures, so ratios of Ar/He (= ^{40}Ar/^{4}He) near the generation ratio are interpreted as evidence of deep crust (hot) origin; lower ratios are expected where Ar remains trapped at cool temperatures. Higher ratios are expected in potassic environments where diagenesis releases trapped gases (such as sandstones). Argon is also very abundant in air.

On a plot of argon/helium vs. argon/nitrogen, two trends are seen (upper figure).:

- Ar/N_2 correlates with Ar/He with a slope near 1:1. This indicates that Argon is independent from both nitrogen and helium.
- The other trend has relatively constant Ar/N_2 near 0.011 and elevated Ar/He. This is caused by air contamination, probably in the sampling process.

The Ar/He ratio decreases as helium increases (lower figure, right). This characteristic is expected where the argon concentration has little correlation to helium concentration. The Ar/He ratio intersects the generation ratio at the lower end of the economic helium concentrations. Most low He gases have Ar/He greater than generation; the very high helium gases have ratios lower than the generation ratio. (cautionary statement: about 2/3 of the 12,700 analyses in the USBM database do not report argon concentrations. This typically means Ar < 0.1%.)

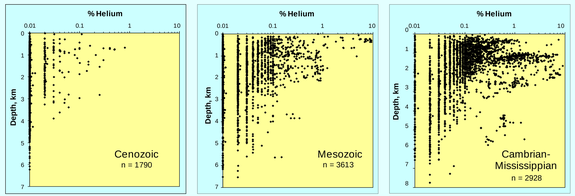




This behavior argues against a hot (deep) crust origin.

DEPTH (PRESSURE) CONTROLS

Due to age effects, the helium - depth distribution has to be analyzed over age ranges. In any generalized age range, helium concentrations peak near 0.5 km and decrease with increasing depth.

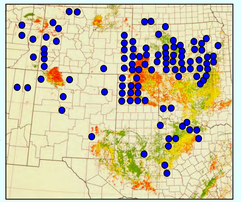


There are only two high helium gases (He >0.5%) reported from Cenozoic reservoirs (left figure, below), both of which were sampled at depths shallower than 1 km. Mesozoic reservoirs (middle figure) contain high helium gases down to about 2 km. Paleozoic reservoirs (right figure) contain high helium concentrations down to about 5 km. All Paleozoic gases with high helium at depths below 4 km are associated with the Riley Ridge field area, Montana.

PETROLEUM VS. HELIUM DISTRIBUTION

(Figure at right) The distribution of high helium gases is vs. distribution of oil and gas fields. Each blue dot represents a county with at least one gas sample with helium concentrations in excess of 0.7%. This mapped area includes about 96% of all gas analyses with high helium in the USBM database. Petroleum field distribution from Mast, et al. (1998).

Several patterns are evident:



(1) High helium gases are rare or sparse in centers of prolific gas basins such as the Delaware basin, San Juan basin, Piceance basin, and Anadarko basin. In rich petroleum basins with a few high-helium gases (e.g., greater Midland basin), high-helium gases occur in zones with less petroleum production or have exceptionally high nitrogen content.

(2) High helium gases occur peripheral to some gas basins (e.g., Anadarko and San Juan basins), but not other basins (e.g., Permian basin).

(3) Many high helium gases are from basins with little petroleum production. not associated with prolific petroleum basins.

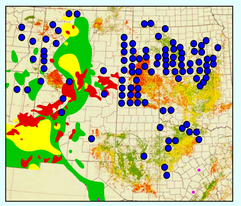
(4) Some younger sedimentary basins, (e.g., Gulf of Mexico and Denver-Julesburg basins), have no high-helium gases.

Interpretations: (1) In older basins, prolific methane generation dilutes helium concentrations to sub-economic levels. (2) Gases near the margins of basins are those that first interact with water during migration, so these are the most likely to pick up helium during long-distance migration. (3) Helium can be entrained in other gases besides methane gases. (4) Younger basins do not have sufficient age to generate high-helium gases. These interpretations support an interpretation where helium is not co-genetic with hydrocarbon gases. They can occur together (if not diluted by excessive methane generation, but they need not be associated with each other.

VOLCANICS VS. HELIUM

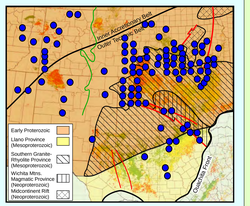
The map at right compares distribution of high helium gases (> 0.7%) to distribution of shallow igneous bodies in the southwestern USA (after Christiansen 1992). Shallow Cenozoic and Mesozoic igneous rocks are absent in Kansas, Oklahoma and Texas east of the Pecos River and west of the Ouachita front. Late Cretaceous igneous bodies are present in areas mapped as green in Colorado and SE Arizona.

Helium shows no obvious relationship to regional distribution of igneous bodies. Note especially that most high helium gases occur east of the Laramide and younger igneous rocks.



BASEMENT VS. HELIUM DISTRIBUTION

The map at right compares helium occurrence and basement geology. The following correlations between helium occurrence and basement are possible in this area: (1) High helium gases are absent in areas where basement is Paleozoic accreted terrane (south and east of Ouachita front). This may be a function of sediment age rather than source area. (2) High helium gases appear to be associated with basement faults bounding inversion of the Oklahoma Aulacogen. This is not true of other basement faults. This association may be fortuitous related to shallow depth of reservoirs and limited charge compared to areas north and south.



Distribution of high helium gases to basement type (geology after Van Schmus et al. 1993). Blue dots are counties with at least 1 gas analysis with He >0.7%. Red lines: major basement fault/fracture zones. Green line: approximate Rocky Mountain front. Faults associated with Tertiary basin-range faulting and the Rio Grande Graben are not shown.

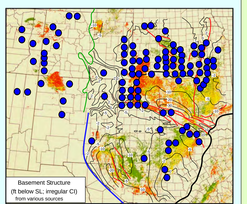
Interpretations: Distribution of helium-rich gases does not obviously correlate to basement province, basement age, proximity to major basement faults, or basement tectonic type. The only observed correlation, that to pre-Phanerozoic aged basement, may be fortuitous because basement age correlates to age of strata above basement.

Regional basement geology does not appear to be a major control on the regional distribution of high-helium gases. One reason why this may be the case is discussed at right.

BASEMENT HIGHS VS. HELIUM

Map comparing top basement structure (Contours) in areas east of the Rocky Mountain front (Green line) and Basin-Range front (Blue line). Contours are thousands of feet below sea level. Red lines are generalized basement faults.

There is some correlation between high helium gases (blue dots) and basement highs in central Kansas. Basement structure reflects structure of overlying carrier beds, so this correlation may be fortuitous and indicative of gas migration patterns.



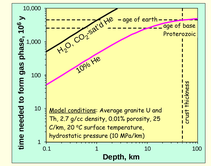
Blue dots are counties with at least 1 gas analysis with He >0.7%. Structure is generalized and from many sources.

MIGRATION EVIDENCE FOR HELIUM SOURCE

HELIUM MIGRATION FROM THE BASEMENT

Helium generated in the deep crust must migrate to the shallow subsurface to charge traps and mix with hydrocarbon gases. There are three possible mechanisms:

- **Diffusion**. Widely accepted to be ineffective due to long distances due to km-scale migration distances.
- **Bulk fluid flow**. Two possible fluids: melt and water. Not effective in cratonic areas due to absence of melt and water flow from crust and dehydrated nature of deep crust.
- **Two-phase flow**. Buoyancy drives flow of low density fluid in pore spaces. This is the most likely mechanism for flow from the deep crust. Requires formation of a fluid less dense than water, such as gas or CO_2. Such a fluid forms where their fugacities sum to the total pressure. Results for such models are shown at right for low temperature gradients characteristic of cratons.



Two conditions are modeled: (1) helium, steam, and CO_2 are the only volatile species, and (2) some unknown gas species is available such that helium fugacity has to be only 10% of the total pressure to form a gas phase (unlikely but optimistic). The vertical axis is the time needed to generate sufficient helium to saturate water in a rock with 0.01% porosity, and the horizontal axis is the depth. Model 1 requires time greater than the age of the earth to form a gas phase, at 1 km or deeper by helium generation. Model 2 requires helium generation for about 2.5 billion years to form a gas phase at depths greater than 10 km. This is older than the age of the basement in the midcontinent. In other words, a helium-rich gas phase cannot form in the deeper crust in the stable craton. Helium cannot migrate to shallow depths in a gas phase.

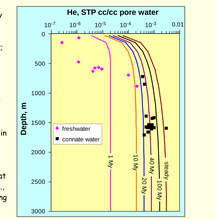
Helium can migrate to the surface from the deep crust and mantle in magmas and immiscible CO_2-rich fluid where heat flow is high. Both require the high heatflow typical of continental margins and active rifts. These transfer mechanisms appear to be ineffective for forming economic high helium gases, because no economic high-helium gas accumulation has been found in arc systems or in active rift systems.

HELIUM FORMATION IN STRATA

Models can be used to estimate the generation and migration of helium as a function of depth in a sedimentary column (Right). Helium concentration increases with depth due to the less loss of helium to the surface by diffusion. The base of the model is assumed to have zero helium flux; that is, no helium supplied from the basement.

The modeled helium concentration are consistent with observed helium concentrations in pore water 20 - 100 million years old (Right). Lines are expected helium concentrations for different generation duration. Symbols are helium concentrations measured in the Paris basin (Castro et al. 1998). Black squares are concentrations in saline ("Connate") pore waters, whereas pink diamonds are in fresh and brackish waters.

Trend for sampled saline pore water follows trend expected for source entirely within the sediment column with zero basement flux. Relatively young age indicates that assumed helium generation in sediment is a bit too high; i.e., average Vshale < 1. The freshwater samples show decreasing concentration with shallower depth related to younger age of hydrodynamic, meteoric waters.



Model assumptions: typical shale U and Th concentration, 3000 m sediment column, 2.6 g/cc density, 10% porosity, 0.835E-9 m^2/s effective diffusion coefficient for He dissolved in pore water of a porous medium. For comparison, He diffusion coefficient in water at 60C is 1.23E-8 m^2/s.

Conclusion: Helium in sedimentary basin pore water can be explained entirely from a sediment source without calling on basement. Deep basement in cratonic areas cannot supply helium to the sedimentary section. The helium in pore waters in cratonic basins is therefore predominantly supplied by the sedimentary section and the upper km or so of basement.

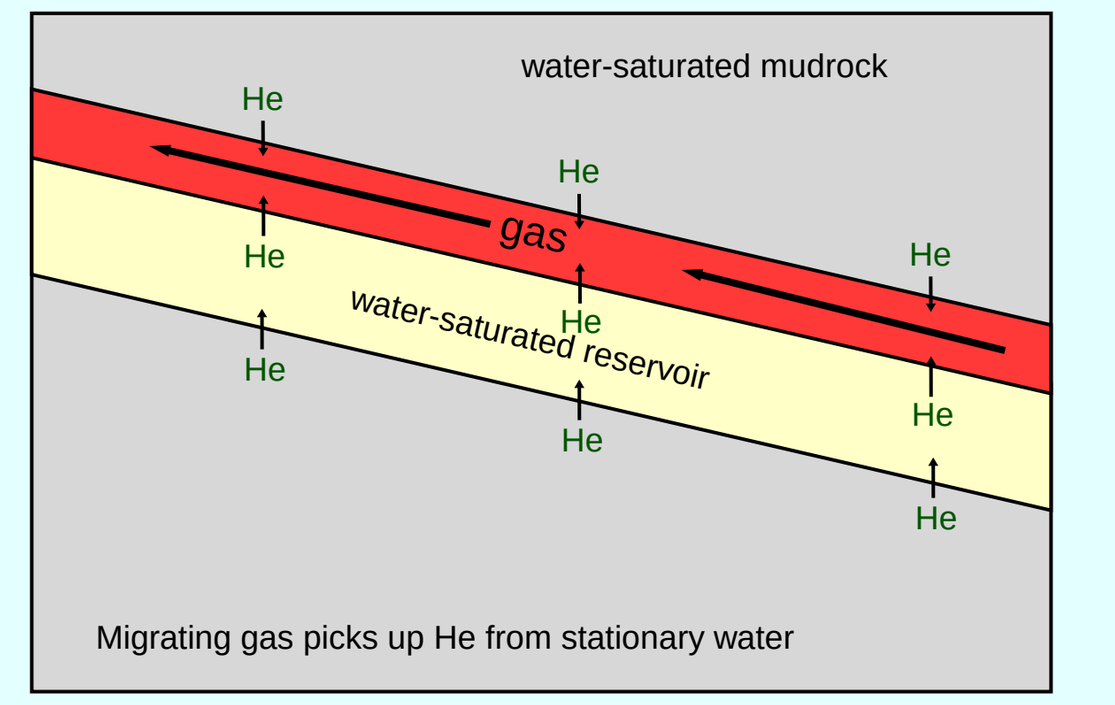
AAPG Annual Convention, New Orleans, April 2010

FORMATION OF HIGH HELIUM GASES: A GUIDE FOR EXPLORATIONISTS

SHEET 3: EXPLORATION MODELS

MODEL 1: HELIUM ACQUIRED DURING MIGRATION

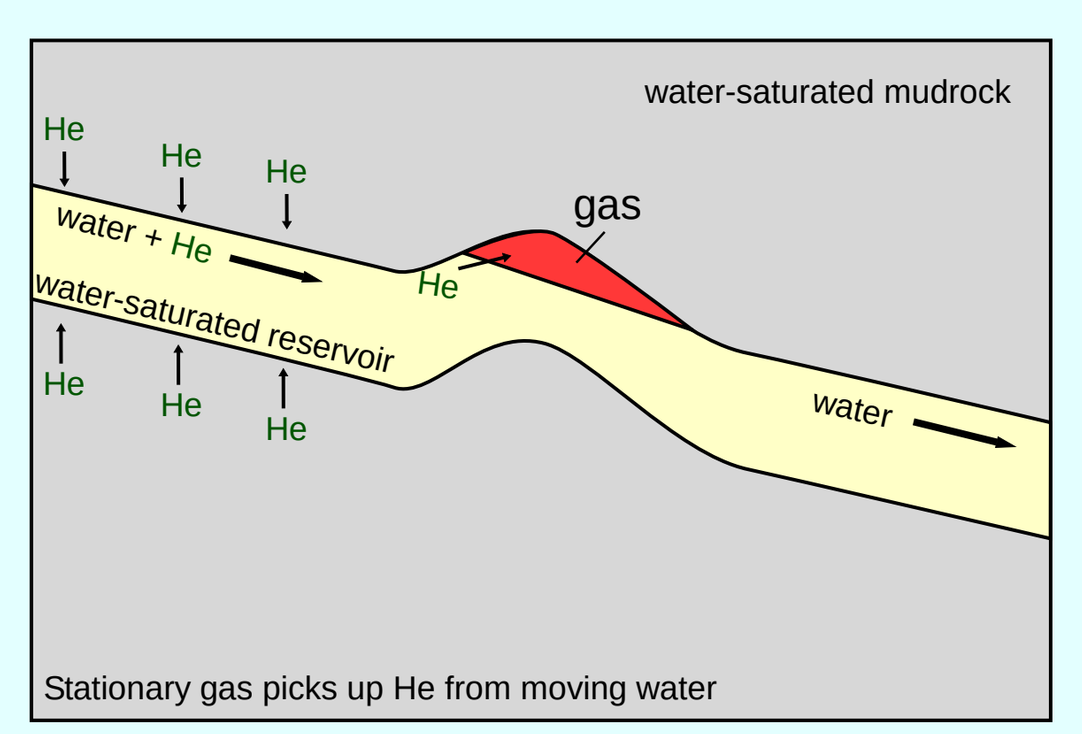
Gas migrates through old water that has accumulated high helium concentrations from the reservoir or surrounding shales. Gas extracts helium dissolved in the reservoir pore water. As reservoir pore-water helium concentration decreases, helium in the surrounding reservoir and shales diffuses towards the migrating gas. Rocks with 10% porosity or more within 100 to 300 m of the migrating gas lose 90% of their stored helium to the gas. Gas migrating through reservoirs over a duration of about 1 My extract most of the helium and nitrogen dissolved in the carrier bed and adjacent shales and carry it with them to the trap.



Key criteria for forming high helium gas:
- Rock with moderate to high U, Th
- Pore water is old at time of gas migration (>100 My)
- Moderate to low porosity along migration pathway
- Low volume of migrating gas, either by low HC generation or by location at leading edge of migrating gas.

MODEL 2: HELIUM ACQUIRED AFTER MIGRATION

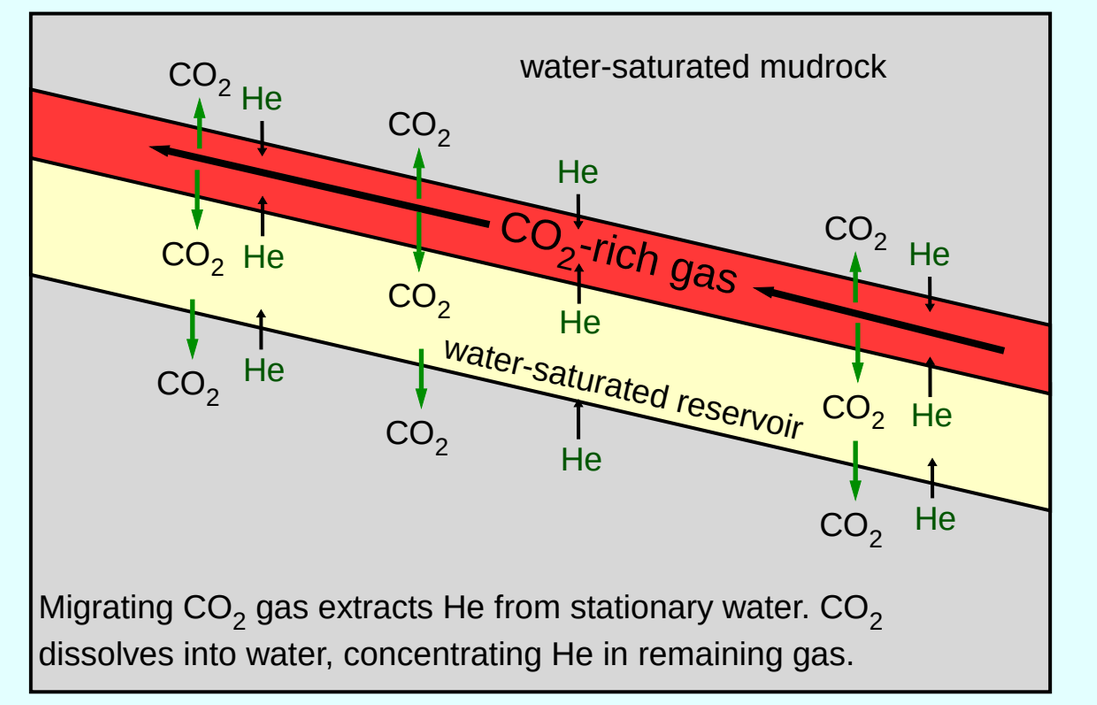
A pre-existing gas accumulation can gain helium by interacting with moving pore water with high dissolved helium content. Gas extracts helium dissolved in the reservoir pore water as it moves under the gas and through the transition zone. Most helium is lost at the up-flow end of the gas accumulation, because helium in water decreases down flow as it is lost to the gas. The moving water must be old and high in helium. These conditions develop where updip recharge of meteoric water displaces old, saline pore water down dip. This mechanism works best where the aquifer is thick, because the moving water must contain all of the helium.



Key criteria for forming high helium gas:
- Hydrodynamic conditions where old, saline, helium-rich water moves under gas accumulations.
- Thick reservoir unit and long duration of hydrodynamics. Large volumes of water are needed.

MODEL 3: CO_2-MEDIATED HELIUM CONCENTRATION

CO_2-rich gas forms near intrusives from either mantle or decarbonation source. The CO_2 gas migrates updip or through fractures/faults just like other gases. The CO_2 gas picks up helium, nitrogen, and methane dissolved in pore water as it migrates, so He and N_2 increase with migration. The total gas volume decreases with migration as CO_2 dissolves into pore water and reacts with minerals. If migration interacts with a sufficiently large volume of carrier bed, almost all CO_2 is removed from the gas by reaction, leaving a gas rich in nitrogen, helium, and trace hydrocarbons. The maximum helium concentration by this mechanism is controlled by the concentration ratio of helium to N_2 in the pore water. Helium concentration can be exceptionally high.



Key criteria for forming high helium gas:
- Igneous intrusions that form high CO_2 gases from either decarbonation or mantle sources.
- Intrusion into or below old sedimentary rocks with good helium generation potential that have not been swept by thermogenic gases.
- Sufficient migration distance for helium to accumulate in the CO_2 gas and for the CO_2 to react with the carrier bed during migration.

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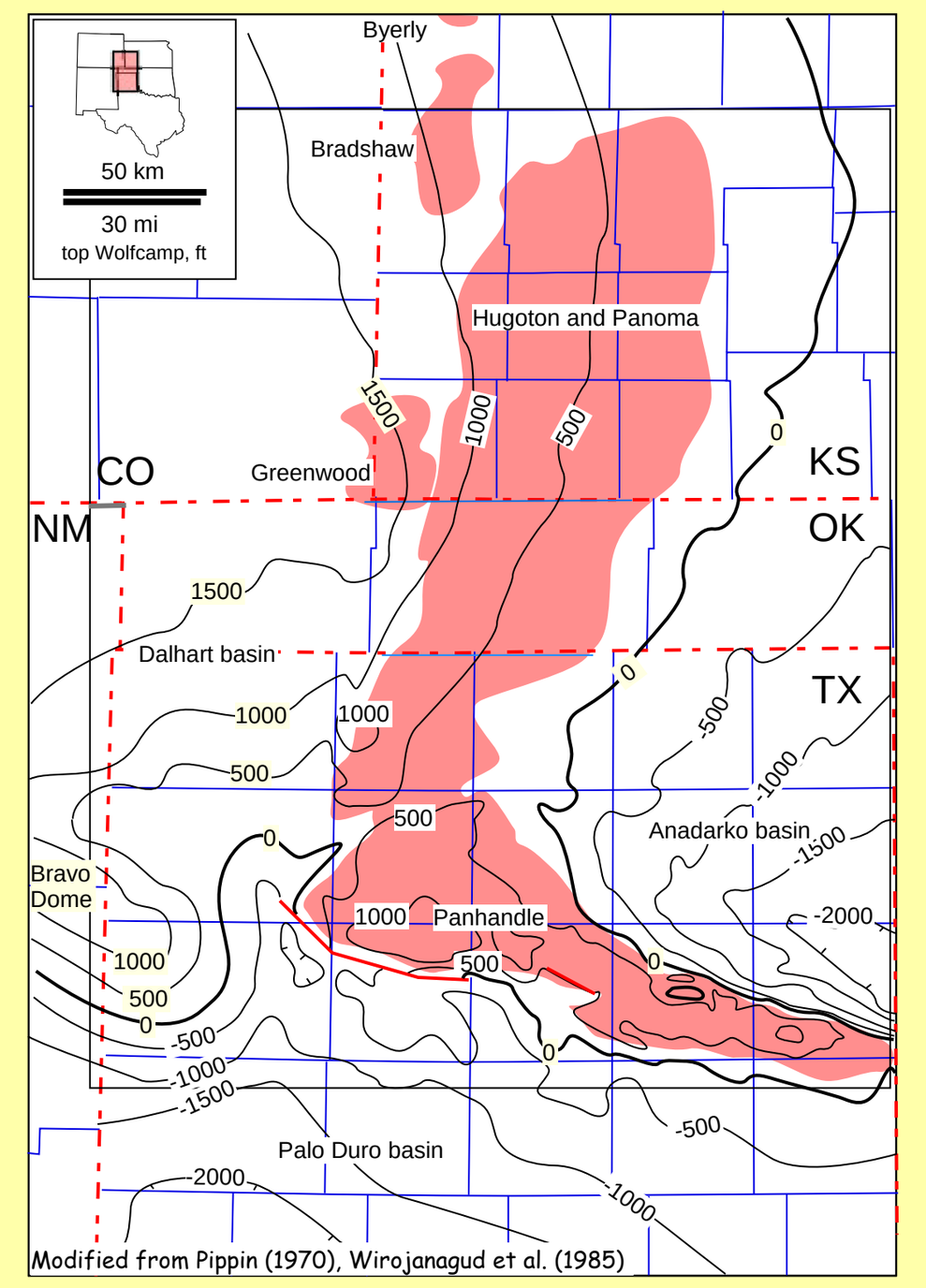
EXAMPLE 1: PANHANDLE-HUGOTON FIELD (MODEL 2)

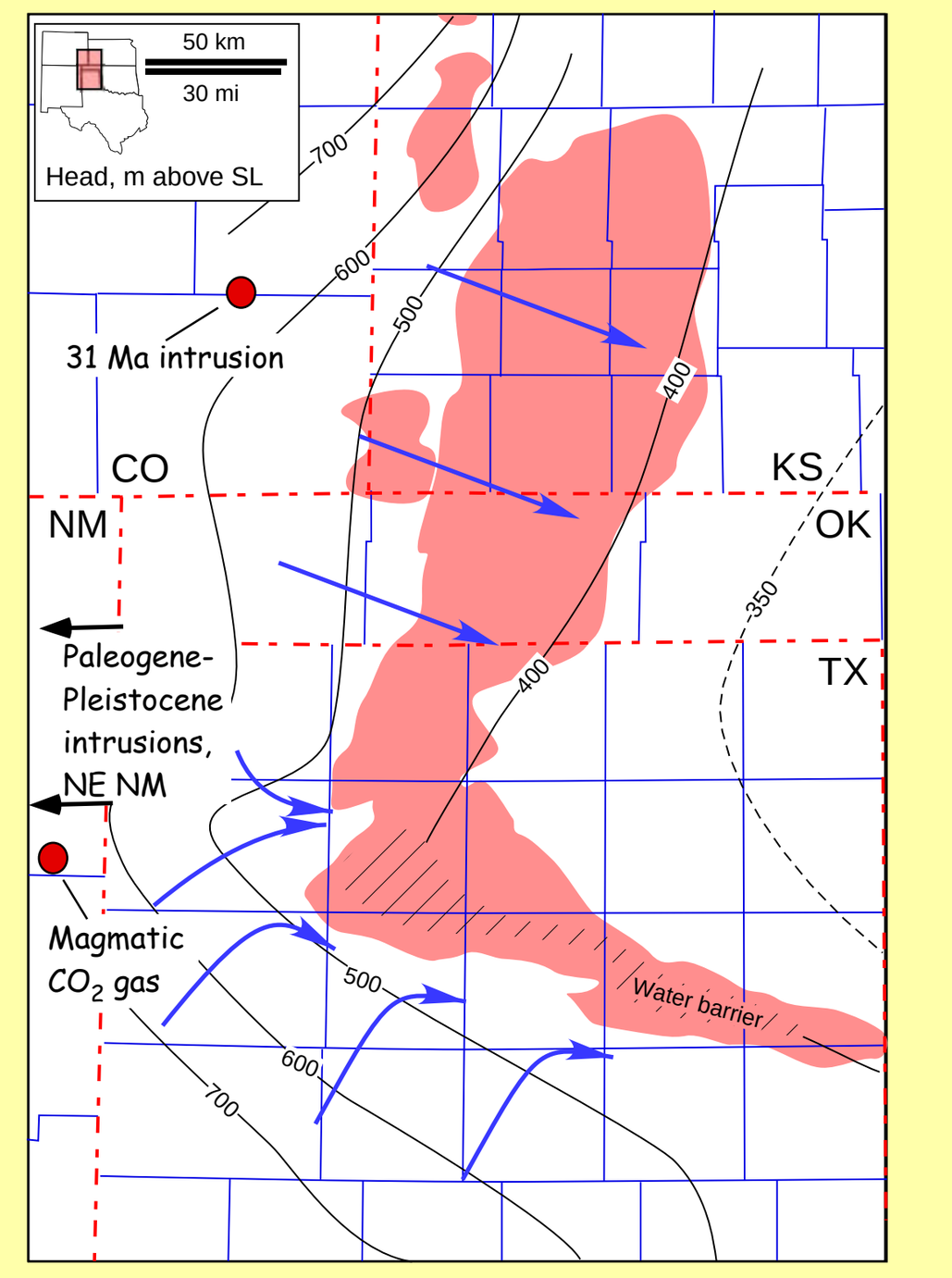
BACKGROUND

The Panhandle-Hugoton field extends from the Texas Panhandle to western Kansas. Three components lead to trapping (Pippin 1970): (1) structural closure (Panhandle field; near right), (2) updip facies change (Hugoton field), and (3) hydrodynamics (both; far right). The potentiometric surface decreases from west to east. This tilts the Hugoton gas-water contact to the east and enhances stratigraphic sealing at its updip end. In the Panhandle field, basement extends into the gas column, preventing water flow across the field, and steering hydrodynamic water flow around the Panhandle part of the field (Far right).

Oil and gas were trapped in the Panhandle part of the field contemporaneous with generation in the Anadarko basin. The reservoir depressured during the Cenozoic, and the gas column expanded north into the Hugoton field (Sorenson 2005).



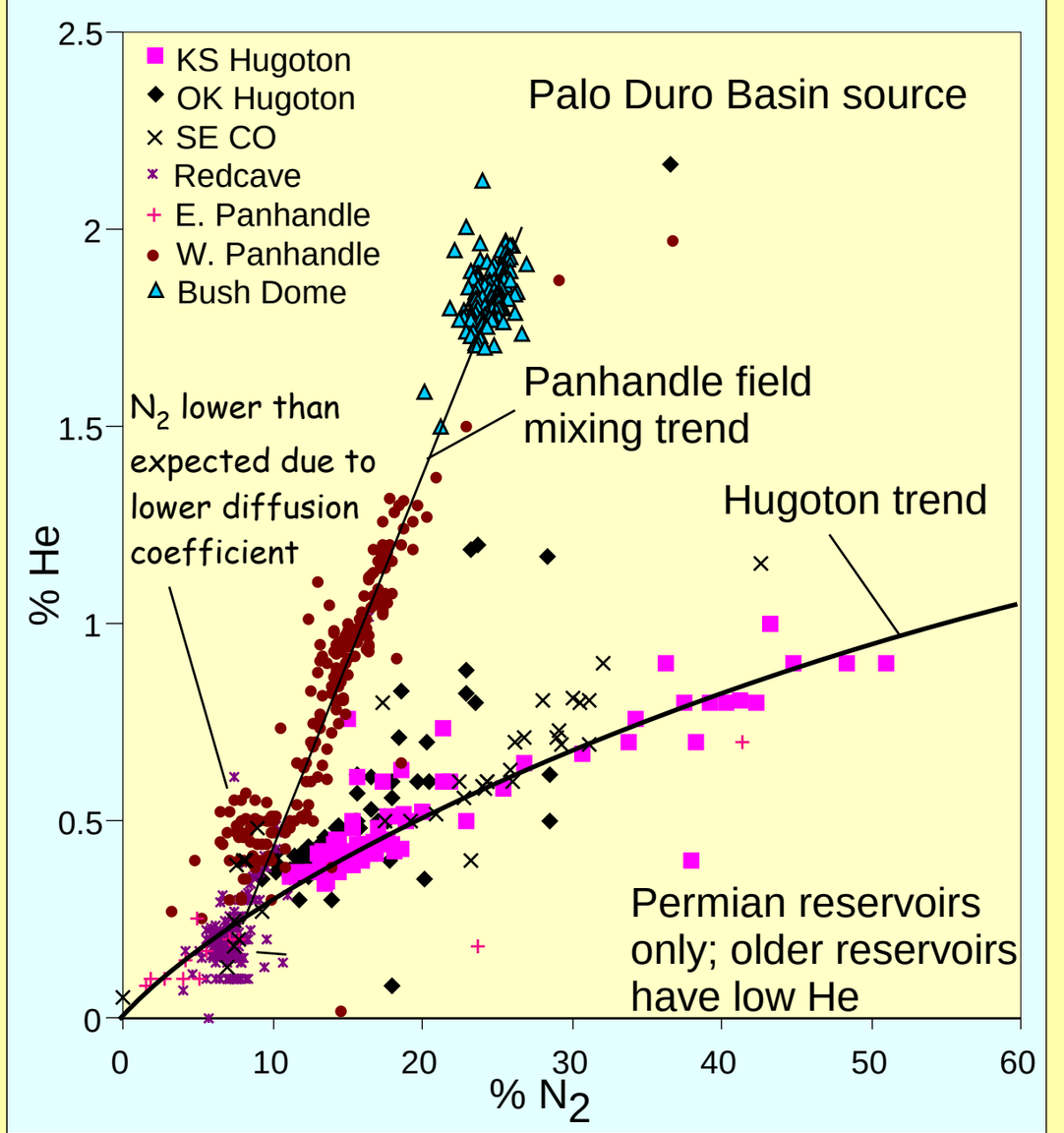
Structure, top Wolfcampian



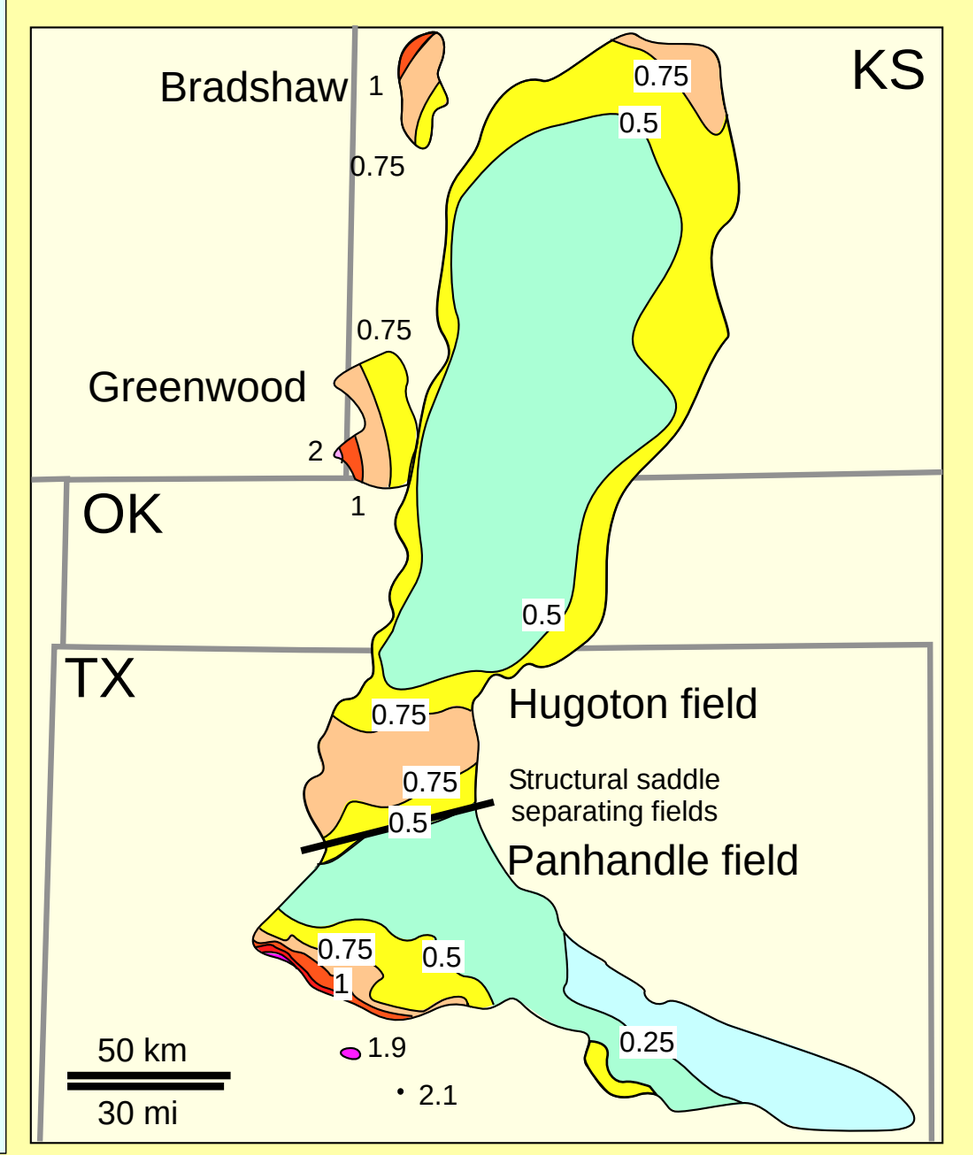
Potentiometric surface in Wolfcampian and Virgilian strata. Modified from Wirojanagud et al. (1985) with field pressure data. Potential sources of ^{3}He are also shown.

HELIUM IN PANHANDLE-HUGOTON FIELD

Helium/nitrogen ratio is relatively constant and high in the Panhandle field, with helium concentration increasing towards the Palo Duro basin (below left fig). Hugoton field has relatively uniform, lower He/N_2 and higher He on all edges of the field, especially the west and north side. The different He/N_2 indicates separate sources for helium enrichment in the Panhandle and Hugoton fields. From compositional trends, Panhandle He is from the Palo Duro basin. Hugoton He is associated with the Hugoton Embayment. He charge was late; otherwise, He concentrations would be equilibrated. Helium concentration prior to enrichment is about 0.1%, the values in the Red Cave reservoir and eastern Panhandle field.



Helium-nitrogen concentration trends in the Panhandle-Hugoton field and adjacent areas.



Helium concentration in Wolfcampian and Virgilian reservoirs near the Panhandle-Hugoton field.

HELIUM BALANCE

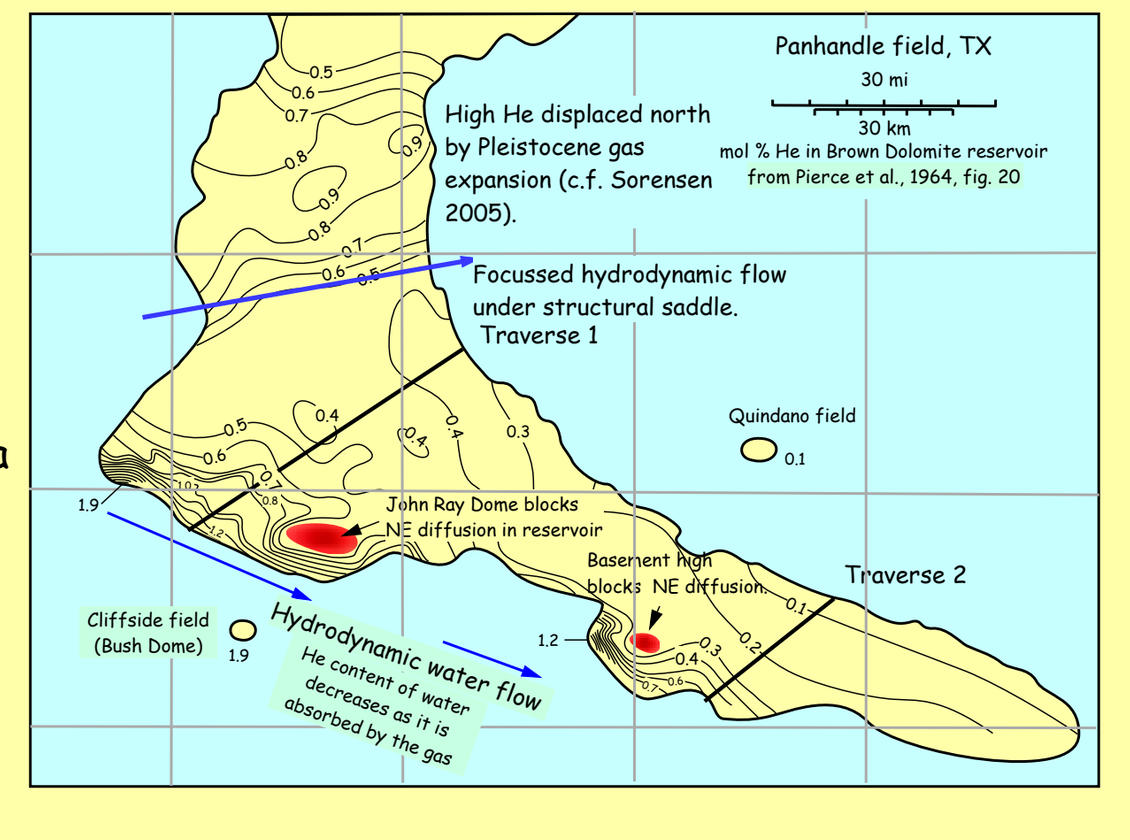
About 0.4 TCF of helium is trapped in Panhandle-Hugoton field. This is split into three groups based on geochemistry and geographic distribution: (1) background helium, (2) excess helium in Hugoton field, and (3) excess helium in Panhandle field.

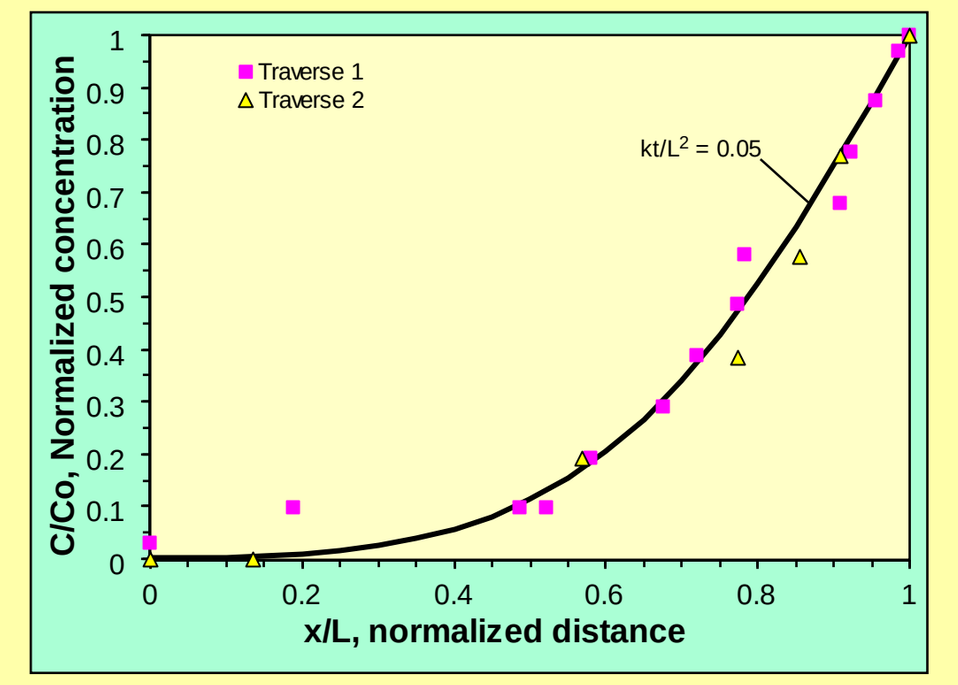
(1) Helium concentration prior to expansion of gas into Hugoton field is about 0.1%, or 0.08 TCF He. This helium could accumulate from shallow basement, granite wash and other sediment near the gas accumulation. Rock volume required to generate this volume in 300 My is 3550 km^3, compared to 3760 km^3 basement plus about 500 km^3 granite wash on and adjacent to the high.

(2) An additional 0.4% He accumulated in the volume of gas expanded into Hugoton field during the Cenozoic, or 0.19 TCF He. This corresponds to a source volume of 11,800 km^3. This helium was derived from three volumes: (a) reservoir volume the Hugoton field, as gas expanded into the field (16,700 km^2*0.3 km rock thickness = 5000 km^3), (b) volume extracted from area to SE by gas expanding and spilling from downdip fields (2000 km^3), and (c) extraction of gas from the hydrodynamic aquifer draining a rock volume of 5500 km^3 W of Hugoton field. The multiple sources cause the "ring" of high He around the Hugoton field.

(3) An additional 0.4% helium accumulated in the volume of gas remaining in the Panhandle structure after expansion of gas into Hugoton field. This requires a source rock volume of 8540 km^3. This is supplied by the volumes of Wolfcampian and Virgilian strata in the Palo Duro basin (11,000 km^3) and Dalhart basin (5500 km^3), west to the Roosevelt high and Sierra Grande Arch, respectively.

According to Wiroganagud et al (1985), current hydrodynamic flow velocity immediately SW of the Panhandle field is on the order of 10 cm/y. This is sufficient to bring water across the Palo Duro basin in about 4 My.

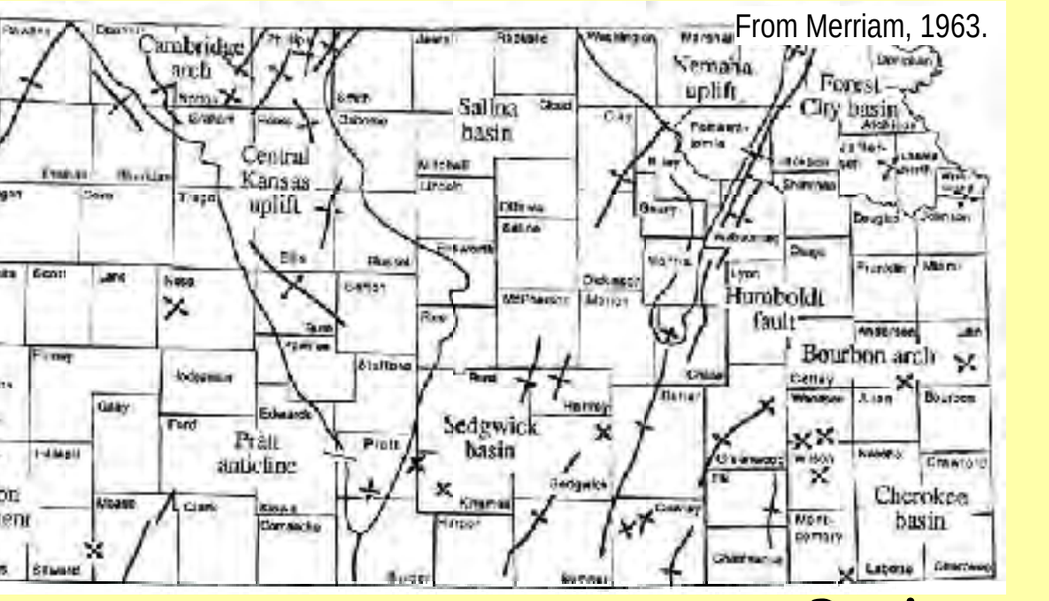


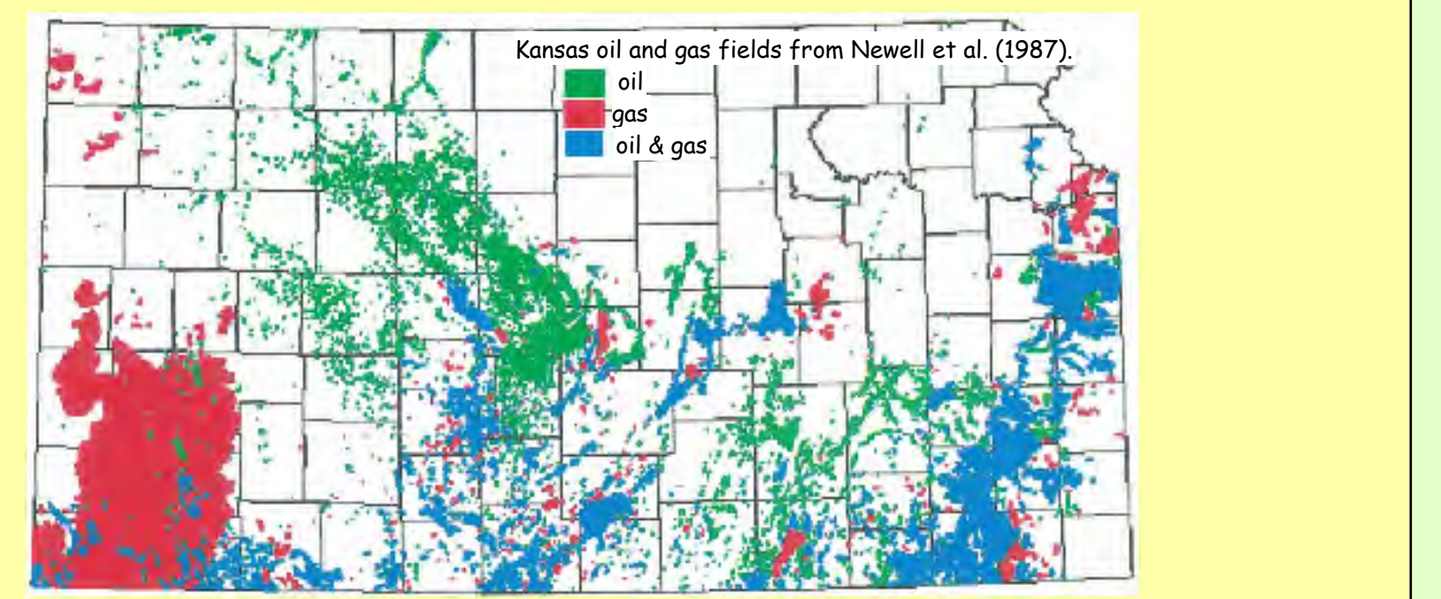


Duration of Panhandle He Charge

Helium charge from the aquifer was assumed to be a constant composition boundary condition for diffusion into a slab of gas-saturated reservoir with a low, uniform initial composition. Two traverses were selected, He concentrations measured along the traverse, and the concentrations and distances were normalized to the maximum values of both. The normalized concentration-distance plot was fit with a diffusion model to determine the value of kt/L^2. The value of k was estimated from free-gas He diffusion at reservoir temperature($0.0225 cm^2/s$) and tortuosity of 5, the expected value for reservoir rocks with porosity in the 10% range. This gives a duration of diffusion of 5 and 20 Ma. for the two traverses. The difference is probably caused by tortuosity differences related to presence of fractures and bed continuity.

EXAMPLE 2: CENTRAL KANSAS (MODEL 1)



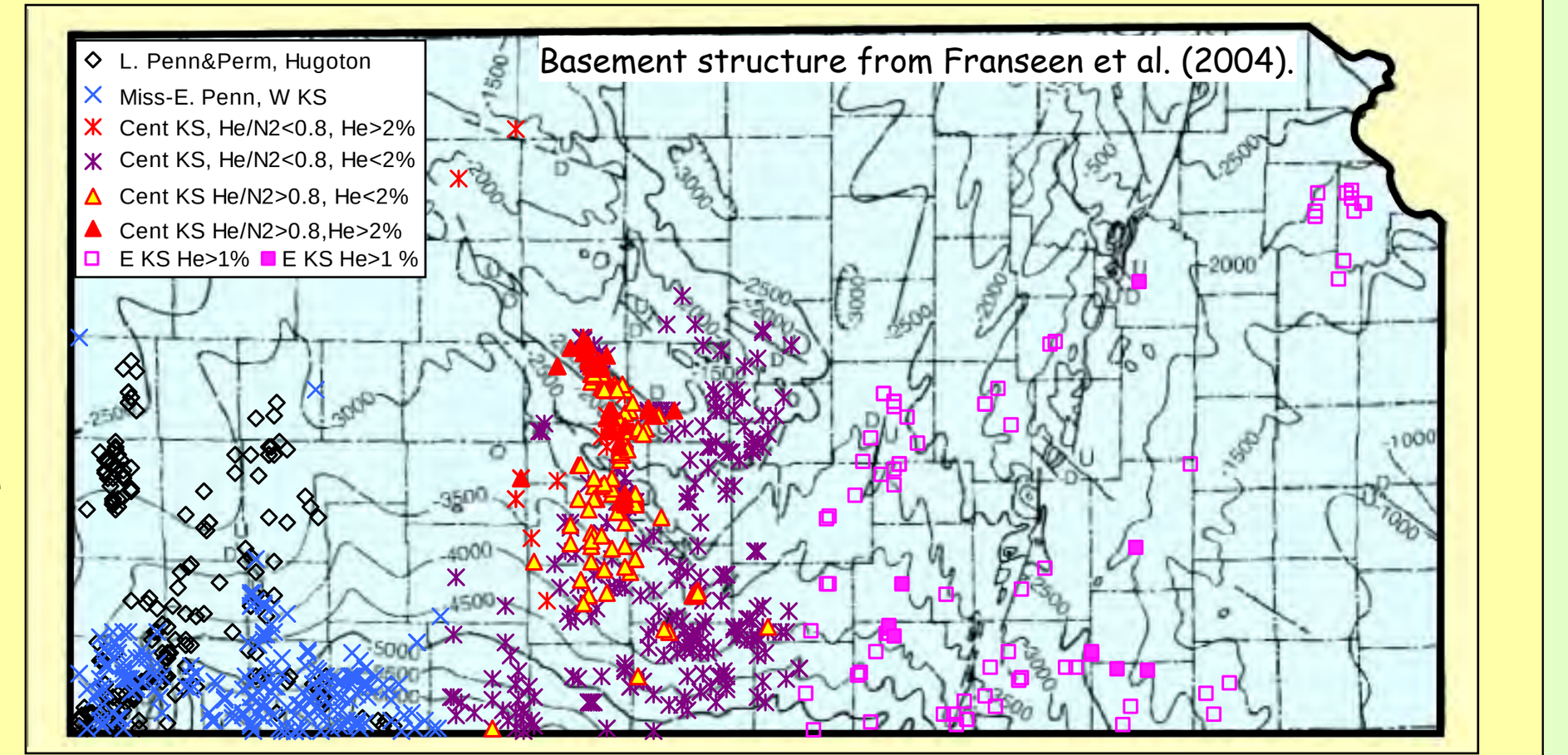


Background

Central and eastern Kansas gas is mostly in the southern part of the state. Gas source for western Kansas, the Central Kansas Uplift, Sedgwick basin, and Nemaha uplift is the foreland basins in Oklahoma (Jenden et al. 1988). Anadarko basin gas was generated during Late Pennsylvanian to Permian, mainly from the Woodford Formation (Brown, 2002). Minor remigration is related to Cretaceous and Cenozoic regional tilting (Walters 1958). The small volumes of gases in the Forest City and Cherokee basins appear to be locally generated from a marginally mature thermogenic source with a microbial component in some gases (Jenden et al. 1988).

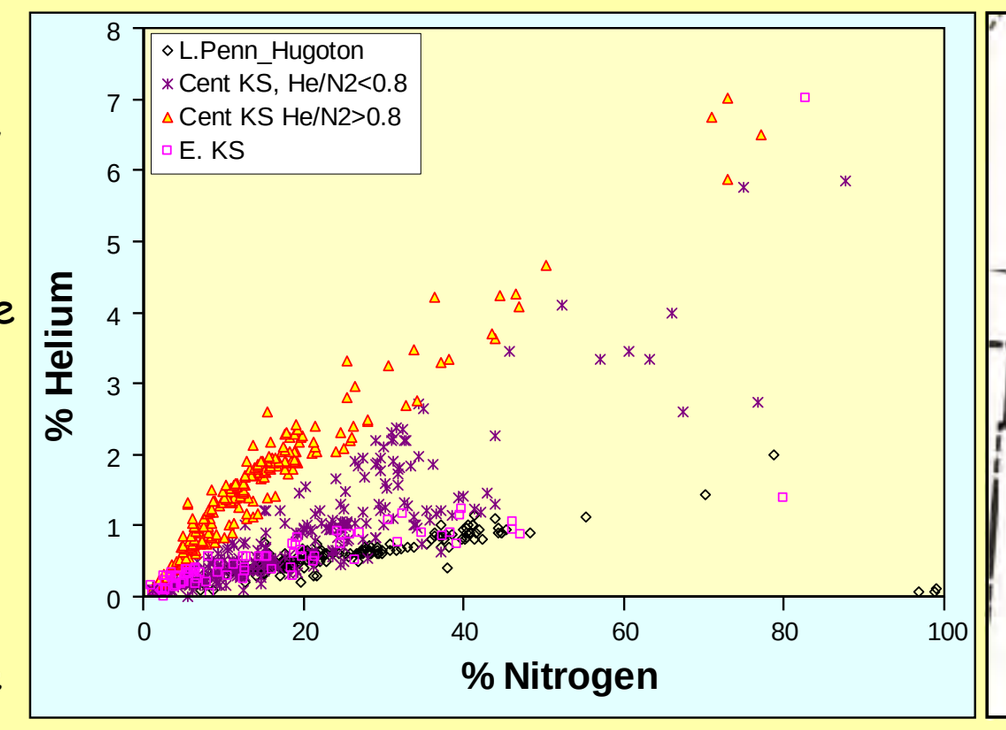
Helium Distribution

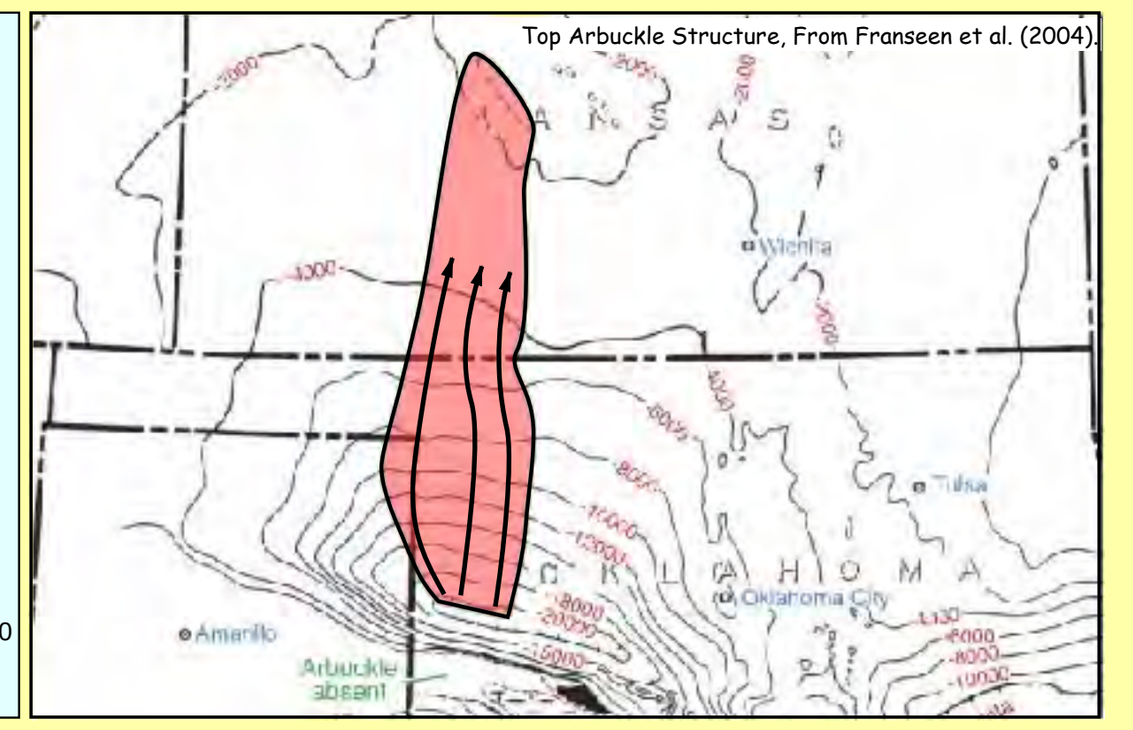
Central and eastern KS gas analyses from the USBM database and from Jenden et al. (1988) were divided by location and He/N_2. High helium gases were plotted for different groups. (Figure right). Gases with the highest helium occur at the updip ends of the gas migration chains. This is the up-dip end of a generalized helium concentration gradient that decreases towards the hydrocarbon gas kitchens in southern Oklahoma. Highest helium concentration in central Kansas (4-7%) are in the Ordovician Arbuckle Fm, near the base of the stratigraphic column. The southern Cherokee basin high He gases are also lower Paleozoic. The one high He gas in the Forest City basin is very shallow gas remigrated from the Nemaha Uplift with an exceptionally high N_2 content.



He/N_2

As in the Panhandle-Hugoton field, most areas of central and eastern KS are characterized by linear He-N_2 trends. The He/N_2 ratio is high on the western side of the Central Kansas Uplift and Pratt Anticline (Left figure). These gases lie within a drainage area connecting the western part of the Central Kansas Uplift (CKU) with the Anadarko basin source area (Right figure).





Gases in western Kansas and eastern Kansas have low He/N_2 ratios (left figure). Gases along the eastern side of the CKU and in the western Sedgwick basin have scattered He/N_2 indicative of mixing between the western CKU and Sedgwick basin trends. The gases with different linear He/N_2 trends indicate different source areas. Trends are formed by mixing migrating hydrocarbon gas with gases dissolved in water with relatively uniform He/N_2.

Interpretation

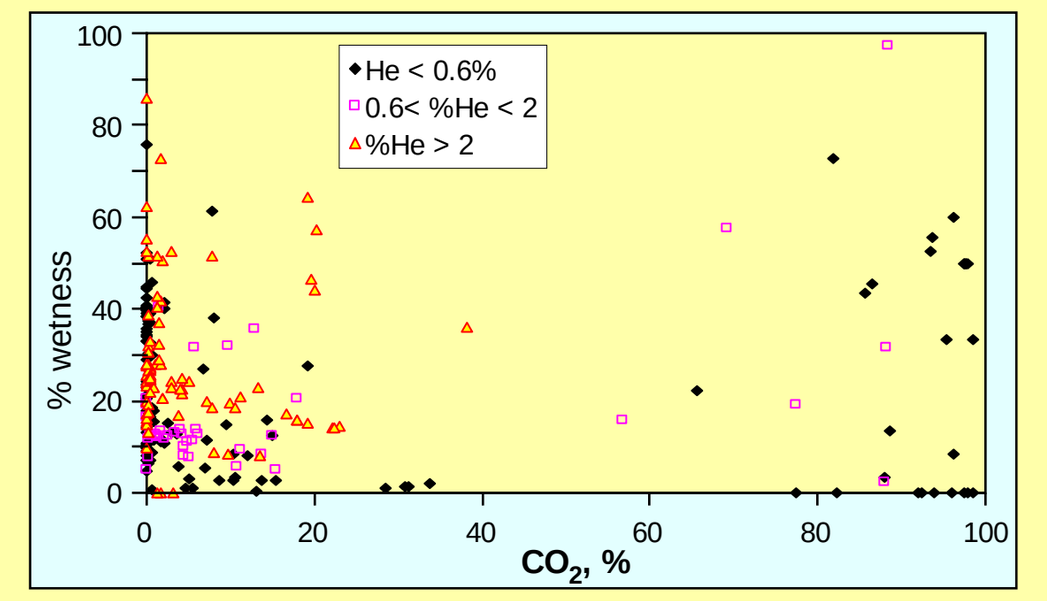
The helium concentration patterns in Central Kansas are consistent with helium Model 1: migrating gas accumulating He at the leading edge of migrating gas. The entire section is shallow, so depth has less control on helium concentrations than migration pathway. The Arbuckle Fm. is a minor gas migration pathway compared to Pennsylvanian pathways, so helium is not diluted by high petroleum charge. The maximum He concentration in gas is consistent with the age of water in Ordovician carrier beds and their porosities at time of migration (200 My old during Pennsylvanian migration; see figure on sheet 1). Interaction of gas with oil may also be responsible for the highest He concentrations. Source rock volume is less of an issue here because total volume of helium is much less than at Panhandle-Hugoton field.

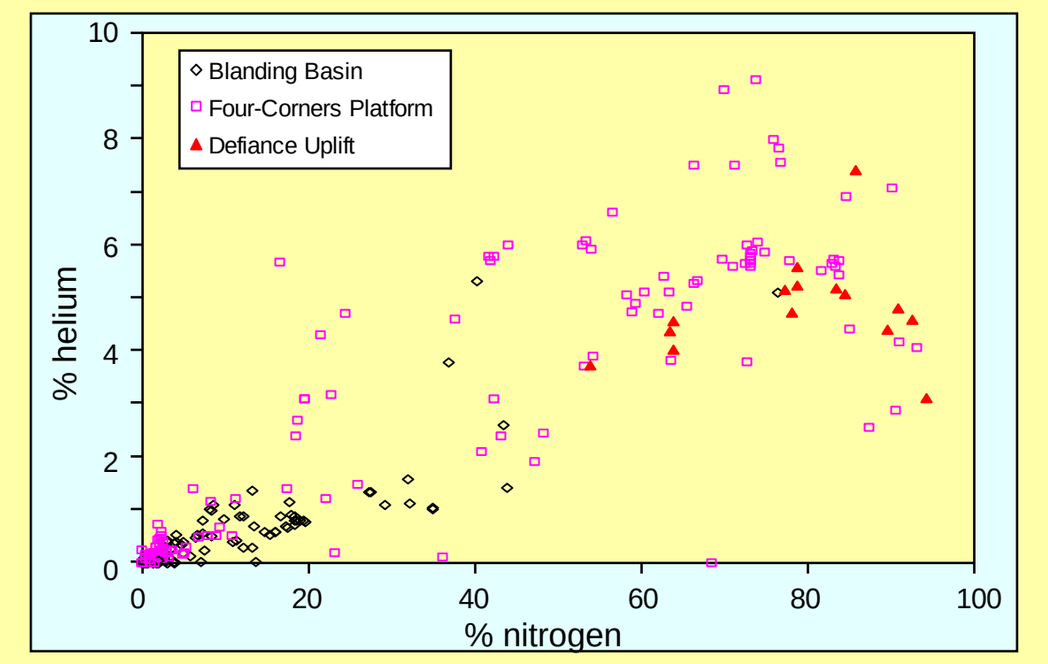
Origin of nitrogen in low maturity gas is not well understood. Nitrogen is probably derived from ammonium sorbed into clays during early diagenesis that is released during later diagenesis and converted to nitrogen. Nitrogen in organic matter is refractory through the oil and early gas window, based on N/C ratio. If nitrogen is early diagenetic, dissolved nitrogen is controlled by depositional environment and clay content and should be relatively constant with time after the rock has been exposed to burial. If so, He/N_2 increases by one of the following. mechanisms: (1) lower depositional organic productivity or predominantly non-marine depositional setting (lower N_2 in sediments) or (2) increasing age and radioactive materials, because He increases with time whereas N_2 remains relatively constant. Age differences cannot be that important in southern Kansas, because an order of magnitude age difference would be required to account for the large He/N_2 differences.

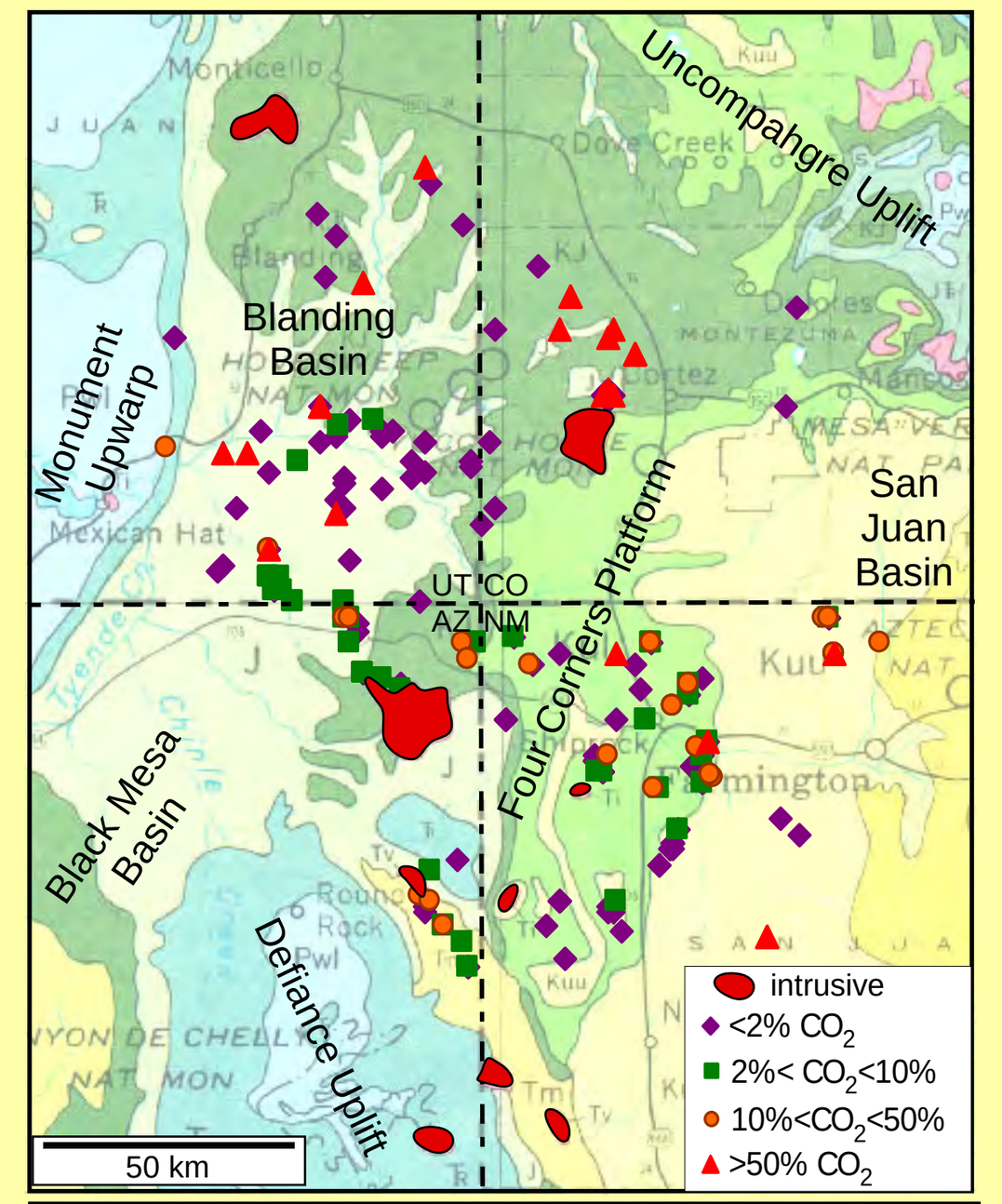
EXAMPLE 3: FOUR CORNERS AREA (MODEL 3)

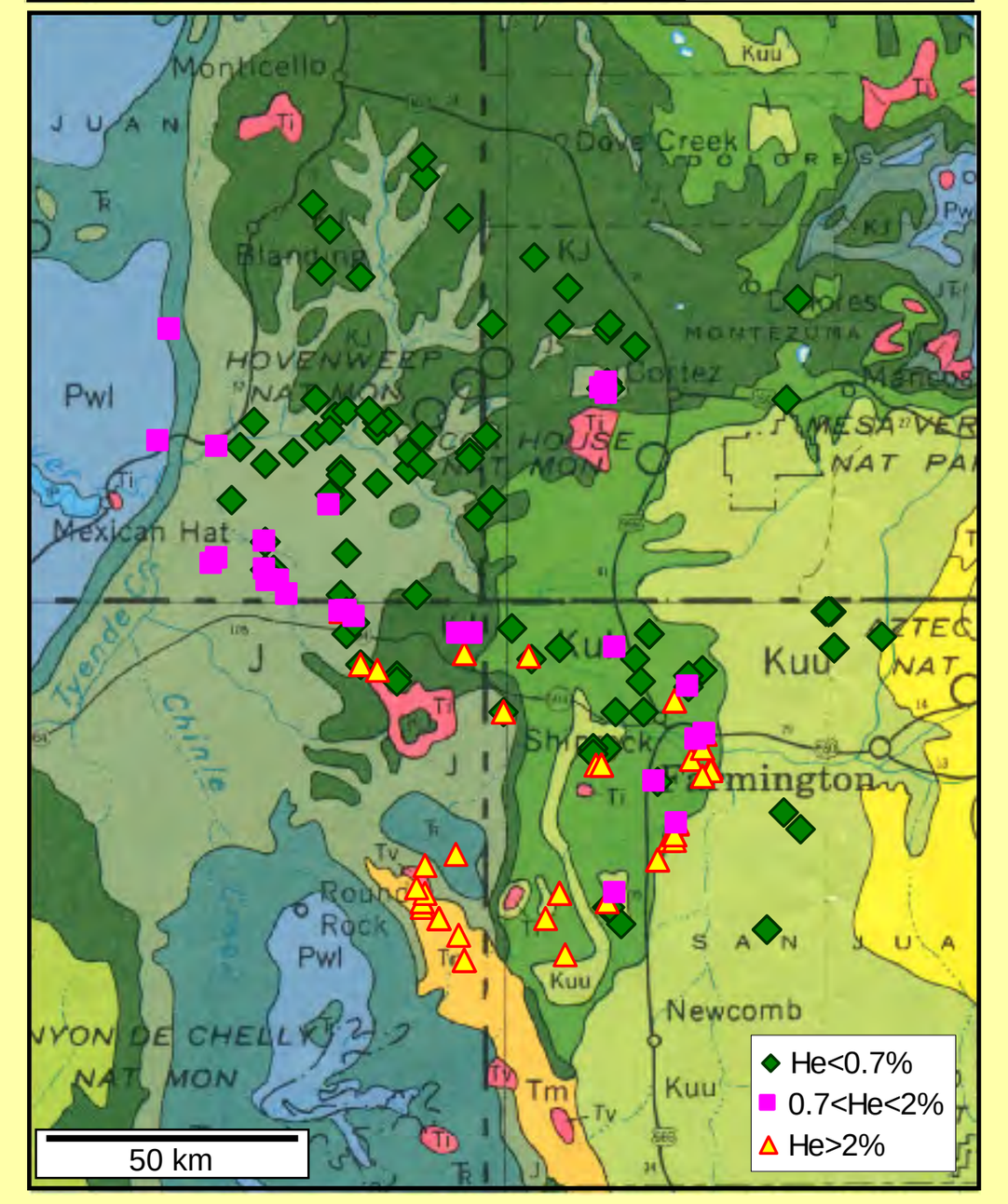
Background

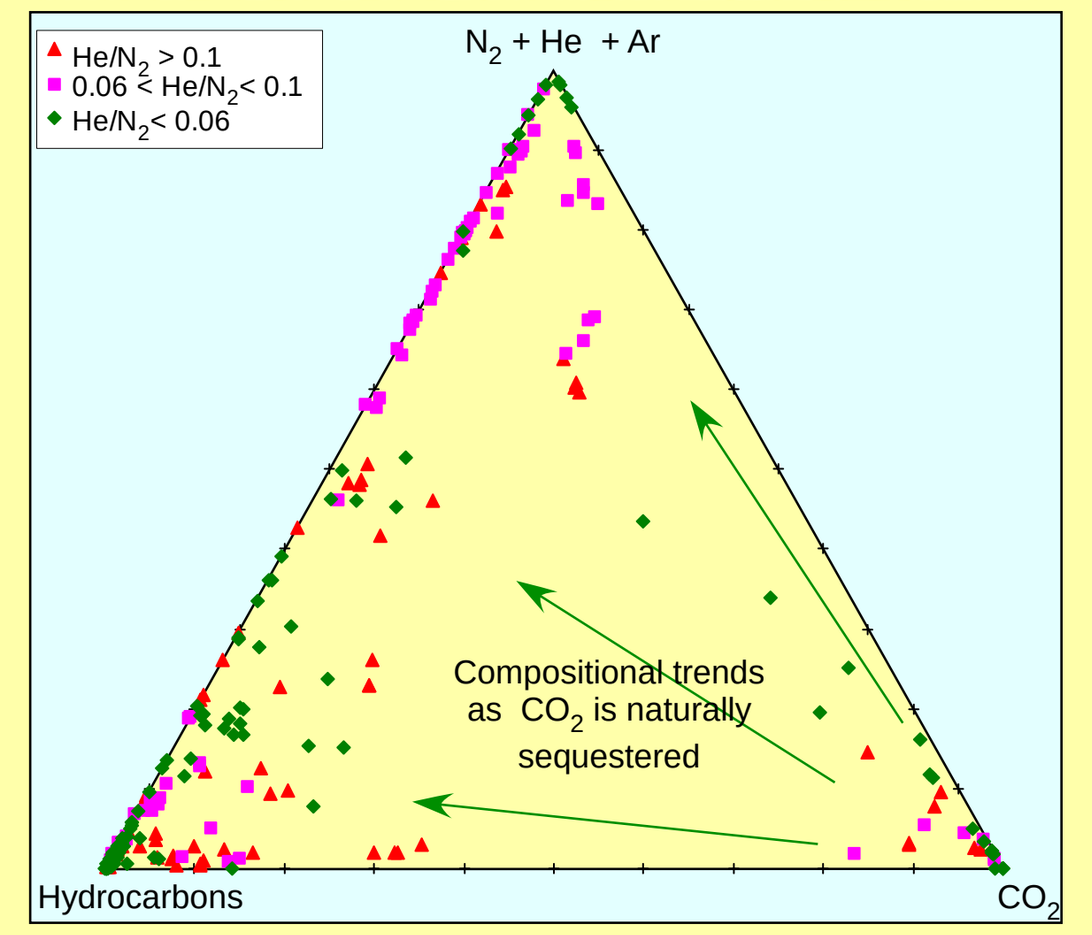
High helium gases (>2%, map at right below) are mainly in structural traps in Devonian-Triassic reservoirs on the south side of the Four Corners Platform in a position where gas from under the San Juan basin. can charge the traps. High helium gases are most abundant below the oil source rocks in the Paradox Formation shales. There are numerous mid-Cenozoic (30 - 20 Ma) intrusives associated with the Navajo volcanic field (Christiansen 1992). Many Paleozoic gases have high CO_2, even those under the western San Juan basin (map at right). The CO_2 in these gases is probably volcanic in origin. Methane carbon in Ute field is heavy (-35 to -37 ‰ $\delta^{13}C$, PDB), indicative of high maturity (Rice 1983). Ute gases are dry, low N_2, low He, and high CO_2. All gas analyses from Cretaceous and Jurassic reservoirs have low helium. Gases toward the central Blanding basin also have low helium at all stratigraphic levels.











Helium Association and Origin

High helium gases on the Four Corners Platform are relatively wet (top plot above), yet the single methane carbon analysis for Hogback field shows similar isotopic composition as that at Ute field (-35.8 ‰ $\delta^{13}C$, PDB, Zartman et al. 1963). This indicates contamination of a high maturity gas with heavy hydrocarbons extracted from oil-window maturity rock during migration.

Low-helium gases show a relatively uniform He/N_2 (bottom plot above). The uniform He/N_2 probably results from stratal migration. High helium gases have a wide range of He/N_2, with no systematic relationship to stratigraphic or geographic position. This pattern probably results from cross-stratal migration that mixes gases with different He/N_2 ratios.

Helium Model

The best explanation for these high helium gases is Model 3. Non-flammable, helium-bearing gases develop where the original CO_2 gas was dominated by nitrogen and helium (triangle plot, above left). As CO_2 ir removed by reservoir reactions, Helium and nitrogen are concentrated into the remaining gas until they are the dominant gases after long migration. Volcanogenic CO_2 interacted with numerous stratal horizons, resulting in variable He/N_2.

Helium Mass Balance

Estimates of helium OGIP could not be located in the literature. Over a BCF of helium gas has been produced from reservoirs in NW New Mexico through 2003 (Broadhead 2005). Assuming that this is about half the original helium in place, original helium in place in economic gas accumulations is about 2 BCF of in the Four Corners Platform. Assuming 200 my of generation, this requires a source volume of about 66 km^3 of shale. Assuming source layer 100 m thick source area is 660 km^2, or about 7.2 townships. There are about 25 townships in the NM-AZ part of the Four Corners Platform west of the Hogback Monocline. Structural drainage is towards the SW, consistent with sweep by high CO_2 gases from under the San Juan basin.

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CONCLUSIONS

Helium exploration requires the same skills and data as conventional petroleum exploration: evaluation of source, migration, and trapping. However, sources are different, and interaction with water is much more important. Here are some general guidelines for helium exploration

- Explore in old sediment with old pore waters. Use He/N_2 and lithology (GR logs) as a guide to the helium generation potential.
- Explore for relatively shallow traps. He partitions into gas better at shallow depth, higher salinity pore water, and cooler temperatures.
- High grade prospects with long fetch areas, because long migration maximizes gas exposure to helium-bearing water.
- Avoid central parts of supercharged petroleum systems because helium will be too diluted by methane charge. Explore along the edges of these systems or in reservoirs bypassed by most migration.
- Carefully consider migration of volcanogenic CO_2 gases where shallow intrusives penetrate old strata. Prospects must be up dip from potential CO_2 sources and sufficiently far from the source for CO_2 to be consumed during migration.

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