Helium – Relationships to other reservoir gases and some implications for exploration: The New Mexico example

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Summary

Helium (He) has widespread occurrence in natural gases but is uncommon in concentrations > 0.1%.While He is a minor component of gases, Nitrogen (N_2), carbon dioxide (CO_2) and hydrocarbons are the dominant components. He is derived primarily from radioactive decay of uranium and thorium in crystalline basement rocks; major gas components have different sources and migrate into subsurface reservoirs at different rates than He. Mapping of He concentrations of natural gases within the state of New Mexico and analyzing the concentration of He relative to the concentrations of the major gas components has revealed geologic relationships that affect the concentration of He in reservoirs. Examples are shown where: (1) CO_2 derived from Tertiary igneous activity has substantially diluted He in some, but not all, reservoirs; (2) hydrocarbons migrated from a different direction than the He, resulting in lateral variation in He concentration within a hydrocarbon-dominant reservoir, and (3) possible variation in the He-generating capacity of the crystalline basement has resulted in variable He:N_2 potential ratios in overlying strata.

Theory and Method

Helium (He) is the second most abundant element in the universe after hydrogen but is relatively rare on earth. He occurs as two stable isotopes, ^{3}He and ^{4}He. ^{4}He is the dominant isotope in crustal gases and is formed by radiogenic decay of uranium and thorium that reside in crustal rocks mainly granitic basement (Hunt, 1996; Oxburgh et al., 1986; Jenden et al., 1988; Ballentine and Lollar, 2002). ^{3}He is dominantly primordial and primarily originates from the earth's mantle. ^{3}He also may be generated by neutron capture by ^{6}Li in lithium-rich sediments (Hiyagon and Kennedy, 1992; Mamyrin and Tolstikhin, 1984; Oxburgh et al., 1986). He occurs in most natural gases in extremely low, subeconomic concentrations, < 0.1%. It is uncommon in concentrations > 1% and may be found in concentrations > 7% in only a few very small reservoirs.

Other gases that constitute the dominant components of helium-bearing natural gases are nitrogen (N_2), carbon dioxide (CO_2) and hydrocarbons, chiefly methane (CH_4). The highest He concentrations occur where the dominant gas is N_2 but most He has historically been produced as a byproduct of gases that are dominantly hydrocarbons. The presence of hydrocarbons in a reservoir is dependent upon the presence of a mature source rock in the basin and a migration path between the source rock and the reservoir. Large accumulations of nearly pure CO_2 in the southwestern U.S. resulted from the degassing of rising Tertiary magmas and subsequent migration of the gases into crustal reservoirs (Staudacher, 1987; Gilfillan et al., 2008). N_2 appears to originate mostly from degassing of the mantle (Holloway and Dahlgren, 2002; Ballentine and Lollar, 2002) but may also be formed in some strata by several processes including thermal maturation of kerogens (Hunt, 1996; Klein and Juntgen, 1972; Boudeau and

Espitalie, 1995), and diagenetic alteration of clays (Brown, 2017) or organic compounds in red bed sequences (Guseva and Fayngersh, cited in Hunt, 1996).

The presence of economic concentrations of He in reservoir gases is dependent not only on an adequate source of ^{4}He generated from granitic basement rocks but also on accommodating flux rates of N_2, CO_2, and CH_4. These gases differ in their origins, places of generation and rates of generation, and migration mechanisms and paths. While basement-derived ^{4}He and N_2 enter reservoirs at slow rates over long periods of geologic time, hydrocarbons and CO_2 enter the reservoir over much shorter time periods and dilute the previously accumulated ^{4}He and N_2. Basement-derived N_2 and He may be characterized by differing He:N_2 ratios which may indicate greater rates of He production within the crust in some areas. The half-lives of ^{4}He-forming emission decays are 4.47 billion years for ^{238}U, 0.703 billion years for ^{235}U and 14.0 billion years for ^{232}Th (Holden, 2020), indicating that He generation rates have been continuous with slow decline since early in the earth's history. A large portion of the earth's ^{4}He generating system is still in place. In contrast, emplacement of CO_2 is geologically quick with the CO_2 in the Bravo Dome field having been emplaced between 1.2 and 1.5 million years ago (Sathaye et al., 2014). Similarly, maximum hydrocarbon expulsion from source rocks in the Simpson-Ellenburger petroleum system on the Central Basin Platform in the Permian Basin occurred over a 30 million year period (see Katz et al., 1994)

The work summarized in this presentation was based on mapping of the He, N_2, CO_2 and hydrocarbon content of 943 analyses of natural gas samples mostly recovered from oil and gas exploratory wells drilled throughout New Mexico (Broadhead and Gillard, 2004) with additional data obtained from wells drilled on Chupadera Mesa. This discussion is derived from Broadhead (2023).

The He content of gases in the geologic systems was mapped and contoured on a statewide level (Broadhead and Gillard (2004) and in more detail in the Chupadera Mesa area of central New Mexico (Broadhead, 2009). Investigation of relational aspects of He to the major reservoir gases (N_2, CO_2, hydrocarbons) involved detailed analysis of He distribution in gases, cross plotting He content of the gases vs. content of the major reservoir gases by geologic system both on a statewide basis and also in more detail for selected gas systems in the Permian Basin area of southeastern New Mexico and the Chupadera Mesa area of central New Mexico (Figure 1). Calculation of the ratio of He:N_2 for basement-derived He and N_2 provided further insights. For two areas studied in more detail and for which sufficient data were available, the Pecos Slope Abo gas pools at the northwestern extent of the Permian Basin and Chupadera Mesa of central New Mexico, it was possible to develop additional insight into the relationship between He and the major reservoir gases and resulting implications for He exploration.

Observations and Conclusions

Statewide, He content of gases increases with N_2 content where CO_2 is absent or present only in small amounts. A plot of He content vs heating value of Pennsylvanian gases (heating value is used as a proxy for hydrocarbon content) indicates helium content decreases with increasing heating value. However, CO_2 in concentrations more than approximately 20% results in decreased helium content, more so in Pennsylvanian reservoirs than in Permian reservoirs.

A plot of He vs N_2 for Permian reservoirs in southeast New Mexico indicates two different families of gases. One family of gases is present in the Pecos Slope Abo gas reservoirs located near the northwestern boundary of the Permian Basin. The Pecos Slope Abo gases form a linear trend with a zero intercept on both the He and N_2 axes, consistent with a source in the basement with similar migration pathways for both gases. The He:N_2 ratio is 0.069. A NE-SW strike-slip fault acted as the main migration path from the basement into the shallow sedimentary crust. At Pecos Slope, both He and N_2 contents decrease to the southeast, away from the fault along with increasing hydrocarbon content. The hydrocarbon gases migrated northwestward from the deeper parts of the Delaware Basin and are at the end of their migration path. The second family of gases has lower He content but variable N_2 content ranging from a few percent to more than 80%. There is no associated increase of He with N_2 in this second gas family. It therefore seems likely that the source of the N_2 is not the basement but has been generated within the sedimentary section, perhaps by alteration of clays within the red bed clastics that are abundant in the Lower Permian section or by reaction of ferric oxides in the red beds with kerogens that contain N_2.

A plot of He vs N_2 for gases in Silurian and Ordovician reservoirs on the Central Basin Platform and the eastern part of the Northwest Shelf again indicates the presence of two families of gases similar to those in the Permian section. One gas family exhibits a linear increase of He with increasing N_2 content and the second family exhibits no linear relation between He and N_2 contents. The He:N_2 ratio of the first family is 0.039, only 57% of the He:N_2 ratio of the Pecos Slope Permian gases. The relatively higher He contents and higher He:N_2 ratios of the Pecos Slope gases may be the result of restricted migration of N_2 from the mantle at Pecos Slope when compared to the Central Basin Platform or may be the result of greater He production in the Precambrian basement at Pecos Slope and therefore increased He potential.

Exploratory drilling for He on Chupadera Mesa in the late 1990's and early 2000's encountered He-rich gases in Lower Permian strata. He contents of recovered gases are as high as 3.44%, the highest known values in New Mexico outside of the commercial productive helium reservoirs on the Four Corners Platform of northwest New Mexico (Fig. 1). Chupadera Mesa is characterized by large volcanic intrusive bodies of Tertiary age, smaller igneous dikes and sills, and an absence of thermally mature hydrocarbon source rocks (Broadhead, 2009). Marked differences in the CO_2 concentrations in different strata in the same well indicate that some strata acted as carrier beds for magmatically-derived CO_2 while strata with He-rich gases were not as well connected to CO_2 sources. Similar He:N_2 ratios indicate an He-N_2 system common to multiple stratigraphic intervals. Identification of CO_2 sources and carrier beds for the CO_2 should be components of He exploration in a region characterized by igneous intrusive activity. Furthermore, the presence or absence of CO_2 carrier beds may differentiate between economic and subeconomic concentrations of He.

Acknowledgements

This research was conducted under the auspices of the New Mexico Bureau of Geology and Mineral Resources during the author's working career and subsequent retirement. Early stages of the work were funded by the New Mexico State Land Office. The late Ben Donegan, Wheeler Sears, Jack Frizzell and Ed Beaumont provided gas analyses and other data from

Chupadera Mesa. The New Mexico Bureau of Geology and Mineral Resources provided computer and office access during my retirement.

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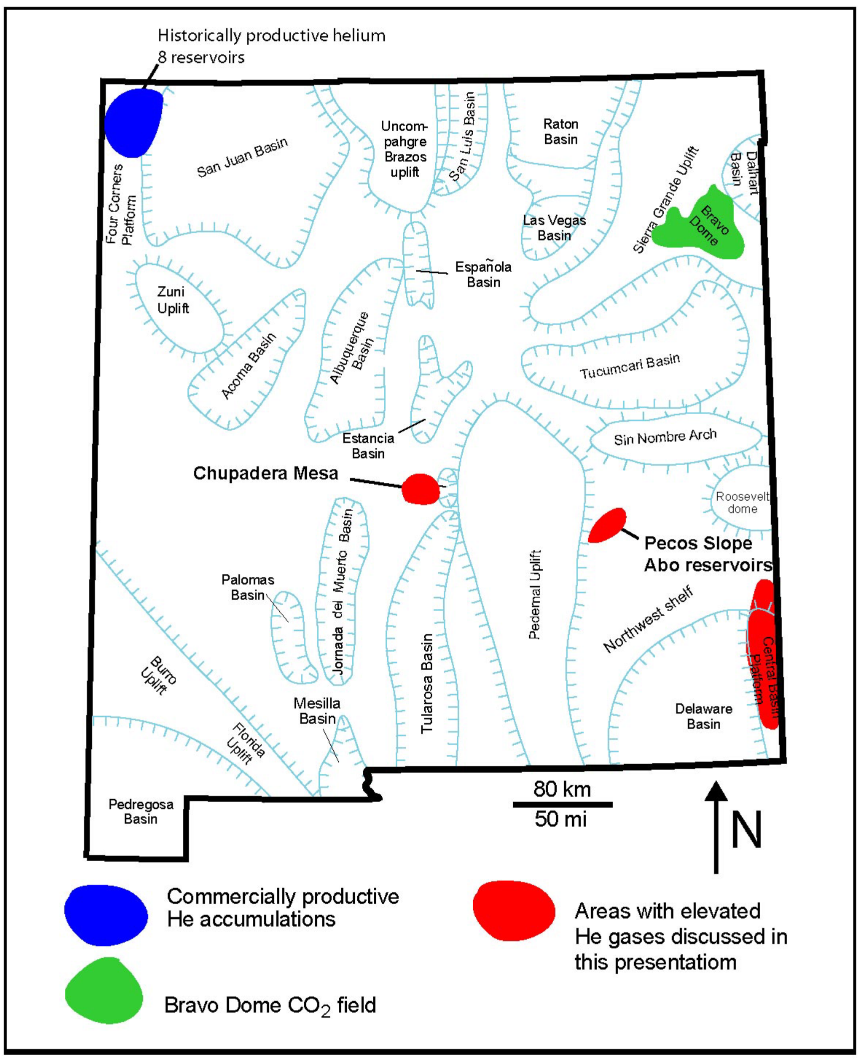

Figure 1. Outline of New Mexico showing areas of gases with enhanced He concentrations and discussed in this presentation and the Bravo Dome CO_2 field. Geologic base from Broadhead (2017).