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Mantle and crustal gases of the Colorado Plateau: Geochemistry, sources, and migration pathways

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Abstract

The Colorado Plateau hosts several large accumulations of naturally occurring, non-hydrocarbon gases, including CO_2, N_2, and the noble gases, making it a good field location to study the fluxes of these gases within the crust and to the atmosphere. In this study, we present a compilation of 1252 published gas-composition measurements. The data reveal at least three natural gas associations in the field area, which are dominated by hydrocarbons, CO_2, and $N_2 + He + Ar$, respectively. Most gas accumulations of the region exhibit compositions that are intermediate between the three end members. The first non-hydrocarbon gas association is characterized by very high-purity CO_2, in excess of 75 mol% (hereafter, %). Many of these high-purity CO_2 fields have recently been well described and interpreted as magmatic in origin. The second non-hydrocarbon gas association is less well described on the Colorado Plateau. It exhibits He concentrations on the order of 1–10%, and centered log ratio biplots show that He occurs proportionally to both N_2 and Ar. Overall ratios of N_2 to He to Ar are ≈100:10:1 and correlation in concentrations of these gases suggests that they have been sourced from the same reservoir and/or by a common process. To complement the analysis of the gas-composition data, stable isotope and noble-gas isotope measurements are compiled or newly reported from 11 representative fields (previously published data from 4 fields and new data from 7 fields). Gas sampled from the Harley Dome gas field in Utah contains nearly pure $N_2 + He + Ar$. The various compositional and stable and noble gas isotopic data for this gas indicate that noble gas molecule/isotope ratios are near crustal radiogenic production values and also suggest a crustal N_2 source. Across the field area, most of the high-purity $N_2 + He + Ar$ gas accumulations are associated with the mapped surface trace of structures or sutures in the Precambrian basement and are often accumulated in lower parts of the overlying Phanerozoic sedimentary cover. The high-purity gas association mostly occurs in areas interior to the plateau that are characterized by a narrow range of elevated, moderate heat flow values (53–74 mW/m^2) in the ancient (1.8–1.6 Ga) basement terranes of the region. Collectively, the geochemical and geological data suggest that (1) the $N_2 + He + Ar$ gas association is sourced from a crustal reservoir, (2) the gas association migrates preferentially along structures in the Precambrian basement, and (3) the sourcing process relates to heating of the crust. Prospecting for noble-gas accumulations may target areas with elevated Cenozoic heat flow, ancient crust, and deep crustal structures that focus gas migration. High-purity CO_2 gas may also migrate through regional basement structures, however, there is not always a clear spatial association. Rather, CO_2 accumulations are more clearly associated with zones of high heat flow (>63 mW/m^2) that sit above hot upper mantle and are proximal to Cenozoic volcanic rocks near the plateau margins. These observations are consistent with previous interpretations of a magmatic gas source, which were based on geochemical measurements.

Keywords: CO_2; N_2; He; Colorado Plateau; Gas

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1. INTRODUCTION

Naturally occurring non-hydrocarbon gases, including carbon dioxide (CO_2), nitrogen (N_2), and the noble gases, are important to a variety of issues that concern modern geoscientists. First, because CO_2 is a greenhouse gas, it is important to understand CO_2 degassing rates from the solid earth to either reconstruct or predict atmospheric temperatures (e.g. Kump et al., 2000; Kerrick, 2001; Mörner and Etiope, 2002; Rogelj et al., 2012). Second, because anthropogenic global warming could be mitigated by subsurface storage of CO_2 in geologic formations (e.g. Lal, 2008), naturally occurring subsurface accumulations of CO_2 provide critical settings to evaluate the long-term safety and efficacy of geological carbon sequestration (e.g. Bickle et al., 2013). Third, in addition to CO_2, other gases such as N_2 and helium (He) in the subsurface may represent either exploitable natural resources (e.g. U.S. Geological Survey, 2014) or risk factors in hydrocarbon exploration that may displace, dilute, or degrade accumulated hydrocarbons (e.g. Littke et al., 1995; Zhang et al., 2008).

The Colorado Plateau has numerous, large accumulations of a variety of non-hydrocarbon gases, including CO_2, N_2, He, and, to a lesser degree, argon (Ar) (e.g. Picard and Holland, 1962; Broadhead, 2005; Moore et al., 2005), making it a good location to study non-hydrocarbon gas systems. Various isotopic measurements, but particularly $CO_2/^3He$ ratios and $\delta^{13}C$ of CO_2, in large, high-purity CO_2 accumulations (e.g. McElmo Dome and St. Johns Dome gas fields on the Colorado Plateau, and McCallum Dome and Sheep Mountain gas fields adjacent to the northeastern Colorado Plateau margin; see Fig. 1) suggest a mantle gas source (Gilfillan et al., 2008, 2009, 2011). Moreover, recent compositional and isotopic analysis of carbonic and geothermal spring water and associated gas from springs distributed along the southeastern portion of the plateau reveals active mantle degassing across parts of the region (e.g. Newell et al., 2005; Kennedy and van Soest, 2007; Crossey et al., 2009; Karlstrom et al., 2013). However, the origin, distribution, and presence of other non-hydrocarbon gases in the region remain less well-known. The objectives of this paper are to (1) identify distinct non-hydrocarbon gas associations from the Colorado Plateau, (2) characterize the compositions and isotopic characteristics of these gas associations, and (3) place various gas associations into a geologic and geophysical framework.

To accomplish these objectives, we present a compilation of Colorado Plateau produced gas composition measurements reported by the U.S. Bureau of Mines and the U.S. Bureau of Land Management between 1949 and 2007. These data provide the basis for defining three distinct gas associations, which are hydrocarbon gases, high-purity CO_2 (e.g. Moore et al., 2005; Gilfillan et al., 2008) and high-purity N_2 and He, the latter of which tends to be associated with smaller amounts of Ar. Not surprisingly, many reservoirs contain mixes of these gases. We complement this analysis with isotopic data from 11 gas fields that are representative of the non-hydrocarbon gas associations, including data from 4 gas fields compiled from previous literature (Gilfillan et al., 2008, 2009) and data from 7 new gas fields. Stable isotopic data includes $\delta^{13}C$ of CO_2 and $\delta^{15}N$ of N_2. We also report isotope concentrations and ratios for the light noble gases (He, neon (Ne), and Ar). The various isotopic data help to resolve the sources of the non-hydrocarbon gas associations. We compare the locations of both CO_2 and $N_2 + He + Ar$ gas accumulations to Quaternary faults, Tertiary sedimentary basins, sutures in the Paleoproterozoic basement of the region, regional patterns in heat flow, and locations of Tertiary and Quaternary volcanic rocks, in order to constrain gas sources, charging mechanisms, and migration pathways.

2. REGIONAL GEOLOGIC SETTING

2.1. Basement provinces of the Colorado Plateau

The Colorado Plateau (Figs. 1 and 2) is underlain by several Paleoproterozoic basement provinces which have been defined on the basis of regional geochronology, thermochronology, and isotopic analysis (Fig. 1) (e.g. Bennett and DePaolo, 1987; Karlstrom and Humphreys, 1998; Whitmeyer and Karlstrom, 2007 and references therein). We adopt the basement province mapping of Karlstrom and Humphreys (1998), which includes three distinct provinces (Fig. 1). From northwest to southeast, they are (1) the Mojave province, which consists of crustal rocks older than 1.8 Ga and volcanic-arc rocks dated between 1.8 and 1.7 Ga; (2) the Yavapai province, which consists of juvenile crust dated between 1.8 and 1.7 Ga; and (3) the Mazatzal province, which consists of juvenile crust dated between 1.7 and 1.6 Ga (Karlstrom and Humphreys, 1998; Whitmeyer and Karlstrom, 2007 and references therein). The boundary between the Mojave Province and the Yavapai Province is thought to be a 75-km wide zone that is approximately enveloped by the northwest-dipping Gneiss Canyon and Crystal shear zones in Arizona and projected along strike to a similarly oriented suture zone on the southern side of the Cheyenne Belt (Hawkins et al., 1996; Ilg et al., 1996; Tyson et al., 2002). The boundary between the Yavapai and Mazatzal provinces is a suture zone that defines the southern limit of crust that is older than 1.7 Ga (Bennett and DePaolo, 1987; Shaw and Karlstrom, 1999; Whitmeyer and Karlstrom, 2007 and references therein). To the north of the suture zone, a northeast-striking structural fabric developed during the suturing of the Yavapai and Mazatzal provinces (Shaw and Karlstrom, 1999).

2.2. Surface geology and structure

The Paleoproterozoic basement of the Colorado Plateau is covered by Precambrian and Phanerozoic strata, including a relatively conformable, well-described Phanerozoic stratigraphic succession in many parts of the region (e.g. Mallory et al., 1972; Blakey, 2008; Lawton, 2008; Miall, 2008; Miall et al., 2008) (Fig. 3a). Regional geologic map patterns largely reflect the spatial distribution of structural highs and sedimentary basins that formed during the Turonian to Eocene Laramide orogeny (Fig. 1) (Dickinson et al.,