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Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA

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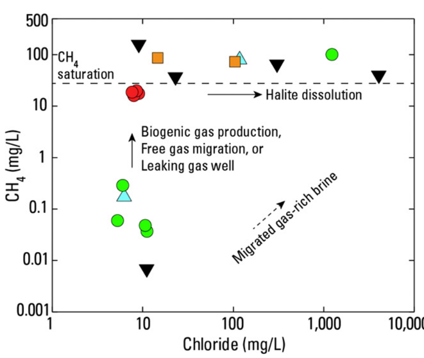
HIGHLIGHTS

- Leaking gas well contaminated shallow groundwater with thermogenic methane.
- Gas well drilled in 1956 and plugged and abandoned in 1990.
- Uncemented annular space behind production casing was likely migration pathway.
- Oxidation in thick unsaturated zone rendered methane undetectable at land surface.

GRAPHICAL ABSTRACT



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ABSTRACT

Site-specific and regional analysis of time-series hydrologic and geochemical data collected from 15 monitoring wells in the Piceance Basin indicated that a leaking gas well contaminated shallow groundwater with thermogenic methane. The gas well was drilled in 1956 and plugged and abandoned in 1990. Chemical and isotopic data showed the thermogenic methane was not from mixing of gas-rich formation water with shallow groundwater or natural migration of a free-gas phase. Water-level and methane-isotopic data, and video logs from a deep monitoring well, indicated that a shale confining layer ~125 m below the zone of contamination was an effective barrier to upward migration of water and gas. The gas well, located 27 m from the contaminated monitoring well, had ~1000 m of uncemented annular space behind production casing that was the likely pathway through which deep gas migrated into the shallow aquifer. Measurements of soil gas near the gas well showed no evidence of methane emissions from the soil to the atmosphere even though methane concentrations in shallow groundwater (16 to 20 mg/L) were above air-saturation levels. Methane degassing from the water table was likely oxidized in the relatively thick unsaturated zone (~18 m), thus rendering the leak undetectable at land surface. Drilling and plugging records for oil and gas wells in Colorado and proxies for depth to groundwater indicated thousands of oil and gas wells were drilled and plugged in the same timeframe as the implicated gas well, and the majority of those wells were in areas with relatively large depths to groundwater. This study represents one of the few detailed subsurface investigations of methane leakage from a plugged and abandoned gas well. As such, it could provide a useful template for prioritizing and assessing potentially leaking wells, particularly in cases where the leakage does not manifest itself at land surface.

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1. Introduction

Recent estimates indicate there may be 2 to 3 million abandoned oil and gas wells in the U.S. (Brandt et al., 2014; Townsend-Small et al., 2016). The fraction of abandoned wells that leak formation fluid is not well known but important to consider. With respect to methane, its release in the subsurface could lead to explosion hazards if the gas migrated to land surface and accumulated to high levels in confined spaces. Methane oxidation in the subsurface generates carbon dioxide that could promote mineral dissolution and subsequent trace-element mobilization, and release of methane directly to the atmosphere could have consequences for global warming given its potency as a greenhouse gas (Kang et al., 2016; Cahill et al., 2017). Methane releases were detected in 6.5 to 76% of abandoned oil and gas wells recently studied in Canada, the U.K., and U.S. (Watson and Bachu, 2009; Boothroyd et al., 2016; Kang et al., 2016; Townsend-Small et al., 2016).

Detection of methane releases from abandoned oil and gas wells often relies on near-surface monitoring techniques or indicators. Data from soil-gas probes, soil gas-flux chambers, and air monitoring, and evidence from infrared cameras or in the form of dead vegetation or gas bubbles in pooled water near abandoned wells, could indicate the presence of a gas leak (Chafin, 1994; Erno and Schmitz, 1996; Kang et al., 2014; Townsend-Small et al., 2016; Atherton et al., 2017). Methane oxidation in the unsaturated zone, however, can attenuate methane emissions from soils (Striegl et al., 1992; Erno and Schmitz, 1996; Warren and Bekins, 2015; Cahill et al., 2017), making it difficult to detect subsurface methane releases from abandoned wells using near-surface monitoring techniques. In those instances, groundwater monitoring wells may be needed to detect releases (Dusseault et al., 2014). Deciding which abandoned-well sites warrant the investment of monitoring wells is a challenge but could be based in part on information such as whether the well was plugged at the time of abandonment, vertical extent of the cement used to seal the well, age of the well, gas pressures present in the producing and overlying formations after well abandonment, and whether corrosive formation water was in long-term contact with the metal well casing (Watson and Bachu, 2009; King and King, 2013; Dusseault and Jackson, 2014).

There are few detailed subsurface studies of abandoned oil and gas wells in the literature. This paper uses time-series hydrologic and geochemical data collected from nested groundwater-monitoring wells together with soil-gas measurements, video logs, and gas-well construction information to evaluate whether thermogenic methane in groundwater at a site in the Piceance Basin, Colorado was from a nearby plugged and abandoned gas well. Other monitoring wells in the basin were sampled to provide regional context for the chemical data collected at the study site. The site was chosen for study because (1) it is characterized by a relatively thick unsaturated zone (18 m) that could be conducive to oxidation of methane moving upward from depth, (2) it has a gas well that was drilled in 1956 and plugged and abandoned in 1990, (3) it has three monitoring wells near the gas well that are screened in different aquifers, and (4) a video log from the deepest monitoring well showed vigorous degassing at the water surface in that well. Results from this study are considered in a larger context by examining oil and gas well abandonment records for the State of Colorado and proxies of groundwater depth to assess how many old oil and gas wells in the State might be associated with relatively large depths to water.

2. Geologic setting

The 2300-km^2 study area is in the Piceance and Yellow Creek watersheds within the Piceance structural basin, northwest Colorado (Fig. 1). The vertical thickness of sedimentary rocks in the basin is about 8550 m (Johnson and Rice, 1990). Fresh groundwater in the study area is primarily present in the upper ~750 m of the sedimentary section in narrow alluvial valley-fill aquifers and underlying bedrock aquifers in the Eocene Uinta Formation and Parachute Creek Member (PCM) of the Green River Formation (Fig. 1). Sediments of the PCM were deposited in Eocene Lake Uinta and consist of calcareous and dolomitic marlstone, calcareous sandstone, siltstone, and mudstone, with alternating lean and rich oil-shale zones (Johnson, 1981) (Figs. 1, S1). The PCM and deeper sections of the Green River Formation in the study area contain the world's richest oil-shale deposit (Johnson et al., 2010), a kerogen-rich rock that has high potential for oil formation if heated to high enough temperatures, but which contains very little oil at current in situ temperatures. Halite and nahcolite ($NaHCO_3$) occur in deeper zones of the PCM that have been partially leached by circulating groundwater (Johnson and Brownfield, 2013). Fractures in marlstone and vugs and breccias from dissolution of halite and nahcolite are the primary sources of permeability in the PCM. Rocks in the overlying Uinta Formation are a mix of sandstone, siltstone, mudstone, and marlstone deposited in a fluvial-deltaic system that filled Eocene Lake Uinta (Johnson, 1981). In general, the oil shale-rich Mahogany zone (MZ) within the PCM acts as a regional confining layer that separates the bedrock groundwater-flow system into an upper aquifer system composed of water-bearing units in the Uinta Formation and PCM above the MZ (PCMA) from a lower aquifer system composed of water-bearing units in the PCM below the MZ (PCMB) (Fig. 1) (Robson and Saulnier, 1981). Regional groundwater flow is generally from upland areas in the south and west toward the White River in the north (Fig. 1). In this northern area, saline groundwater in contact with halite and nahcolite from deeper zones of the PCM discharges at land surface (Thomas, 2015). Locally, groundwater-flow directions could be more variable than regional flow directions due to the effects of local topography and drainage systems on flow directions.

Natural-gas production has occurred in the basin since at least the 1950s. Most production occurs from vertical and directionally drilled wells in the Wasatch Formation, Mesaverde Group, and other geologic units below the aquifers (Fig. 1) (Johnson and Rice, 1990; Cumella and Ostby, 2003). Many gas wells, particularly those in tight sandstones of the Williams Fork Formation in the Mesaverde Group, are hydraulically fractured. Ninety percent of the gas wells in the study area for which depth information was available had depths >1600 m, and the median depth of gas wells was 3600 m (Colorado Oil and Gas Conservation Commission, 2017).

3. Materials and methods

Fifteen monitoring wells completed in the Uinta and PCM units were sampled 1 to 7 times from 2010 to 2016 for major ions and trace elements; methane, methane H and C isotopic compositions, and C_1–C_5 gas composition; N_2 concentrations in water; and noble gas concentrations and isotopic compositions (Fig. 1). Details on the methods of sample collection and analysis are described in the Supplementary information. Construction information and geochemical data for the sampled wells are listed in Table S1. Most of the wells were installed by the USGS in the 1970s as part of a project to characterize bedrock aquifers in the oil-shale region. One well, 13U, was installed by the USGS in 2010.

Three monitoring wells co-located at site 13 (13U, 13A, 13B) were the primary focus of this study. The wells were located 24 m (well 13B), 27 m (well 13U), and 51 m (well 13A) from a plugged and abandoned gas well (API 05-103-05143, Sulphur Creek #1) (Colorado Oil and Gas Conservation Commission, 2017) (Figs. 1, 2). Depths of the open intervals in the monitoring wells were 48.5–72.8 m (well 13U), 170–195 m (well 13A), and 237–265 m (well 13B) below land surface (Fig. 3). Wells 13A and 13B were completed in the PCMA and PCMB, respectively. The Uinta Formation and PCMA are complexly intertongued at their contact (Donnell, 2009); therefore, 13U may be completed in both the Uinta Formation and PCMA. As discussed in detail below, groundwater from 13U contained high concentrations of thermogenic methane. Sulphur Creek #1 was drilled into the Mesaverde Group to a