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The Conceptual Hydrogeologic Model: A Tool for Assessing the Source of Shallow Aquifer Contamination by Methane Gas

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Summary

Potential contamination of the shallow groundwater resource by natural gas drilling activities is increasingly a public concern. Contamination of shallow drinking water wells with methane gas has been the subject of recent Oscar-nominated documentaries (i.e., HBO's *Gasland*), lawsuits (e.g., *Businessweek*, 2010), and scientific investigations (e.g., the Mamm Creek area of Garfield County, Colorado, SSPA, 2007). In some geographic areas, regulators require baseline testing of water wells within some distance of a gas well prior to drilling (e.g., Alberta Environment, 2006). Baseline testing data allows for a relatively straightforward assessment of whether methane contamination in a water well is due to natural or anthroprogenic causes. Specifically, methane gas from an accumulation at depth could be introduced anthroprogenically by natural gas drilling activities, or naturally by seepage along a fault (e.g., Johnson and others, 1993) and shallow bacterial processes. However, baseline testing data is not always available, which makes it difficult to resolve landowner claims that a water well has been impacted by methane. A conceptual hydrogeologic model (CHM) of the shallow aquifer is a useful tool for understanding how methane was introduced. The CHM is used to identify pathways along which hydrocarbon gases could enter the shallow aquifer system, as well as the direction that hydrocarbon gas would be transported by groundwater and effects of mixing. When combined with hydrocarbon gas isotope data, the CHM is a powerful tool for resolving whether contamination of an aquifer by hydrocarbon gas is natural or anthroprogenic.

Introduction

The potential for contamination of shallow groundwater resources by natural gas drilling activities is increasingly a public concern. Natural gas wells typically penetrate deep formations with non-potable groundwater that potentially contains high concentrations of hydrocarbon gases. Leakage of the deep formation water and gas into a shallow aquifer has the potential to degrade water quality and impair the drinking water resource. Several examples of shallow aquifer contamination by deep hydrocarbon gas accumulations have been reported in areas of active or historical natural gas drilling. However, the cause of contamination (drilling-related or natural seepage) is difficult to determine, especially in the absence of baseline (i.e., pre-drilling) water quality data. For example, many studies are able to confirm that hydrocarbon gas has leaked into a shallow aquifer by comparing the isotopic compositions (i.e., thermogenic or biogenic) of hydrocarbon gases from an accumulation at depth and hydrocarbon gases in the shallow groundwater (e.g., Tilley and Muehlenbachs, 2007). This approach is relatively definitive when hydrocarbon gas in the shallow aquifer has a biogenic signature, and gas from the accumulation at depth has a thermogenic signature, indicating that gas in the shallow aquifer is not related to the gas from the accumulation at depth. However, when gas in the shallow aquifer and accumulation at depth both have a thermogenic signature, the hydrocarbon gas isotopes alone do not elucidate whether the groundwater contamination is anthroprogenic or natural. A conceptual hydrogeologic model (CHM) can be a useful tool for determining whether gas from an accumulation at depth has entered a shallow aquifer by natural or anthroprogenic processes. This paper discusses hydrocarbon gas fate and transport in the shallow aquifer, and provides an example of how a CHM can be used to evaluate the mechanism by which hydrocarbon gases from a deep accumulation were introduced into the shallow aquifer.

Theory

Hydrocarbon gases in shallow aquifers occur primarily in the dissolved state (Kohlbecker, 2010). This is shown in Figure 1, which displays in situ concentrations of methane in groundwater from shallow wells at the Hanford Site in Washington. The methane concentrations generally plot below the solubility curve (after Duan and Mao, 2006), indicating that groundwater is generally undersaturated with methane, and that methane occurs dissolved in groundwater.

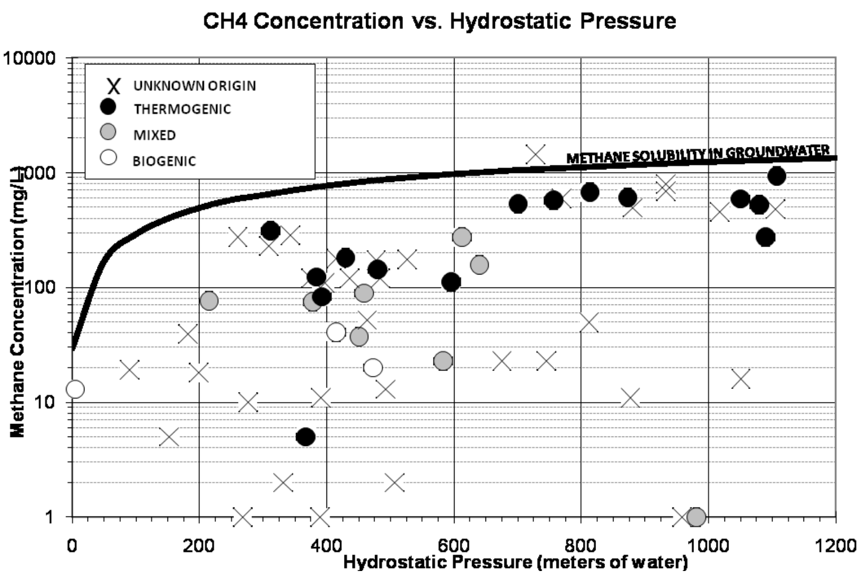

Figure 1: Methane Concentrations in Groundwater, Hanford, Washington State, USA. Data from Early and others (1986), from Kohlbecker and Papadopoulos (2010).

Because hydrocarbon gas occurs dissolved in groundwater, the gas can be transported laterally and vertically by groundwater advection (Webb, 2006), in some cases several kilometers (Johnson and others, 1993). Gas can also be transported vertically upwards by buoyancy or downward by downwelling of groundwater. During transport, hydrocarbon gases from different sources (e.g., thermogenic and in-situ bacterial gas) mix, which affects gas concentrations and isotope ratios. In addition, because C2+ compounds are less soluble in water than methane at the high hydrostatic pressures encountered in deep groundwater (Carroll and others, 1998), dry components of a gas are transported further by groundwater than wet components of a gas. Therefore, the shallow groundwater system affects hydrocarbon gas extent, concentration, isotope signature, and composition.

Examples

A conceptual hydrogeologic model is a useful tool for determining whether gases in the shallow groundwater system are due to natural or anthroprogenic causes. CHMs describe the hydrogeology of a groundwater flow system, including flow directions, recharge and discharge areas, boundaries to flow (i.e., aquifer compartmentalization), and preferential pathways. This paper uses an existing CHM (Early and others, 1986) for the Hanford Site in Washington State, USA, to support a determination of hydrocarbon gas source in shallow groundwater.

A CHM has been developed for the shallow aquifer at the Hanford site as a part of the basalt waste isolation project. A complete description of the CHM is beyond the scope of this paper, however, the primary components of the CHM are:

- Groundwater in the shallow basalt aquifer flows to the southeast, towards the center of the Pasco Basin (from left to right in Figure 2a below).
- Vertical groundwater gradients favor downwelling of groundwater across the Hanford site to a depth of about 2,000 feet bgs.
- Below 2,000 feet bgs, vertical gradients are neutral, so neither upwelling nor downwelling of groundwater is favored by groundwater advection.
- Faults act as boundaries to horizontal groundwater flow, and as conduits for vertical groundwater flow.

This CHM is illustrated in Figure 2a below.

(a) (b)

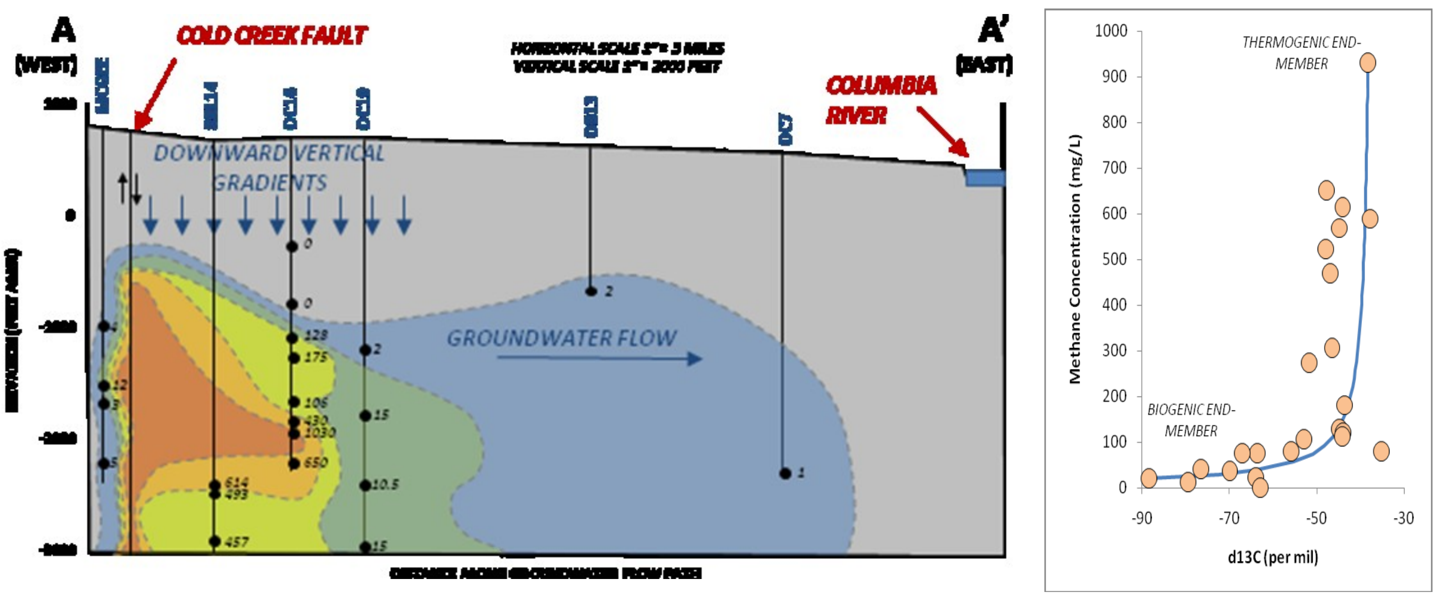

Figure 2: Methane Concentrations in Groundwater, Hanford, Washington State, USA. Data from Early and others (1986), modified from Johnson et al (1993). The concentration profile indicates that the source of methane is the Cold Creek Fault. Mixing curve in Figure 2b is $d13C_{mix} = [(x)(C_t)(d13C_t)+(1-x)(C_b)(d13C_b)]/C_{mix}$, where "b" is biogenic gas, and "t" is thermogenic gas, "C" is concentration, and "x" is the proportion of thermogenic gas. The biogenic end member is d13C = $-88^{0}/_{00}$, concentration = 10 mg/L, and thermogenic end member of d13C = $-47.8\ ^{0}/_{00}$, concentration of 650 mg/L.

High concentrations of methane (>100 mg/L) are encountered in the shallow basalt aquifer at the Hanford Site. Geochemical studies indicate that the methane is both thermogenic [from an accumulation located several thousand feet below ground surface (Johnson and others, 1993)], and biogenic (from organic material within interflow zones in between basalt flows). The gas is also dry (>99.9% methane, Johnson and others, 1993). Figure 2a shows methane concentrations in basalt groundwater at the Hanford Site.

Using the CHM to interpret the hydrocarbon gas data collected at the Hanford Site, it is evident that methane is introduced into the shallow aquifer by natural causes—specifically, leakage along a fault. As shown in Figure 2a, methane concentrations are highest adjacent to the Cold Creek Fault, which is a vertical pathway for groundwater flow. Methane is transported upwards along the fault dissolved in groundwater by buoyant and advective groundwater flow. Upward methane transport is limited by downwelling of groundwater caused by downward vertical gradients. Downgradient of the fault, methane concentrations descrease along the groundwater flowpath (Figure 2a) as methane is transported laterally with groundwater flow. Concentrations decrease as methane-bearing groundwater is mixed with groundwater that contains little to no methane, and carbon isotope ratios become more depleted (i.e., more negative) as thermogenic methane is mixed with in-situ bacterial methane in the shallow aquifer (see mixing curve in Figure 2b).

In addition to evaluating the source of the methane in groundwater at the Hanford Site, the CHM can be used to evaluate other important aspects of methane contamination in shallow groundwater. For example:

- Why methane is present in some water wells, and not present in others (related to location relative to the Cold Creek Fault, and well depth)
- The rationale for why methane at a given well is biogenic or thermogenic (i.e., which is in part related to distance downgradient of the Cold Creek Fault and the amount of mixing that has occurred)
- Mixing proportions of the thermogenic and biogenic gas at a given sampling location, using the mixing curve.

Conclusions

In situations where baseline testing data is not available, a CHM is a valuable tool for interpreting the occurrence of hydrocarbon gases in shallow groundwater, and determining whether gas in shallow aquifers was introduced naturally or anthroprogenically.

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