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Natural seepage of shale gas and the origin of "eternal flames" in the Northern Appalachian Basin, USA

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ABSTRACT

Natural hydrocarbon gas seeps are surface expressions of Petroleum Seepage Systems, whereby gas is ascending through faults from pressurized reservoirs that are typically associated with sandstones or limestones. A spectacular "eternal flame" in western New York State marks a gas macroseep of dominantly thermogenic origin emanating directly from deep shale source rocks, which makes this a rare case in contrast to most Petroleum Seepage Systems where gas derives from conventional reservoirs.

The main flaming seep releases about 1 kg of methane per day and may feature the highest ethane and propane ($C_2 + C_3$) concentration ever reported for a natural gas seep ($\sim$35 vol. %). The same gas is also released to the atmosphere through nearby invisible and diffuse seepages from the ground. The synopsis of our data with available gas-geochemical data of reservoir gases in the region and the stratigraphy of underlying shales suggests that the thermogenic gas originates from Upper Devonian shales without intermediation of a conventional reservoir. A similar investigation on a second "eternal flame" in Pennsylvania suggests that gas is migrating from a conventional sandstone pool and that the seep is probably not natural but results from an undocumented and abandoned gas or oil well. The large flux of the emitted shale gas in New York State implies the existence of a pressurized gas pool at depth. Tectonically fractured shales seem to express "naturally fracked" characteristics and may provide convenient targets for hydrocarbon exploration. Gas production from "tectonically fracked" systems might not require extensive artificial fracking.

1. Introduction

Natural gas seeps provide opportunities for direct sampling of gas from subsurface hydrocarbon accumulations without upfront need for drilling or other means of petroleum exploration (Link, 1952; Jones and Drozd, 1983; Etiope, 2009). Hydrocarbon gas and oil can migrate upward along faults in active Petroleum Seepage Systems (Abrams, 2005) until gas vents and oil seeps from soil or rocky outcrops become diagnostic natural hydrocarbon point sources within Total Petroleum Systems (Magoon and Schmoker, 2000; Etiope et al., 2009a). An assessment of the flux and geochemical characteristic of seeping gas constrains the subsurface hydrocarbon potential, genesis and gas quality, e.g., by discriminating shallow microbial gas from deeper thermogenic gas, and by quantifying undesirable non-hydrocarbon gases carbon dioxide (CO_2), nitrogen (N_2), and hydrogen sulfide (H_2S). Significant and widespread subsurface oil biodegradation affects the majority of the world's conventional oil reservoirs and increases the cost of recovery and refining (Head et al., 2003; Aitken et al., 2004; Jones et al., 2008). Oil biodegradation is undetectable by geophysical methods and is typically diagnosed geochemically after drilling and recovery of hydrocarbon samples. However, low quality, biodegraded subsurface petroleum can sometimes be recognized by specific geochemical signals in seeping gas (Dimitrakopoulos and Muehlenbachs, 1987; Etiope et al., 2009b), such as ^{13}C-enrichment of CO_2, ethane (C_2H_6) and propane (C_3H_8). Natural hydrocarbon seeps thus serve as natural windows to depth and can predict deep biodegradation even before drilling. Last but not least, natural geologic gas seepages, including exhalations from mud volcanoes and other types of seeps (e.g., Etiope, 2009) are important natural sources of greenhouse gases on a global scale. Geologic methane emissions from hydrocarbon seeps are second in size only to wetlands (Etiope et al., 2008; Etiope, 2012) and are often

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accompanied by photochemical pollutants and ozone precursors C_2H_6 and C_3H_8 (Etiope and Ciccioli, 2009).

Natural gas seeps with significant, continuous and long-lasting gas fluxes are generally driven by pressurized deep gas pools, which are attributed to conventional reservoir rocks (typically porous sandstones or limestones) and are connected to the surface by faulting of overlying cap rocks. There are no studies documenting gas seeps issuing directly from less porous shales as source rocks.

This study presents the first geochemical and flux data of a natural shale gas seep. We document an extraordinary case in the northern Appalachian Basin, at Chestnut Ridge County Park in the state of New York, where gas seepage has supported a spectacular "eternal flame" throughout the available recorded history, and may have burnt naturally for many hundreds or even thousands of years (Fig. 1). We compared molecular and isotopic compositions of seep gases with published data of regional shale and reservoir gases (Jenden et al., 1993; Osborn and McIntosh, 2010) to test whether emanating thermogenic gas originates directly from shale or passes through intermediate storage in a conventional reservoir. In addition, we used portable gas detectors to measure CH_4 and CO_2 fluxes into the atmosphere (with indirect estimates of C_2H_6 and C_3H_8 emissions) at the burning seep and in the surrounding area to evaluate invisible diffuse seepage along exposed fault lines. The overall gas emission rate and spatial flux pattern characterize the seepage system as it contributes to global atmospheric hydrocarbons, which represent a major contribution to greenhouse gases and photochemical pollutants (US EPA, 2010; Etiope and Ciccioli, 2009).

A similar detailed survey was made at another flaming gas seep near Clarington, Pennsylvania, to determine gas origin, provenance (either from a sandstone reservoir or shale), and whether the seepage is natural or due to a leak from an abandoned gas or oil well (Fig. 1).

The eternal flame in Chestnut Ridge County Park in New York is a regional touristic attraction, whereas the seep in Pennsylvania is only known to a few nearby residents. To the best of our knowledge, neither seep has ever been scientifically studied although they may represent the largest current gas seeps in the Appalachian Basin that are supporting open, unattended flames. The natural eternal flame in Chestnut Ridge County Park not only boasts a stunning beauty as it shines from behind the veil of a cascading waterfall, but its gas also exhibits a unique and extremely unusual molecular composition. Scientific inquiry along the ongoing controversy about the safety of fracking for shale gas production mandates reliable geochemical baseline data of natural, uncontaminated shale gas for direct forensic comparison with shallow hydrocarbon gases in potentially contaminated ground water that are suspected to result from improper drilling and fracking techniques, in particular by faulty casing cementation. The gas supporting the

Figure 1. "Eternal flame" behind the veil of a waterfall in Chestnut Ridge County Park in New York State (top) and near Clarington in Pennsylvania (bottom).