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New gas material balance to quantify biogenic gas generation rates from shallow organic-matter-rich shales

M. Cokar [a], B. Ford [b], M.S. Kallos [a], I.D. Gates [a,*]

[a] *Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, Canada*
[b] *Husky Energy Inc., 707 8 Ave., SW Calgary, AB, T2P 1H5 Canada*

HIGHLIGHTS

- New theory to describe production from shallow biogenic shale gas reservoirs applied to two fields in Western Canada.
- Significant fraction of stabilized rate due to currently generated biogenic gas.
- Biogenic shale gas productivity potentially enhanced if microbes are stimulated.
- Two new Langmuir isotherms obtained from preserved core samples presented in paper.

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ABSTRACT

With increased demand for fossil fuels of more than 50% in the next 25 years, several methods of either enhancing oil and gas production from existing fields or finding new fields and tackling unconventional sources, such as shale gas reservoirs, are currently underway. Microbially-generated methane gas is a significant portion of commercial gas production around the world. At least 20% of the world's methane originates from methanogens that reside within organic-matter-rich shales and coals. The metabolic processes and chemical reactions carried out by microorganisms in shale gas reservoirs are currently unknown making it difficult to predict or enhance gas generation rates within a given reservoir. Field production data reveal that gas production from these reservoirs declines initially and then stabilizes after a specified time. The stabilized rate is controlled by contributions from biogenic gas generation, desorption of gas from kerogen, and diffusion and transport of gas through nanometer to potentially even micron scale pore systems. It still remains unclear which one of microbial gas generation or gas transport is the key limitation on production of biogenic gas from shale gas reservoirs. This paper presents a modified gas material balance on production data for shale gas wells to account for biogenic gas generation. Although the gas material balance approach is well established, it has not been used to estimate biogenic gas generation rates. By using actual gas production data from a field where biogenic gas production is known to be the main source of gas generation, the amount of biogenic gas that was produced within the reservoir during the resource lifetime of the well could be determined. The results of the theory presented here were compared to gas production data from Nexen's Bigstick Field and Husky's Abbey Field. The results reveal that a significant fraction, up to about one-third, of gas production is sourced from constant biogenic gas generation. The implication is that biogenic shale gas productivity can be potentially enhanced if microbes are stimulated.

1. Introduction

Shale gas is an unconventional gas resource that is found in organic rich, fine grained low permeability formations. It is estimated that the Western Canadian sedimentary basin (WCSB) contains over 1000 trillion cubic feet of gas in its shale deposits. Shales are the source rock for hydrocarbon production and are known to produce methane gas through biogenic, thermogenic or combination mechanisms [1]. Biogenic gas is generated from anaerobic bacteria that produce methane during early diagenesis. Thermogenic gas originates from thermal cracking of kerogen at extremely high temperatures and pressures [2]. With increasing natural gas demands within Canada and North America and beyond, shallow biogenic gas reserves are viable sources for natural gas [3]. Within biogenic shale gas formations, the natural gas can be stored as free gas within fractures or rock pores, adsorbed gas on organic materials such as kerogen or inorganic materials such

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[*] Corresponding author. Tel.: +1 403 220 5752; fax: +1 403 284 4852.
E-mail address: ian.gates@ucalgary.ca (I.D. Gates).

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Nomenclature

C_E	equilibrium isotherm (mol/m^3)
C_{Ei}	initial equilibrium isotherm (mol/m^3)
c_φ	porosity compressibility (1/Pa)
D	day
G_p	gas produced (m^3)
n	moles of gas
n_p	moles of gas produced
$n_{2\mathrm{i}}$	moles of gas initially in secondary porosity
n_{1i}	moles of gas initially in primary porosity
γ	moles of gas produced during production period by microbes
n_2	moles of gas in secondary porosity
n_1	moles of gas in primary porosity
P	pressure (Pa)
P_i	initial Pressure (Pa)
P_{sc}	pressure at standard conditions (Pa)
P_L	langmuir pressure constant (Pa)
R	universal gas constant (J/mol K)
S_{gi}	initial gas saturation
S_{wi}	initial water saturation
S_{wavg}	average water saturation
T	temperature (K)
T_{sc}	temperature at standard conditions (K)
V	volume (m^3)
V_E	volumetric adsorption isotherm (standard m^3/m^3)
V_L	volume constant for Langmuir isotherm (standard m^3/m^3)
V_{b2}	bulk volume of the secondary porosity (m^3)
z	gas compressibility
z_i	initial gas compressibility
z_{sc}	gas compressibility at standard conditions
φ_i	initial Porosity

as clays, or gas that has been dissolved into water within the reservoir [1].

Natural gas systems are usually placed into three categories, illustrated in Fig. 1. The first category, the deepest one, is the thermogenic kitchen where temperatures are relatively hot and gas is produced by thermogenesis, this region is capped off by the thermogenic ceiling. The depth of the thermogenic ceiling varies with temperature and geothermal gradient, and does not always occur at the same depth. Thermogenic gases are produced by degradation of kerogen or oil at temperatures above 150–160 °C up to about 250 °C [4]. In the second category, the shallowest one, is a favorable environment for microbes to generate methane gas; the bottom of this level is known as the biogenic floor. The depths of the biogenic floor and the thermogenic ceiling will vary between reservoirs, but on average the biogenic floor is about 550 m below the surface [3]. The third category sits between the thermogenic and biogenic categories and contains thermogenic gas that has been displaced from deeper intervals and some biogenic gas. Biogenic gases originate from bacterially-mediated anaerobic mineralization of organic matter in sediments up to about 75 °C. Microorganisms in the reservoirs produce biogenic gas, which is mainly made up of methane, however it can also contain up to 2% of other gases such as ethane, propane, butane, and pentane [5,6]. More than 20% of all natural gas in reservoirs in the world is from biogenic gas [5].

A series of microbial ecosystems are involved in the production of biogenic gas. Initially, if present, oxygen is consumed by aerobic bacteria. After the oxygen is depleted, sulfate reduction from the pore water becomes the dominant form of respiration within the system. After the sulfate is consumed, then methane generation occurs mainly by reduction of CO_2 by hydrogen [5]. Hydrogen is produced by bacteria that metabolize organic materials that are present within the reservoir. Although biogenic gas is generated relatively slowly inside shale formations, economic amounts of methane have already accumulated within these reservoirs.

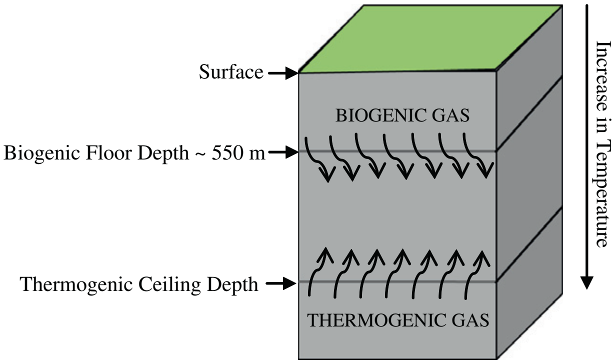

Fig. 1. Sketch of relative depths of biogenic floor and thermogenic ceiling.

Microorganisms generate methane via the following two metabolic pathways: carbon dioxide reduction and acetate formation. Most of the methane is produced via carbon dioxide reduction, except for fresh water environments where acetate formation is more common [3]. There are five main environmental and physiological constraints on methane producing archaea:

1. *Anoxic environment* – these microorganisms are anaerobic and need an oxygen-free environment.
2. *Sulfate-deficient environment* – methane will accumulate in areas where there is little or no sulfate.
3. *Temperature* – temperatures between 0 and 75 °C are required.
4. *Organic Matter* – organic matter is the main nutrient source and is metabolized by several oxidation – reduction reactions.
5. *Space* – the size of individual bacteria is 1–10 μm, therefore they cannot live in highly compacted shale environments.

There are several limitations in our understanding of production, storage and transport mechanisms of natural gas in shallow biogenic gas systems. Production of methane by microbial activity depends on geochemical, geological, hydrological and biochemical properties of the formation. However, storage and transport of biogenic gas depends on rock permeability and porosity [2]. For biogenic shale gas reservoirs, production data typically follows a decline from an initial peak production rate which stabilizes to a nearly constant value after a specified time. The stabilized rate is controlled by contributions of biogenic gas generation, desorption of gas from kerogen, and diffusion and transport of gas through nanometer to potentially even micron scale pore systems. It still remains unclear which one of gas generation versus gas transport limits production from shale gas reservoirs. Here, we present a modified gas material balance on production data for shale gas wells to account for biogenic gas generation to examine contributions from biogenic gas generation. More specifically, we derive a modified gas material balance that includes a biogenic gas generation