Towards net zero: lowering steam-to-oil ratios with thermophilic bacteria and N_2 biogas

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Summary

Heavy oil reservoirs make up the vast majority of Canada's crude oil reserves and are a major driver of its economic prosperity, contributing 6% of the country's GDP. Greenhouse gas (GHG) emissions associated with oil sands production can be double that of conventional oil production. Canada and Canadian oil producers have committed to work towards net zero emissions, which will require innovations that lower GHG emissions per barrel in the oil sands. This work applies the revolution in life sciences and microbial genomics by approaching oil reservoirs as habitats with microbiomes that can be harnessed for emissions reduction. Thermophilic bacteria occurring as dormant spores in low temperature heavy oil formations can be activated by heat conduction from adjacent reservoir zones that are produced via steam injection. For example, steam chambers in SAGD target only a portion of the resources in place, with overlying inclined heterolithic strata (IHS) containing as much or more heavy oil. During steam injection, over time, IHS layers spend years in the 50-100°C temperature range, which is ideal for thermophilic bacteria. Conductively heated zones in reservoirs thus represent a target zone for stimulating microbial enhanced oil recovery by awakening dormant microbes and promoting their metabolic production of non-condensable gas. Nutrient cocktails designed to stimulate thermophiles in the reservoir to produce N_2 biogas (instead of CH_4 biogas) are readily stimulated in oil sands samples. Liquid nutrients introduced into target zones (e.g., by uncapping pre-existing delineation wells) can be converted into biogas volumes that are up to 40-fold greater than the original volume of liquid at these warm temperatures, owing to the high solubility of the nutrients. Introducing liquid nutrients avoids the inherent inefficiency of injecting non-condensable gas (e.g., CH_4) directly. Since the dormant microorganisms are distributed ubiquitously throughout the reservoir sandstone, their biogas production promotes an evenly distributed 'squeezing' mechanism in the IHS zone of the reservoir, akin to compaction drive. The generation of N_2 non-condensable gas by bacteria throughout the target zone of the reservoir creates a uniformly distributed source of reservoir energy that drives a primary recovery process. This causes the less viscous oil in the conductively heated IHS to flow down-dip towards production wells (see Figure 1). The production of additional oil without introducing any additional steam lowers the steam-to-oil ratio and the emissions intensity of these oil production practices.

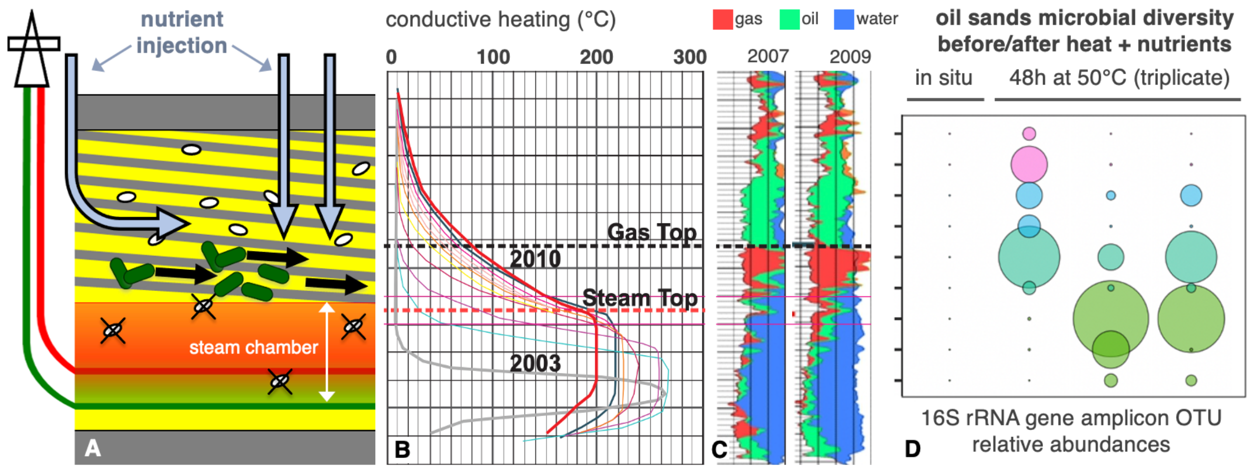

Figure 1. *Oil sands reservoir architecture and steam assisted gravity drainage (SAGD) shown in (A) depicting horizontal wells for steam injection (red) and oil production (green) situated where the steam chamber (bottom shaded area) establishes at the base of the reservoir. SAGD usually consists of 6-8 well pairs at each of several well pads in a 1-2 km^2 area (Strobl et al, 2014; see also YouTube animation: https://www.youtube.com/watch?v=ndT_eU0cJgo). IHS of interbedded oil sands (yellow) and mudstone (grey) harbour dormant bacterial endospores (white ovals) that are killed by the ~200°C steam but can germinate into active cells (green rods) during conductive heating at less extreme temperatures in IHS, e.g., shown in (B) with data from Cenovus, Christina Lake (AER, 2010) collected by thermocouples installed in vertical delineation wells originally drilled for exploration (NB: vertical wells can be repurposed for nutrient addition as shown in A). Comparing 2003 (start of SAGD) with 2010 demonstrates an enlarging habitable zone of 50-100°C for thermophiles during conductive heating of IHS. Dormant thermophiles in oil sands include Geobacillus thermodenitrificans (D: lower right, green circles), which increase from below detection to 60-90% of the total microbial community present, after 48 h at 50°C (see also Fig. 3B). This shows that viable thermophilic spores in oil sands and can be stimulated to germinate. Activating dormant thermophiles to produce biogas (black arrows in A) facilitates additional drainage without additional steam injection. Thermophile activation may already be contributing to drainage from IHS, given the gas build-up during conductive heating at temperatures <100°C during the first few years of SAGD (panel C shows gas build-up data collected in 2007 and 2009 from the Cenovus site shown in B).*

Background

Over a century ago, microbial ecologists observed that microorganisms can be found in settings that do not promote their growth and metabolism, leading early pioneers Beijerinck and Baas-Becking to suggest that "*everything is everywhere, but, the environment selects*" (e.g., Baas-Becking, 1934). An example of this is the discovery of thermophilic bacteria in cold sedimentary environments, such as anaerobic thermophiles in permanently cold Arctic marine seabed samples that exist as dormant endospores (Hubert et al, 2009). The presence of viable endospores can be demonstrated dramatically in experiments on sediment samples from low temperature environments, where heating from ambient (~4°C) up to 50°C shows that metabolic rates increase dramatically (Figure 2). By providing additional nutrients as well as temperature, this increase in metabolism can be amplified even more (Figure 2).

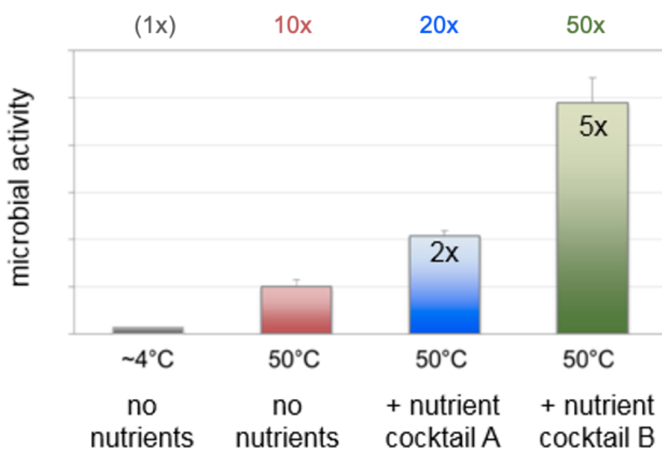

Figure 2. *When sediment samples in a 4°C environment are heated to 50°C, rates of metabolism by anaerobic bacteria increase by an order of magnitude. If nutrients are also provided, then this metabolic rate increases even further (by 2x with nutrient cocktail A, and by 5x with nutrient cocktail B). These principles can be applied to enhance oil recovery by activating and stimulating thermophilic bacteria that are ubiquitously present in conductively heated zones of shallow, low ambient temperature heavy oil reservoirs.*

Results

In order to demonstrate the potential for non-condensable N_2 gas generation by ubiquitous thermophiles in heavy oil reservoirs, easily accessible oil sands were sampled from outcrops along the Hangingstone River in Fort McMurray, Alberta. Incubation of oil sands together with a liquid nutrient cocktail designed to promote N2 production resulted in the rapid growth of anaerobic bacteria, as shown in Figure 2. *Geobacillus thermodenitrificans* and other thermophiles were identified in the cultures. Genome sequencing confirmed that these organisms have the genes that are required to convert liquid nutrients into N_2 gas. The heat tolerance of the dormant bacterial spores in these samples was tested by three rounds of autoclaving at 121°C, interspersed with short <12h periods at 50°C. Spores of bacteria capable of N_2 production were able to survive this heat treatment, underscoring the suitability of this approach and using these bacteria for enhancing non-condensable gas based oil recovery mechanisms associated with steam injection that results in conductive heating of reservoir target zones.

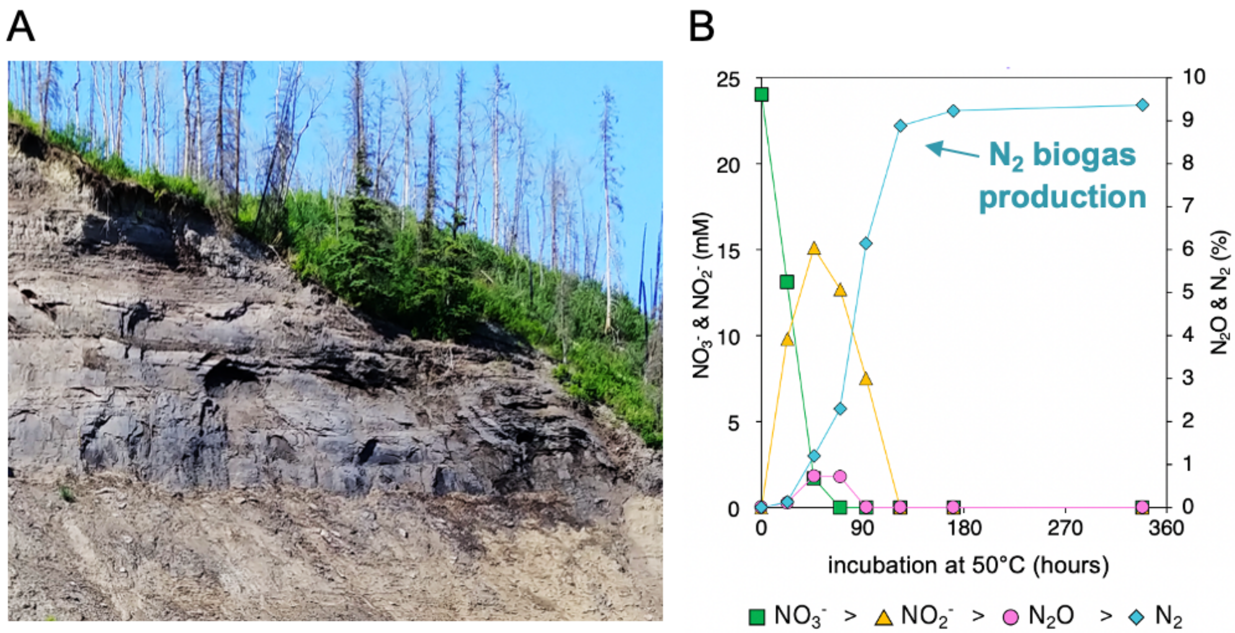

Figure 3. *The Hangingstone River outcrop shown here (A) was sampled as an easily accessible source of large-volume heavy oil reservoir samples (outcrops are tectonically uplifted reservoir intervals). The samples were combined with liquid nutrients and incubated at 50°C (B) resulting in rapid generation of N_2 biogas in <100 hours, and a corresponding enrichment of thermophilic spore-forming bacteria such as Geobacillus thermodenitrificans (Fig. 1D).*

Novel Information

Testing these principles at high pressure in oil and sand pack reactors inoculated with cultures of oil sands thermophiles demonstrates substantial oil volumes can be pushed out of the sand pack with less than three weeks of incubation at 50°C (see video using clear mineral oil: https://youtu.be/xbImEK7rHhY). This is consistent with the rapid growth of biogas-generating bacteria in the presence of appropriate nutrients (Fig 3B).

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