

# Field Evidence for Co-Metabolism of Trichloroethene Stimulated by Addition of Electron Donor to Groundwater

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For more than 10 years, electron donor has been injected into the Snake River aquifer beneath the Test Area North site of the Idaho National Laboratory for the purpose of stimulating microbial reductive dechlorination of trichloroethene (TCE) in groundwater. This has resulted in significant TCE removal from the source area of the contaminant plume and elevated dissolved CH<sub>4</sub> in the groundwater extending 250 m from the injection well. The  $\delta^{13}\text{C}$  of the CH<sub>4</sub> increases from  $-56\text{‰}$  in the source area to  $-13\text{‰}$  with distance from the injection well, whereas the  $\delta^{13}\text{C}$  of dissolved inorganic carbon decreases from  $8\text{‰}$  to  $-13\text{‰}$ , indicating a shift from methanogenesis to methane oxidation. This change in microbial activity along the plume axis is confirmed by PhyloChip microarray analyses of 16S rRNA genes obtained from groundwater microbial communities, which indicate decreasing abundances of reductive dechlorinating microorganisms (e.g., *Dehalococcoides ethenogenes*) and increasing CH<sub>4</sub>-oxidizing microorganisms capable of aerobic co-metabolism of TCE (e.g., *Methylosinus trichosporium*). Incubation experiments with <sup>13</sup>C-labeled TCE introduced into microcosms containing basalt and groundwater from the aquifer confirm that TCE co-metabolism is possible. The results of these studies indicate that electron donor amendment designed to stimulate reductive dechlorination of TCE may also stimulate co-metabolism of TCE.

## Introduction

Trichloroethene (TCE) is a suspected human carcinogen and one of the most widespread and persistent groundwater contaminants in many industrialized nations (1). Remediation of TCE with pump-and-treat or vapor-stripping techniques is difficult and expensive because of its low solubility (1100 mg/L in water) and high density (1.46 g/cm<sup>3</sup>), especially

in deep groundwater aquifers. As a result, there has been significant interest in developing in situ options for degrading TCE. Reductive dechlorination of TCE to ethene and chloride has emerged as one of the most promising methods for accomplishing this goal. In essence, under anaerobic conditions when suitable electron donors (e.g., lactate) are available, microorganisms can utilize TCE as an electron acceptor, sequentially removing chlorine atoms from TCE to form dichloroethene (DCE), then vinyl chloride (VC), and finally ethene. This process occurs naturally at sites where the appropriate conditions exist (2–6).

In TCE-contaminated aquifers, reductive dechlorination can be encouraged by adding electron donor and/or other nutrients to the groundwater to produce an anoxic environment (7–9). At some sites, addition of electron donor does not induce complete reductive dechlorination by the natural microbial populations (leading to accumulation of DCE). Supplementation with microbial consortia enriched from sites where complete reductive dechlorination does occur (bioaugmentation), has been shown to stimulate complete reduction to ethene (10–13).

Another promising method of bioremediation of chlorinated solvents involves co-metabolism of the contaminants by aerobic microorganisms in groundwater and soils (15, 16). Several aerobic microorganisms have been demonstrated to be capable of doing this, including methane oxidizers (17–19), phenol-degraders (20), and toluene-degraders (21). Unlike reductive dechlorination, the chlorinated compounds are completely mineralized to CO<sub>2</sub> and chloride with no intermediates making co-metabolism an attractive alternative where it can be sustained. However, the microorganisms gain no energy from these processes, limiting the ability of cells to co-metabolize chlorinated compounds (22, 23). This, together with the difficulties and high costs of maintaining substrate and anoxic environment, have led to limited field-scale application of co-metabolism for solvent degradation.

In this study, we present data from a field site that has been undergoing long-term electron donor addition to stimulate reductive dechlorination of TCE in groundwater. The primary effect of the electron donor addition has been significant decreases in TCE concentrations, especially within 50 m of the injection well. Changes in the chemistry and microbiology of the groundwater (8, 10, 14) include an increase in the dissolved CH<sub>4</sub> content of the groundwater as far as 250 m down-gradient from the injection well. This suggests that oxidation of the CH<sub>4</sub> by methanotrophic bacteria could lead to enhanced co-metabolism of the chlorinated solvents in the groundwater, providing a secondary mechanism for TCE removal.

## Materials and Methods

**Field Site and Sample Collection.** Test Area North (TAN) is an Idaho National Laboratory (INL) facility located on the Snake River Plain of eastern Idaho (Figure 1). TAN consists of several experimental and support facilities used for research and development on reactor performance and nuclear safety (24). From 1953 to 1972, liquid waste consisting primarily of industrial and sanitary wastewater was pumped into the upper aquifer through a 93 m deep injection well, TSF-05 (Figure 1). This resulted in a TCE plume (defined by TCE concentrations >5 ppb or 38 nM) in the upper aquifer extending 2 km down-gradient from TSF-05. In 1999, a pilot study was conducted to explore the potential for enhancing in situ reductive dechlorination of TCE through injection of

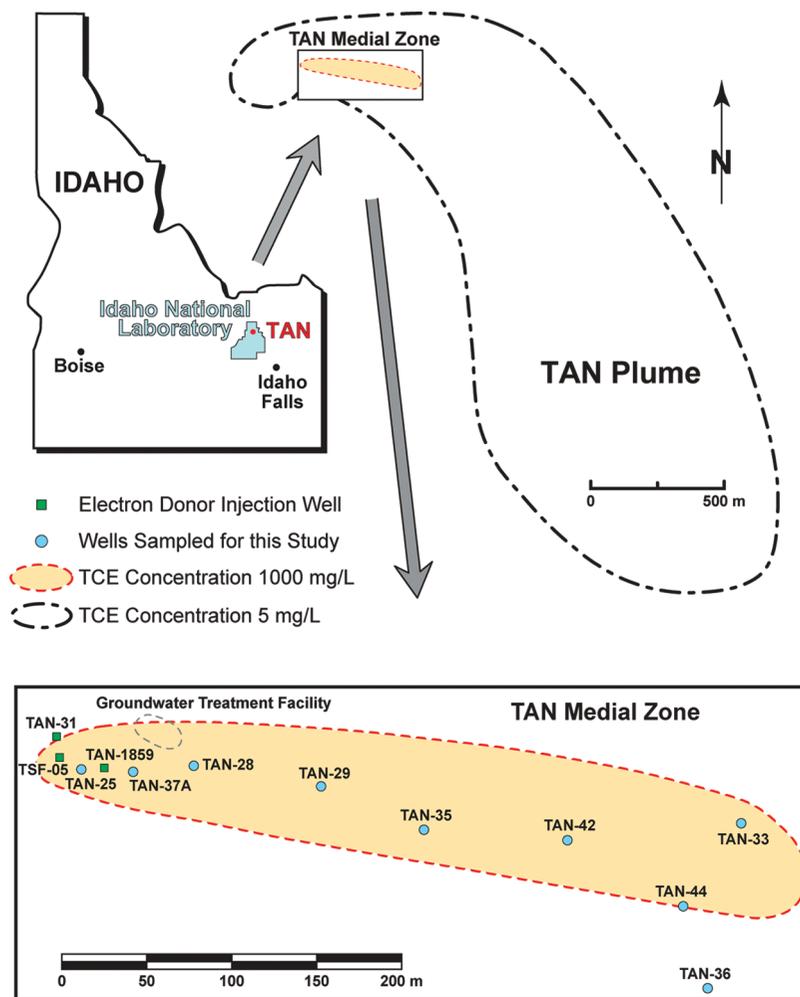
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**FIGURE 1.** Map showing the location of the INL and TAN with an expanded view of the core area ("medial zone") of the TAN plume showing the locations of the monitoring wells sampled for this study (light blue circles) and the wells used for electron donor injection (green squares).

Na-lactate (8). Following favorable results from the pilot test, electron donor addition has been continued through the present.

The geology at TAN consists of highly fractured, permeable basalt flow units ranging in thickness from 1 to 15 m. Between some of the basalt flows are low-permeability sedimentary interbeds composed of fluvial, lacustrine, and aeolian deposits (25). The depth to groundwater at the TAN site is approximately 70 m. The upper aquifer is approximately 65 m thick and is separated from the main Snake River Plain Aquifer by a continuous impermeable sedimentary interbed.

In May 2007, groundwater and biomass samples were collected from 8 wells in the TAN plume for this project (Figure 1). The samples were collected with dedicated down-hole pumps following purging of the groundwater using a low-flow technique to minimize wastewater. Most of these wells have screened or uncased intervals through most of the upper aquifer (Table S.1 in the Supporting Information contains the screened intervals). This is a potential source of variability for the sampling data; however, this is minimized by the low-flow sampling technique.

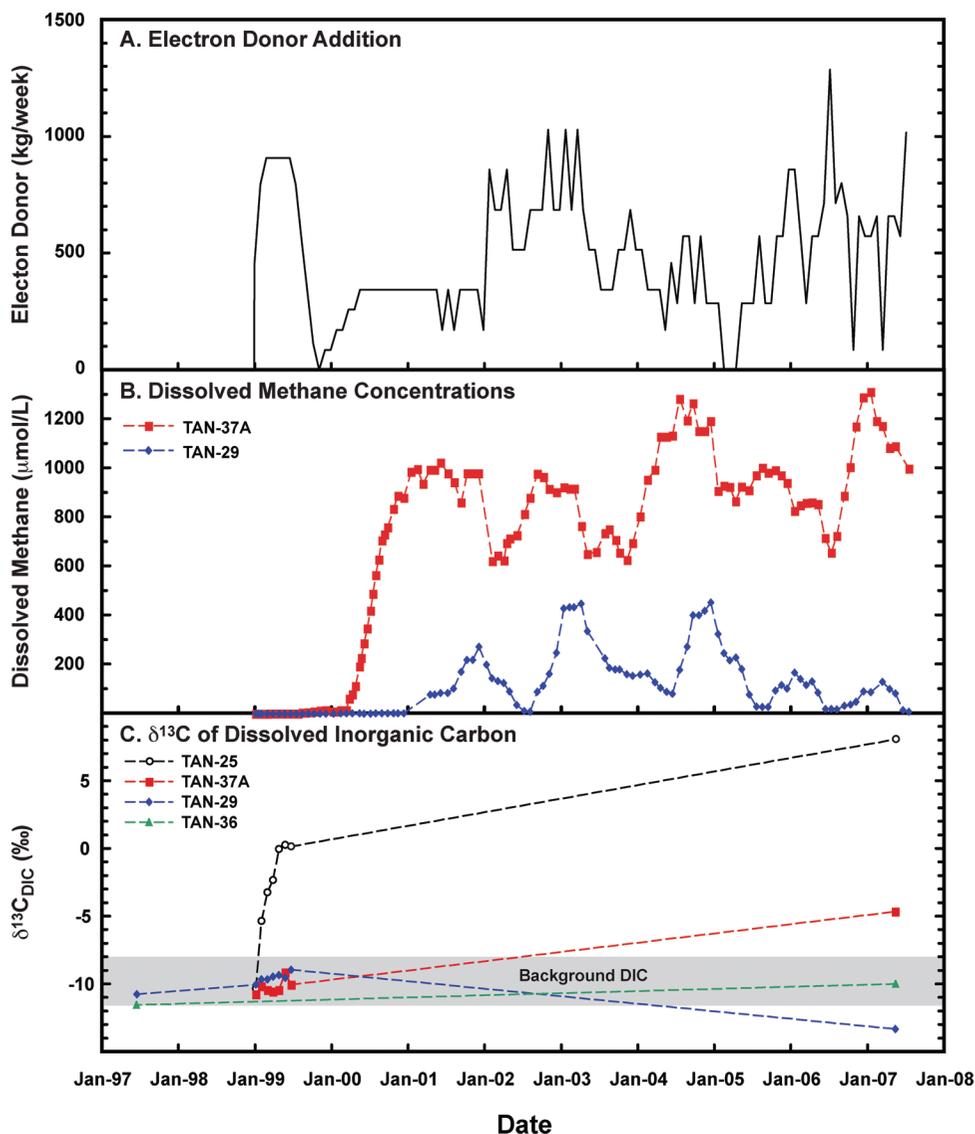
From each well, duplicate samples were collected in 40 mL vials for measurements of the concentrations and isotopic compositions of chlorinated solvents. For CH<sub>4</sub> and dissolved inorganic carbon (DIC) analyses, approximately 400 mL was collected in a custom glass flow-through vessel fitted with Teflon valves at the inflow and outflow ends that could be sealed after the vessel was flushed and filled with groundwater. Biomass samples were filtered from 0.25 to 20 L of

groundwater for molecular analysis of the microbial community structure (more detail on the biomass sampling procedures is contained in the Supporting Information).

To provide material for laboratory incubation experiments to test for the ability of the endogenous microbial community to co-metabolize TCE, six flow-through in situ bioreactors (ISBRs) containing crushed basalt from core collected from the TAN site were suspended in the upper aquifer in TAN-35 for 8 months (November, 2006 through July, 2007) to allow microorganisms from the TAN groundwater to colonize the basalt. Each ISBR was 1 m in length with an inner diameter of 2.5 cm. Water from the aquifer was pumped through the ISBRs at flow rates of 0.1 m/day in three reactors and 1.0 m/day in the other three, representing the minimum and maximum flow rates in the aquifer. Following removal of the ISBRs from the aquifer, the groundwater was drained from the reactors and collected in airtight containers. The basalt was then removed from the reactors for the incubation experiments.

**Analytical Techniques.** The dissolved CH<sub>4</sub> concentrations were measured by replacing a known volume of sample with helium gas in bottles containing a sample collected with no headspace. The CH<sub>4</sub> concentration in the helium bubble was then analyzed and converted back to a dissolved CH<sub>4</sub> concentration using the Henry's Law constant for CH<sub>4</sub> in water.

The δ<sup>13</sup>C values of the DIC and CH<sub>4</sub> from the groundwater and incubation experiments were analyzed at the Lawrence Berkeley National Laboratory (LBNL). The δ<sup>13</sup>C values of DIC



**FIGURE 2.** Plot versus time of (A) time-averaged electron donor addition to the groundwater, (B) time-averaged dissolved methane concentrations in wells TAN-37A and TAN-29, and (C) carbon isotope compositions of dissolved inorganic carbon in groundwater samples from selected wells in the TAN plume. Time averaging was done on a 16-week moving average.

in samples collected during the 1999 pilot test were measured by injecting an aliquot of the sample into an evacuated tube containing phosphoric acid. The  $\delta^{13}\text{C}$  of  $\text{CO}_2$  evolved was analyzed with the Prism Series II isotope ratio mass spectrometer at the Center for Isotope Geochemistry (CIG) at LBNL. The isotopic compositions of the DIC in the 2007 groundwater samples and the samples from the incubation experiments were analyzed following the procedure outlined by Torn et al. (26). For  $\text{CH}_4$  isotopic measurements, the samples were prepared in the manner outlined above for the  $\text{CH}_4$  concentration measurements. Using a Micromass Trace Gas system,  $\text{CH}_4$  in the headspace bubble was converted to  $\text{CO}_2$  that was then fed into a Micromass JA Series Isoprime isotope ratio mass spectrometer for  $\delta^{13}\text{C}$  analysis. For all samples, the isotopic compositions are reported as per mil (‰) variations from Vienna Pee Dee Belemnite (V-PDB) using the conventional  $\delta$  notation:

$$\delta^{13}\text{C} = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000 \quad (1)$$

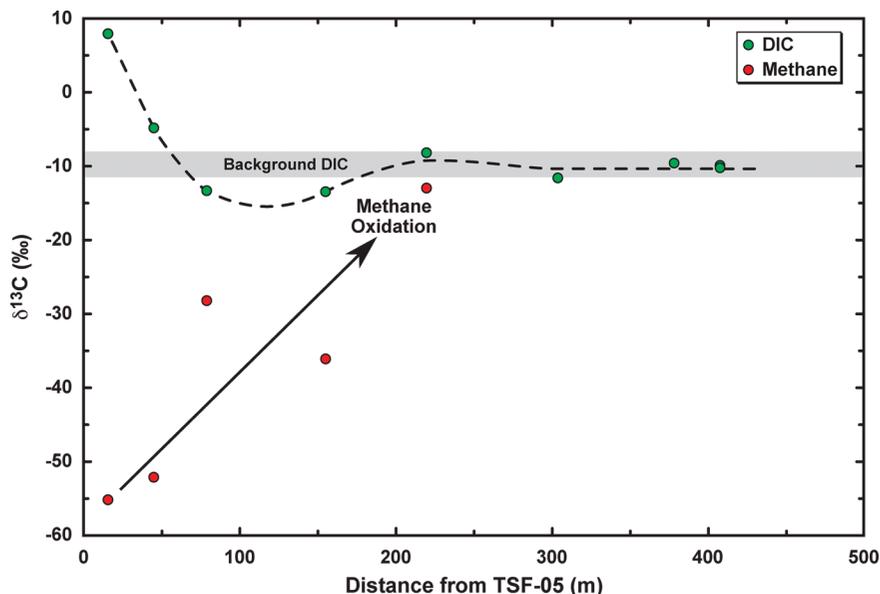
where  $R = {}^{13}\text{C}/{}^{12}\text{C}$ . The reproducibility of reference standards analyzed with the unknown samples is  $\pm 0.3\text{‰}$  ( $1\sigma$ ) for both techniques used for DIC isotopic analyses and  $\pm 0.5\text{‰}$  ( $1\sigma$ ) for  $\text{CH}_4$  analyses.

**Microbial Community Analyses.** DNA was extracted from the biomass filtered from the monitoring wells at LBNL. This DNA was amplified using PCR analysis of the microbial community structure using the PhyloChip. The PhyloChip is a high-density oligonucleotide microarray capable of detecting the presence and relative abundances of almost 9000 bacterial and archaeal taxa (27, 28). More detail on the DNA extraction and amplification and the PhyloChip analyses are given in the Supporting Information for this paper.

## Results and Discussion

**Groundwater Geochemistry.** Electron donor added to the groundwater at TAN is plotted in Figure 2A (in kg/week, calculated as a 16-week moving average). There was considerable variability in both the amount and injection strategies (e.g., variable electron donor concentrations were tested, tests of continuous versus pulsed addition of electron donor). In addition, electron donor was injected into other wells besides TSF-05 (TAN-31 beginning in January of 2006 and TAN-1859 beginning in July of 2006; see Figure 1). In August 2004, the electron donor was switched from Na-lactate to whey powder.

Eight-week moving average concentrations of dissolved  $\text{CH}_4$  concentrations for TAN-37A and TAN-29 are plotted



**FIGURE 3.**  $\delta^{13}\text{C}$  of DIC and  $\text{CH}_4$  in TAN groundwater samples collected during May, 2007 plotted versus distance from TSF-05 (the primary injection well).

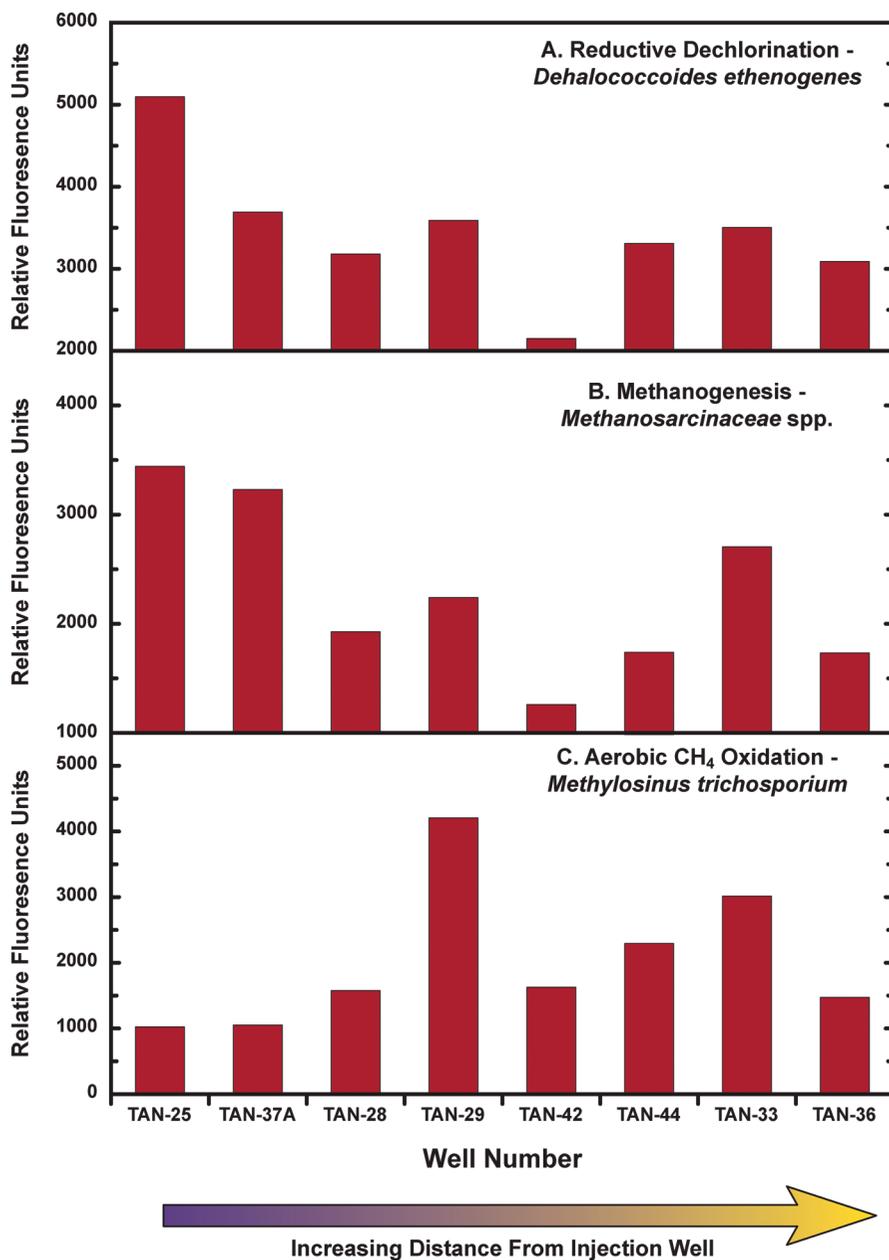
against time in Figure 2B.  $\text{CH}_4$  data for TAN-25 and TAN-28 (the other 2 wells sampled that contain significant dissolved  $\text{CH}_4$ ) are plotted in the Supporting Information, Figure S.1. Also included in the Supporting Information are plots of the concentrations of chlorinated solvents versus time (Supporting Information, Figures S.2-S.6).

TAN-37A and TAN-29 are located 44 and 154 m down-gradient from TSF-05, respectively (Figure 1). Neither well developed significant concentrations of  $\text{CH}_4$  during the 1999 pilot test. Shortly following resumption of electron donor addition in early 2000, dissolved  $\text{CH}_4$  concentrations began to rise in TAN-37A. Approximately one year later, elevated  $\text{CH}_4$  concentrations were observed in TAN-29. Although highly variable, dissolved  $\text{CH}_4$  concentrations remained high in TAN-37A through at least late 2007, averaging  $920 \mu\text{mol/L}$ .  $\text{CH}_4$  in TAN-29 fluctuated between background and  $500 \mu\text{mol/L}$  with spikes to greater than  $1000 \mu\text{mol/L}$  (between April 2001 and September 2007 it averaged  $160 \mu\text{mol/L}$ ). The source of the variability in  $\text{CH}_4$  in these wells is weakly correlated with the changes in electron donor addition, but there may be other causes such as seasonal recharge of oxygenated water to the aquifer.

The  $\delta^{13}\text{C}$  of DIC in four of the wells sampled during 2007 are plotted versus time in Figure 2C. This includes data for two of the wells from an early survey of isotopic compositions in the TAN groundwater from 1997, monthly sampling during the pilot test for three of the wells, and the 2007 samples that we collected for this study. Also shown is the general range of background DIC  $\delta^{13}\text{C}$  values for the upper aquifer at TAN ( $-8$  to  $-11.5\text{‰}$ ). These data are clear indicators of the evolution of the TAN groundwater during electron donor addition. In TAN-25, located 15 m from TSF-05, the  $\delta^{13}\text{C}$  of the DIC increases significantly following the beginning of the pilot test and was even higher in 2007. Inorganic carbon produced from microbial fermentation of acetate by acetoclastic methanogens is highly enriched in  $^{13}\text{C}$  relative to the substrate (29). The significant increase in the  $\delta^{13}\text{C}$  of DIC observed in TAN-25 could only be produced by development of a highly anoxic zone of sustained methanogenic activity near the electron donor injection well. Other microbial processes that are common in anoxic groundwater systems such as iron reduction and sulfate reduction produce inorganic carbon with  $\delta^{13}\text{C}$  values lower than the substrate and could not be a significant source of DIC in TAN-25. High dissolved  $\text{CH}_4$  and low levels of TCE in TAN-25 (data in

Supporting Information) provide evidence that ideal conditions for microbial reductive dechlorination are being maintained in this region of the plume. In TAN-37A, the  $\delta^{13}\text{C}$  of the DIC remained within the background range during the pilot test but increased to  $-4.6\text{‰}$  by 2007. This is consistent with the  $\text{CH}_4$  concentration data that did not increase until after resumption of electron donor addition following the pilot test. This indicates that methanogenesis is the dominant process in this region of the plume and that the zone of active reductive dechlorination now extends to TAN-37A.

In TAN-29, the  $\delta^{13}\text{C}$  of DIC remained in the background range during the pilot test, but dropped below that range to  $-13.3\text{‰}$  in 2007. This shift from high to low carbon isotope ratios of DIC between TAN-37A and TAN-29 indicates a change from methanogenic conditions around TAN-37A to conditions favoring microbial  $\text{CH}_4$  oxidation in the area of TAN-29. Microbial oxidation of  $\text{CH}_4$  produces DIC with  $\delta^{13}\text{C}$  values lower than the  $\text{CH}_4$  substrate (30). Coupled with the low  $\delta^{13}\text{C}$  values of the dissolved  $\text{CH}_4$ ,  $\text{CH}_4$  oxidation can cause significant negative shifts in the  $\delta^{13}\text{C}$  of DIC (31). To produce the shift from  $-4.6\text{‰}$  to  $-13.3\text{‰}$  observed between TAN-37A and TAN-29 would require that between 10% and 15% of the DIC in TAN-29 be derived from  $\text{CH}_4$  oxidation (assuming a  $\delta^{13}\text{C}$  value of  $-70\text{‰}$  for inorganic carbon from  $\text{CH}_4$  oxidation). This estimation is consistent with the significant drop in dissolved  $\text{CH}_4$  concentrations (from  $1.2$  mmol in TAN-37A to  $0.1$  mmol in TAN-29) relative to the total DIC concentration in TAN-29 ( $6$  mmol). This interpretation is simplified and ignores other factors that undoubtedly affect dissolved  $\text{CH}_4$  and DIC concentrations in the groundwater such as dilution during transport or contributions from other sources of DIC (e.g., oxidation of organic acids by iron or sulfate reducing organisms), but it does demonstrate that significant  $\text{CH}_4$  oxidation occurs between TAN-37A and TAN-29. A similar value for the  $\delta^{13}\text{C}$  value of DIC was observed in TAN-28 ( $-13.1\text{‰}$ ) during 2007. Although no data for dissolved  $\text{O}_2$  or oxidation-reduction potential is available for these samples, limited data from other sampling periods does suggest that occasional increases in both of these parameters do occur in TAN-28 and TAN-29. In addition, nitrate and sulfate concentrations returned to background levels in these wells and ferrous iron drops below detection (data in Table S.1 in Supporting Information).

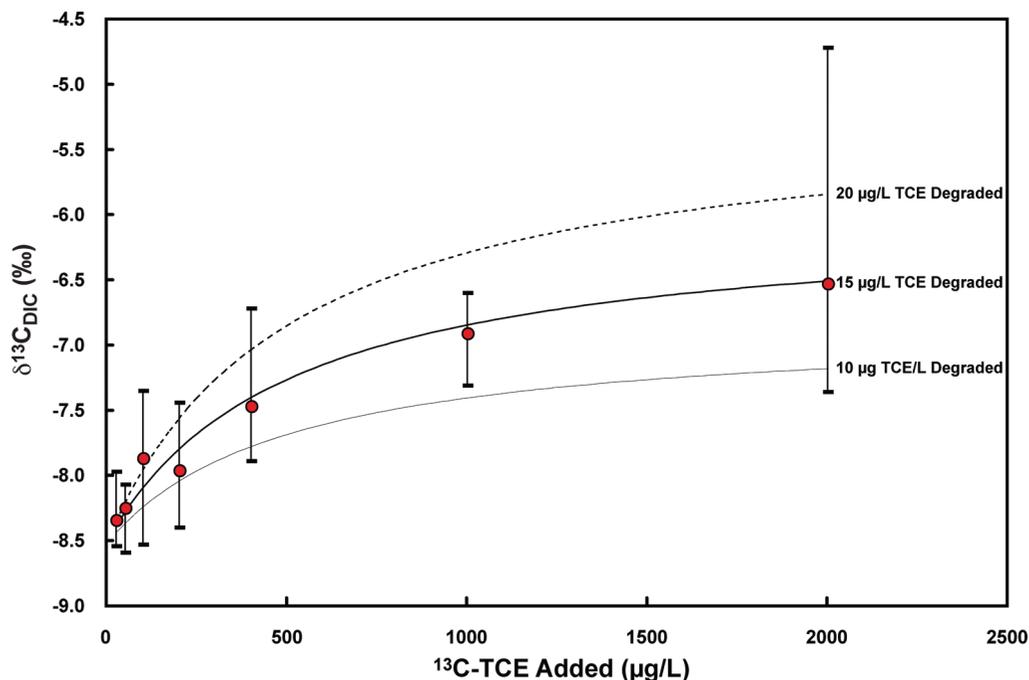


**FIGURE 4.** Relative abundances of *Dehalococcoides ethenogenes* (a representative microorganism capable of complete reductive dechlorination of TCE), *Methanosarcinaceae* spp. (an acetoclastic methanogen) and *Methylosinus trichosporium* (a representative Type II methane oxidizer known to cometabolically degrade TCE) determined using Phylochip analyses of 16S rRNA genes extracted from TAN groundwater wells sampled May 2007. A change in 1000 relative fluorescence units is approximately equivalent to an order of magnitude change in the relative abundance of a given organism (because of differences in hybridization efficiency, the relative intensity varies between organisms).

Also plotted in Figure 2C are data for the  $\delta^{13}\text{C}$  of DIC from TAN-36, one of the down-gradient monitoring wells (Figure 1) sampled during 2007. This well was also sampled during 1997, and the  $\delta^{13}\text{C}$  value of the DIC was in the background range then and in 2007. The other wells located more than 300 m from TSF-05 (TAN-42, TAN-44 and TAN-33) also had  $\delta^{13}\text{C}$  values for DIC in the background range, suggesting that electron donor addition has not had a significant effect at distances further than 300 m from the injection point.

The carbon isotope data for DIC and CH<sub>4</sub> for all of the groundwater samples collected during 2007 are plotted versus distance from TSF-05 in Figure 3. In addition to the eight samples collected during May 2007, data are also included for TAN-35 for samples collected when the ISBRs were removed from the well in July 2007. The data for DIC clearly show the trends discussed above, with very high  $\delta^{13}\text{C}$  values near the injection wells shifting to values less than background

between 80 and 160 m down-gradient before returning to background carbon isotope compositions at 300 m from TSF-05. The  $\delta^{13}\text{C}$  values of dissolved CH<sub>4</sub> are around  $-55\text{‰}$  in TAN-25 and TAN-37A, the two wells closest to the injection wells and are directly impacted by electron donor additions.  $-55\text{‰}$  is a typical  $\delta^{13}\text{C}$  value for CH<sub>4</sub> produced from fermentation of acetate by methanogenic microorganisms (29) and probably represents a good approximation for the initial carbon isotope composition for CH<sub>4</sub> produced in this system. In TAN-28 and TAN-29, the samples with low  $\delta^{13}\text{C}$  DIC, the  $\delta^{13}\text{C}$  values of the CH<sub>4</sub> are much higher ( $-28\text{‰}$  and  $-36\text{‰}$ , respectively). This shift is consistent with the significant levels of CH<sub>4</sub> oxidation in this part of the plume indicated by the low  $\delta^{13}\text{C}$  DIC values. Preferential oxidation of <sup>12</sup>CH<sub>4</sub> by methanotrophic bacteria results in higher  $\delta^{13}\text{C}$  values in the residual CH<sub>4</sub>. The  $\delta^{13}\text{C}$  for dissolved CH<sub>4</sub> from TAN-35 (at 219 m from TSF-05) is shifted to an even higher



**FIGURE 5.** Change in  $\delta^{13}\text{C}$  values of DIC in short-term (2 to 4 day) incubation experiments performed using basalt chips that had colonized for 8 months in TAN-35 and groundwater from TAN-35 plotted versus the amount of  $^{13}\text{C}$ -labeled TCE added to the experiments (in addition to 500 ppb of unlabeled TCE in the groundwater). Vertical bars represent the range of values measured for 3–6 replicates that contained the same amount of added  $^{13}\text{C}$  TCE. Also plotted are changes in DIC carbon isotope ratios calculated for varying amounts of total TCE degradation (dashed and lower solid curves).

value ( $-13\%$ ) indicating a greater amount of oxidation at this point in the plume. This is reasonable given that this well typically has very low  $\text{CH}_4$  with occasional spikes to higher concentrations and appears to be the approximate limit of where  $\text{CH}_4$  generated from electron donor addition extends into the plume.  $\text{CH}_4$  is detected in the monitoring wells beyond this point, but generally at concentrations of less than  $20\ \mu\text{mol/L}$ , which are within the background range for the Snake River aquifer (32).

**Microbial Ecology.** Figure 4 shows changes in the relative abundances of *Dehalococcoides ethenogenes*, an acetoclastic methanogen (clone S30–29, accession number AJ236538 (33)) within the Methanosarcinaceae (hereafter referred to as “*Methanosarcinaceae* spp.”) and a Type II methane oxidizer (*Methylosinus trichosporium*) for the May 2007 groundwater samples determined using the PhyloChip. The data are given in terms of relative fluorescence units and although hybridization efficiencies vary between probe-sets (taxa), a change of 1000 intensity units is about an order of magnitude change in the gene copy number for a given taxon (34).

The samples from TAN-25 and TAN-37A (the 2 wells closest to TSF-05) had the highest relative abundances of both *D. ethenogenes* and *Methanosarcinaceae* spp., reflecting the methanogenic conditions and high levels of reductive dechlorination of TCE observed in those wells. The next two downstream wells, TAN-28 and TAN-29, are characterized by increasing abundances of *M. trichosporium*, a  $\text{CH}_4$ -oxidizing organism, and lower, but still significant abundances of both *D. ethenogenes* and *Methanosarcinaceae* spp., suggesting that this region of the plume represents a transition for anoxic to oxic conditions. It should also be noted that these data represent DNA obtained from cells filtered from groundwater samples and therefore represent the pelagic microbial population. The PhyloChip detects 16S rRNA gene fragments amplified from the samples and only indicates that the organisms were present in the groundwater but not necessarily active at the time of sampling. Therefore, it is possible that microbes transported from up-gradient sites or from mixing of groundwater from different depths within

the wells will be detected, leading to mixing of microbes from zones of different activity. In the distal wells, *Methanosarcinaceae* spp. was present at lower relative abundances in all but TAN-33, which had concentrations similar to those observed in TAN-29. The significance of the relatively higher relative abundances of *Methanosarcinaceae* spp. in this well is not clear at this time. *D. ethenogenes* was also present in the distal wells at relatively low levels.

The abundances of *M. trichosporium* provide further evidence for the transition from methanogenesis to  $\text{CH}_4$  oxidation with increasing distance from the TSF-05 as indicated by the geochemical data. *M. trichosporium* is present at very low concentrations in TAN-25 and TAN-37A. It is higher in TAN-28 and peaks in TAN-29 at abundances approximately 3 orders of magnitude higher than in TAN-25 and TAN-37A. This is likely due to the combination of abundant  $\text{CH}_4$  in the groundwater and elevated concentrations of dissolved oxygen, conditions ideal for aerobic methanotrophs. In the wells further from TSF-05, there are still significant abundances of *M. trichosporium*, but the numbers are lower than in TAN-29, likely because of the limited amount of  $\text{CH}_4$  in the groundwater.

**Co-Metabolism of TCE.** The geochemical conditions between TAN-29 and TAN-42 combined with the higher relative abundance of *M. trichosporium*, a Type II methanotroph known to be capable of co-metabolism of TCE (18), suggest aerobic co-metabolism of TCE should be occurring in the groundwater in this part of the TAN plume. To test this,  $^{13}\text{C}$ -labeled TCE was added to microcosm experiments containing basalt chips and groundwater from the ISBRs incubated in well TAN-35 with a headspace of air. The concentration of dissolved  $\text{CH}_4$  in the microcosms was  $0.8\ \mu\text{mol/L}$ , which is lower than the concentration in the groundwater likely because of the brief exposure to air when the water was drained from the ISBRs. It is also significantly lower than the concentration of TCE in the microcosms (ranging between 4 and  $20\ \mu\text{mol/L}$ ), meaning that methanotrophs in the microcosms will be exposed to more TCE than  $\text{CH}_4$  which will inhibit their activity (22, 23).

The  $\delta^{13}\text{C}$  values of the DIC in the day 1 samples were variable, but leveled off for the day 2 through day 4 samples, suggesting that the maximum capacity of the bacteria in the microcosms to degrade TCE was achieved after 2 days. The average and range of DIC  $\delta^{13}\text{C}$  values for the day 2 through day 4 samples are plotted versus the amount of  $^{13}\text{C}$  TCE added in Figure 5 (see Table S.2 in the Supporting Information for data for the individual samples). Because of the differing amounts of  $^{13}\text{C}$  TCE added to the samples and the relatively high concentration of TCE in the groundwater (500  $\mu\text{g/L}$  with a  $\delta^{13}\text{C}$  value of  $-30\text{‰}$ ), the  $^{13}\text{C}/^{12}\text{C}$  of the TCE in the microcosms ranged from 0.058 to 3.859, resulting in a significant range of expected  $\delta^{13}\text{C}$  values for the DIC produced from co-metabolism of the TCE. The result was an increase of almost 2‰ in the average  $\delta^{13}\text{C}$  value of DIC in the samples with 2000  $\mu\text{g/L}$  of  $^{13}\text{C}$  TCE added relative to the samples with only 25  $\mu\text{g/L}$   $^{13}\text{C}$  TCE added. There are large ranges in the data, but this is to be expected given the highly variable nature of microorganisms expected on the basalt chips added to the microcosms. However, it is important to note that there is no overlap between the range of data for the 25 and 50  $\mu\text{g/L}$  of added TCE samples ( $-8.0$  to  $-8.6\text{‰}$ ) and the range of data for the 1000 and 2000  $\mu\text{g/L}$  of added TCE samples ( $-4.7$  to  $-7.3\text{‰}$ ).

Also plotted in Figure 5 are calculated trends in the  $\delta^{13}\text{C}$  values of DIC at varying concentrations of added  $^{13}\text{C}$  TCE added to the microcosms assuming a constant mass of TCE was degraded per liter of groundwater. A description of how these calculations were made is included in the Supporting Information. Considering the analytical uncertainty of the measurements ( $\pm 0.3\text{‰}$ ), most of the data ( $\sim 80\%$ ) fall between the calculated lines for 10  $\mu\text{g/L}$  and 20  $\mu\text{g/L}$  of TCE co-metabolically degraded with the average  $\delta^{13}\text{C}$  values for the different amounts of  $^{13}\text{C}$  TCE added matching very well with the calculated trend for 15  $\mu\text{g/L}$  of TCE co-metabolically degraded. Similar calculations assuming degradation of a constant proportion of the available TCE do not match the data nearly as well as the constant mass calculations do.

In essence, the microcosms were capable of co-metabolizing TCE, but only for a limited amount of time because of the relatively low amounts of  $\text{CH}_4$  available. This, coupled with the high concentrations of TCE in the aqueous phase in the microcosms, suggests that the microorganisms were primarily degrading the TCE and not  $\text{CH}_4$ , which is likely the cause of the apparent lack of activity after the first few days. In laboratory experiments, Oldenhuis et al. (22) and Alvarez-Cohen et al. (23) found that methane-oxidizing microorganisms have a finite capacity for co-metabolism of TCE.

The results of these experiments, combined with the geochemical and molecular data demonstrating that methanotrophic bacteria are present and active in the TAN groundwater, strongly suggest that  $\text{CH}_4$  generated from metabolism of electron donor injected to stimulate reductive dechlorination of TCE is also causing co-metabolism of TCE in the down-gradient, more aerobic portions of the plume. This could be a significant mechanism for degrading TCE within aerobic portions of plumes located down-gradient from source areas undergoing stimulated reductive dechlorination of chloroethenes.

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## Supporting Information Available

Plots of the concentrations of dissolved  $\text{CH}_4$  and chlorinated solvents, available chemical and isotopic data for the May 2007 samples, additional information on sampling preparation and analyses of microbial community data with the PhyloChip, data for the incubation experiments, and the calculation of predicted  $\delta^{13}\text{C}$  values for the incubation experiments. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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