

Compositional and isotopic characteristics of hydrocarbons generated by a hydrothermal experiment simulating seafloor sediment alteration stepwise heating from 275 to 361°C at 30 MPa

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(Received March 1, 2019; Accepted May 28, 2019)

We conducted a laboratory hydrothermal experiment that simulated generation of low molecular-weight hydrocarbons during seafloor sediment alteration at 275–361°C and 30 MPa. The abundance and carbon and hydrogen stable isotope composition of low molecular weight thermogenic hydrocarbons in the fluids were determined. In general, the abundance of C₁–C₄ alkanes increased with time. The abundance of CH₄ relative to C₂–C₄ alkanes as reflected by C₁/C₂₊ ratios showed progressive increases from 1.2 to 4.3 with continued sediment heating. Alkenes were enriched in early phase and decreased with time. Carbon isotope ratios ($\delta^{13}\text{C}$) of thermogenic CH₄ ranged between –42.0~–24.2‰. Carbon isotope ratios of C₂H₆ and C₃H₈ were similar to each other throughout the experiment ($\delta^{13}\text{C} = -28.0\sim-20.3\text{‰}$). In general, the carbon isotope ratios of C₁–C₄ alkanes were more close to those of substrate organic matter in larger carbon numbers and at later periods of the experiment. Hydrogen isotope ratios (δD) of CH₄ varied from –325~–262‰, more negative than those expected at the isotope equilibrium between CH₄ and H₂O. Compared with results from the experiment, natural hydrothermal fluids show higher C₁/C₂₊ ratio, more diverse $\delta^{13}\text{C}_{\text{CH}_4}$ values among the fields, higher $\delta^{13}\text{C}_{\text{C}_2}$ values, and higher $\delta\text{D}_{\text{CH}_4}$ values. The differences likely result from lower maturity of the experimental fluid and biogenic methane contribution to the natural fluids.

Keywords: carbon isotope ratio, hydrogen isotope ratio, fluid-sediment interaction, low molecular-weight hydrocarbons, Okinawa Trough

INTRODUCTION

Low molecular-weight hydrocarbons (LHCs), particularly CH₄, are ubiquitously present in subsurface sedimentary environments (Bernerd *et al.*, 1976; Whiticar *et al.*, 1986; Wakita and Sano, 1983). There are three origins for subsurface LHCs with respect to carbon sources and processes: thermogenic, biogenic, and abiotic processes (Whiticar *et al.*, 1986; Welhan and Lupton, 1987; Schoell, 1988; Sherwood Lollar *et al.*, 2002; Fu *et al.*, 2007; Proskurowski, 2010; McCollom *et al.*, 2010; Taran *et al.*, 2010; Kawagucci *et al.*, 2013; Etiope and Sherwood Lollar, 2013; Etiope and Schoell, 2014). For example, thermogenic LHCs originate from chemical decomposition of organic matter at high temperature. Subsurface LHCs serve as fossil fuel for modern human activity (Tissot and Welte, 1978), suggest microbial activity under extreme physical-chemical condition (Stevens and

McKinley, 1995; McCollom, 1999; Takai *et al.*, 2008), and imply how chemical evolution driving birth of life occurs on prebiotic planet (Proskurowski *et al.*, 2008; McCollom, 2013). Understanding origin of the subsurface LHCs thus provides us clues in broad spectrum of life-earth linkages.

Geochemical characteristics of LHCs have been used widely as a diagnostic tool for deducing subsurface conditions and processes including the origin of LHCs (Schoell, 1988; Chung *et al.*, 1988; Sakata *et al.*, 1997; Prinzhofer and Pernaton, 1997; Whiticar, 1999; Cruse and Seewald, 2006; Proskurowski *et al.*, 2008; Proskurowski, 2010; Etiope and Sherwood Lollar, 2013; Kawagucci *et al.*, 2013). More accurate interpretations of the origin of LHCs can be achieved using multiple geochemical tracers such as abundance and carbon and hydrogen isotope composition of each LHC (Etiope and Sherwood Lollar, 2013; Kawagucci *et al.*, 2013). This approach requires preceding understandings of the possible diversity of isotopic and chemical composition of LHCs derived from each origin. Whereas the stable isotopic composition of

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CH₄ associated with microbial methanogenesis has been investigated in detail with respect to the mechanisms and relevant environmental factors using laboratory experiments, theoretical calculations, and field observations (Sugimoto and Wada, 1995; Valentine *et al.*, 2004; Penning *et al.*, 2005; Stolper *et al.*, 2014; Kawagucci *et al.*, 2014; Wang *et al.*, 2015; Okumura *et al.*, 2016), there are relatively few experimental studies for stable isotopic and chemical composition of thermogenic LHCs in hydrothermal systems.

This study uses laboratory experiments to investigate the geochemical characteristics of thermogenic LHCs originating from the interaction of seawater saline fluids and unconsolidated seafloor sediment deposited under deep-sea hydrothermal condition. Thermogenic LHCs characteristics, frequently referred to interpret compositional and isotopic characteristics of LHCs in deep-sea sediment-associated hydrothermal vent fluids, have been established based on the observation of petroleum fields (Schoell, 1980; Whiticar *et al.*, 1986; Etiope and Sherwood Lollar, 2013). However, it may be problematic because the petroleum originates mainly from kerogen and is more or less a mixture with biogenic methane (Sakata *et al.*, 1997; Prinzhofer and Pernaton, 1997). From this viewpoint, experimental characterization has an advantage at conditions-controlled simulation for a target process, LHCs generation through hydrothermal fluid-sediment interaction, and can avoid any obscure from complex information imprinted in natural samples. However, some of experiments that attempted to characterize thermogenic LHCs (e.g., Sackett, 1978; Berner *et al.*, 1995; Seewald *et al.*, 1998) may involve reactions, which are unlikely to occur in deep-sea subsurface environment, due to uses of reactive materials such as stainless-steels and/or presence of vapor phase within the experimental apparatus (McCollom and Seewald, 2007). Previous studies used the chemically-inert apparatus for simulation of hydrothermal fluid-sediment interaction and reported abundance and carbon isotope ratio of thermogenic methane (Thornton and Seyfried, 1987; Seewald *et al.*, 1990, 1994). This study provides more comprehensive geochemical dataset for thermogenic LHCs that includes C₁–C₄ hydrocarbons abundance and their carbon and hydrogen isotope ratios. The dataset obtained is useful not only to deduce geochemical origin of subsurface LHCs but also to discuss geochemical condition of subsurface hot zone at sediment-covered hydrothermal systems.

MATERIALS AND METHODS

Hydrothermal experiment

The experiment in this study is hereafter called OTS (Okinawa Trough Sediment experiment). OTS was con-

ducted in October–December 2010 at Woods Hole Oceanographic Institution (WHOI). A flexible gold reaction-cell apparatus (Seyfried *et al.*, 1987), used in this study, can simulate the interaction among whole solid and aqueous compounds that are tightly involved to LHCs behavior under hydrothermal condition (Seewald, 2003). The apparatus consists of a gold reaction cell equipped with TiO₂ fittings connecting with a capillary exit tube and sampling valve, an outer stainless-steel vessel, and a heating shell. The chemically inert reaction cell minimizes reactions unlikely occurring in nature while external pressure to compress the flexible cell prohibits vapor phase formation.

The OTS involved heating a sample of seafloor sediment from the Okinawa Trough Izena Hole and deep-sea water. The sediment sample was collected within 0–5 cm below the seafloor ~50 m apart from the known hydrothermally altered area with a scoop manipulated by the remotely operated vehicle Hyper Dolphin (dive #1185) (Miyoshi *et al.*, 2015). Initially, 54.2 g of whole wet sediment, which consisted of 20.7 g of solids and 33.5 g of pore-water, and 10.3 g of deep seawater into the cell. Thus, 43.8 g of fluid was in the cell at the beginning of the experiment. The dry sediment contained 2.02 wt.% of organic carbon with a stable carbon isotope ratio ($\delta^{13}\text{C}_{\text{org}}$) of -22.0‰ , determined by sediment acidification for carbonate minerals removal followed by analysis with Elemental Analyzer-Isotope Ratio Mass Spectrometer (EA-IRMS) as reported previously (e.g., Shao *et al.*, 2016). The cell was pressurized and released repeatedly to remove air within the cell prior to heating. OTS was conducted at 30 MPa and three increasing temperature stages: 275°C during the first 356 hours, then 320°C for the next 317 hours, and finally 361°C for 504 hours (Table 1).

Aliquots of fluid (3.3 to 6.6 g) were withdrawn from the reaction cell for chemical analyses in glass gas-tight syringes at selected time intervals (Table 1). Fluid pH (25°C) and dissolved gas concentrations were determined immediately after sample withdrawn. For the isotope ratio analyses at Japan Agency for Marine-Earth Science and Technology (JAMSTEC), an aliquot of the fluid was transferred into an evacuated glass vial containing mercuric chloride and butyl rubber septum cap. Prior to each sampling event, the fluid flow path was flushed by withdrawing approximately 0.75 g of sample that was discarded.

Analyses

Dissolved concentrations of gas species and ions in the fluid samples were determined in WHOI according to methods reported previously (e.g., Seewald, 2001; Cruse and Seewald, 2006). Concentrations of total dissolved inorganic carbon (ΣCO_2) and hydrocarbons (C₁–C₄ *n*-alkanes, *i*-butane, and C₂–C₄ *n*-alkenes) were determined

Table 1. Result of OTS experiment. Chemical and isotopic composition through Okinawa Trough Sediment (OTS) experiment simulating fluid-sediment interaction under 30 MPa.

Time h	Temp. °C	CH ₄ mmol/kg	Ethane mmol/kg	Propane mmol/kg	i-butane mmol/kg	n-butane mmol/kg	Ethene mmol/kg	Propene mmol/kg	CO ₂	H ₂ mmol/kg	H ₂ S mmol/kg
0	275	NA	NA	NA	NA	NA	NA	NA	(2.3)	(0)	NA
170	275	0.72	0.16	0.15	0.07	0.15	0.0636	fail	164	0.103	NA
338	275	1.15	0.27	0.31	0.17	0.24	0.0529	0.0708	165	0.097	NA
356	Increased temperature to 320°C										
506	320	5.67	1.39	0.92	0.42	0.41	0.0193	0.0294	187	0.170	NA
672	320	7.94	1.91	1.3	0.47	0.56	0.0001	0.0097	189	0.146	6.8
673	Increased temperature to 361°C										
842	361	17.7	3.10	1.9	0.59	0.67	0.0003	0.0100	229	0.445	8.4
1177	361	26.6	3.64	2.0	0.39	0.55	0.0001	0.0053	227	0.638	9.1

Time h	$\delta^{13}\text{C}_{\text{C}_1}$ permil	$\delta^{13}\text{C}_{\text{C}_2}$ permil	$\delta^{13}\text{C}_{\text{C}_3}$ permil	$\delta^{13}\text{C}_{\text{C}_4}$ permil	$\delta^{13}\text{C}_{\text{C}_{4e}}$ permil	$\delta^{13}\text{C}_{\text{C}_{2e}}$ permil	$\delta^{13}\text{C}_{\text{C}_{3e}}$ permil	$\delta^{13}\text{C}_{\text{CO}_2}$ permil	$\delta\text{D}_{\text{C}_1}$ permil	$\delta\text{D}_{\text{C}_2}$ permil	$\delta\text{D}_{\text{H}_2}$ permil
0											
170	-35.0	-25.1	-28.0	-26.1	-30.3	-18.1	-19.3	-13.7	-318	-248	-422
338	-42.0	-27.3	-28.0	-25.9	-28.9	-20.7	-16.6	-13.8	-325	-243	-417
356											
506	-35.6	-24.9	-25.2	-23.6	-25.3	(-2.3)	-13.7	-14.1	-286	-228	-390
672	-30.1	-22.8	-23.9	-22.7	-23.9	-15.2	-15.1	-14.3	-269	-223	-387
673											
842	-29.5	-22.7	-23.0	-21.4	-20.8	NA	NA	-15.3	-266	-197	-372
1177	-24.2	-20.3	-20.4	-18.2	-16.9	NA	NA	-16.6	-262	-179	-367

Time h	pH 25°C	Na mmol/kg	K mmol/kg	Li mmol/kg	Ca mmol/kg	SO ₄ mmol/kg	Cl mmol/kg	Br mmol/kg	Mg mmol/kg	SiO ₂ mmol/kg	$\delta^{18}\text{O}_{\text{CO}_2}$
0	7.80	472	12.7	NA	10.8	27.2	539	0.94	NA	NA	NA
170	NA	472	27.5	1.0	1.9	2.74	534	1.38	3.42	24.3	41.1
338	3.86	457	27.2	1.2	1.6	2.84	529	1.36	3.16	23.8	42.0
356											
506	3.78	457	28.6	1.9	1.6	1.06	528	1.40	1.05	29.8	41.9
672	4.25	457	28.9	1.9	3.8	0.64	528	1.38	0.60	28.5	41.7
673											
842	5.15	435	30.4	2.2	11.8	0.12	522	1.40	0.14	23.3	41.7
1177	5.99	NA	NA	NA	NA	0.97	508	1.26	0.03	15.2	42.2

Time h	Rb umol/kg	Sr umol/kg	Ba umol/kg	Fe umol/kg	Mn umol/kg	Pb umol/kg	Zn umol/kg	Fluid g
0	NA	42.4						
170	22	35	17	1418	922	54	490	37.9
338	20	35	16	1620	1024	29	510.0	33.6
356								
506	22	50	33	3164	1709	3.3	54	30.3
672	22	72	67	618	1330	NA	29	25.1
673								
842	29	151	354	1585	43	NA	90	21.4
1177	94	94	507	NA	348	NA	NA	14.8

BD = belowdetection.

NA = notanalyzed.

using purge-and-trap Gas Chromatography (GC) with a Thermal Conductivity Detection (TCD) and Flame Ionization Detection (FID) detectors connected in series. Analytical uncertainties are $\pm 5\%$ for C₁–C₄ alkanes and ΣCO_2 concentrations, and $\pm 10\%$ for alkene concentrations. Aqueous H₂ concentrations were determined using a GC-TCD system with N₂ carrier gas after a headspace gas extraction within a gas-tight syringe. Analytical uncertainty for the reported H₂ concentrations are $\pm 10\%$. The pH (25°C) was measured using an Ag/AgCl combination reference electrode. Concentrations of major ions (Na⁺, K⁺, Li⁺, Ca²⁺, Mg²⁺, Cl⁻, Br⁻, and SO₄²⁻) were de-

termined following dilution by ion chromatography with suppressed conductivity detection on a Dionex DX500 system with analytical uncertainties of $\pm 5\%$. Concentrations of minor elements (Rb, Sr, Ba, Si, Fe, Mn, Pb, and Zn) were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) with analytical uncertainties of $\pm 5\%$. Total dissolved sulfide ($\Sigma\text{H}_2\text{S}$) was determined gravimetrically in selected samples following acidification of the aliquot with a 25 wt.% phosphoric acid solution and precipitation of the evolved H₂S gas as Ag₂S in a 5 wt.% AgNO₃ solution.

The $\delta^{13}\text{C}$ and δD values of the LHCs, CO₂, and H₂

were determined by continuous-flow IRMS with an on-line gas purification system connected to a MAT253 mass spectrometer. The analytical procedure for CH₄, CO₂, and H₂ has been presented previously in detail (Kawagucci *et al.*, 2005, 2010; Okumura *et al.*, 2016). For the $\delta^{13}\text{C}$ analyses of C₂–C₄ hydrocarbons, the sample gas was purified by passing through a chemical trap filled with magnesium perchlorate (Merck KGaA, Darmstadt, Germany) and Ascarite II (NaOH-coated silica; Thomas Scientific, New Jersey, USA) for removal of H₂O and CO₂, and a stainless-steel cryogenic trap held at –196°C for removal of N₂ and CH₄. The C₂–C₄ hydrocarbons are separated using a HP-PLOT Q capillary column (30 m long, 0.32 mm i.d.) with a constant flow rate at temperatures from 40 to 220°C and oxidized to CO₂ at the combustion furnace prior to introduction into the mass spectrometer. The $\delta^{13}\text{C}$ values for the C₄₊ alkenes cannot be quantified due to small quantities present. For the δD analysis of ethane, a stainless-steel tube filled with the Schütze reagent (I₂O₅ on silica gel; Leco Co., St. Joseph, USA) was placed in the purification line to remove unsaturated hydrocarbons (Komatsu *et al.*, 2005). Although we attempted to analyze the δD of C₂₊ hydrocarbons, they could be quantified due to baseline fluctuations. Data acquisition for all the IRMS analyses is based on the ISODAT software package. The amount of H₃⁺ ions generated in the ion source during hydrogen isotope analysis, the so-called H₃⁺ factor, was determined using ISODAT and was <4.5 (ppm/mV). The analytical precisions for $\delta^{13}\text{C}_{\text{CH}_4}$, $\delta\text{D}_{\text{CH}_4}$, $\delta^{13}\text{C}_{\text{C}_{2+}}$, $\delta\text{D}_{\text{C}_2}$, $\delta^{13}\text{C}_{\text{CO}_2}$, and $\delta\text{D}_{\text{H}_2}$ values were estimated by repeated analyses of in-house standard gases to be less than 0.3‰, 5‰, 0.5‰, 10‰, 0.5‰, and 10‰, respectively. Values of chemical and isotopic analyses reported (Table 1) represent cumulative changes during this experiment.

RESULTS

All of the experimental results are shown in Table 1. Negligible decrease of Cl[–] concentration after the heating and pressurizing certifies no leakage of the reaction cell. Decrease of sulfate concentrations and non-quantitative increase of sulfide concentrations suggest sulfate mineral precipitation under the experimental condition. Concentrations of K⁺ (27.5–30.4 mmol/kg) and Ca²⁺ (2–12 mmol/kg) of OTS fluids are significantly lower than those in natural hydrothermal fluids at Okinawa Trough (50–100 and 17–27 mmol/kg for K⁺ and Ca²⁺, respectively) (Kawagucci, 2015; Miyazaki *et al.*, 2017a). Concentrations of Li⁺ (1.0–2.2 mmol/kg) of OTS fluids are comparable with those of natural Okinawa Trough fluids (1.3–5.6 mmol/kg). Si concentrations of OTS fluids were excess from the quartz solubility until the fifth sampling but down to the saturation level at the last sampling. This temporal Si behavior is consistent with those in previous

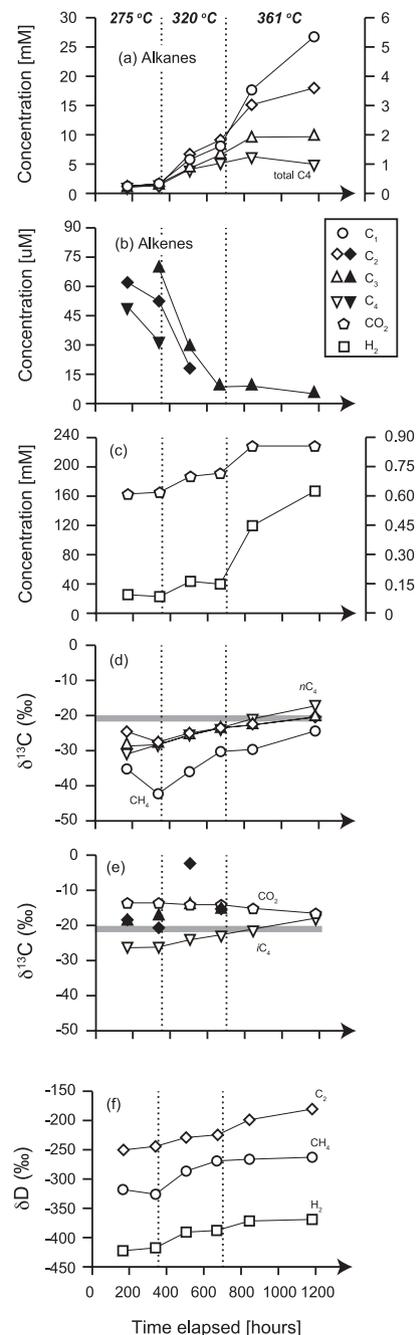


Fig. 1. Temporal variation of volatiles characteristics. (a) Concentrations of C₁–C₄ alkanes (C₄ represents total of n- and i-C₄H₁₀), (b) Concentrations of C₂–C₄ alkenes, (c) Concentrations of H₂ and CO₂, (d) $\delta^{13}\text{C}$ of C₁–C₃ alkanes and n-C₄H₁₀, (e) $\delta^{13}\text{C}$ of C₂–C₃ alkenes, i-C₄H₁₀, and CO₂, and (f) δD of CH₄, C₂H₆, and H₂.

experiments (Seewald *et al.*, 1990, 1994). The solubility-controlled Si level in the OTS last sample is also consistent with those in natural Okinawa Trough hydrothermal fluids (Kawagucci, 2015; Miyazaki *et al.*, 2017a).

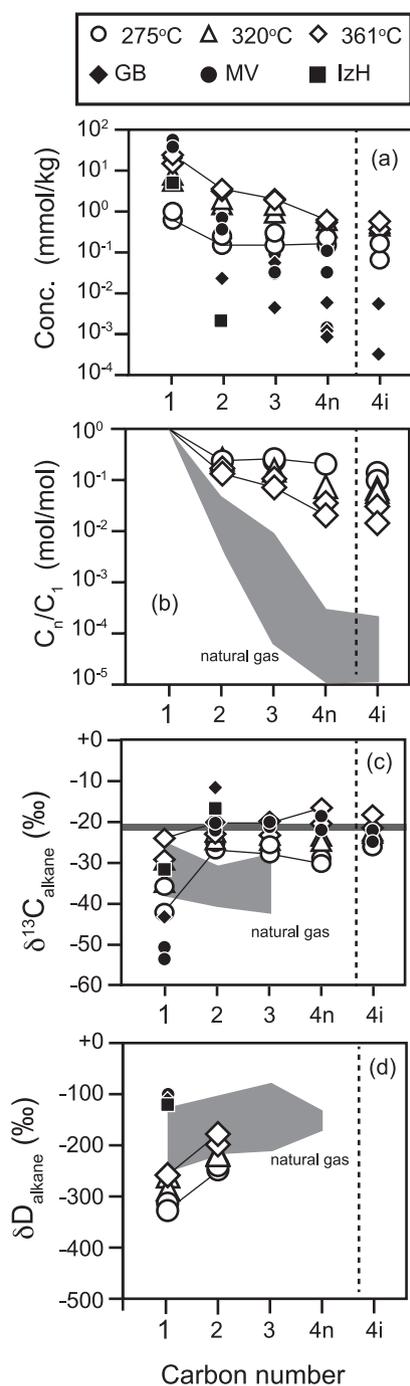


Fig. 2. Plots of compositional and isotopic characteristics of LHCs against carbon numbers. (a) Dissolved concentration (in logarithm), (b) Relative abundance of C_{2+} alkanes with CH_4 (in logarithm), (c) $\delta^{13}C$, and (d) δD . Light grey zones in panels (b-d) represent natural gas values from (Sherwood-Lollar et al., 1994; Burruss and Laughrey, 2010). Dark grey horizontal bar in panel c represents $\delta^{13}C$ of substrate organic matter for OTS experiment. Open symbols are OTS data. Filled symbols are from natural sediment-associated hydrothermal fields (GB: Guaymas Basin (Pearson et al., 2005; Proskurowski et al., 2006; McDermott et al., 2015), MV: Middle Valley (Cruse and Seewald, 2006), IzH: Izena Hole Hakurei (Ishibashi et al., 2014)).

The organic carbon content was down to 1.35 wt.% with $\delta^{13}C_{org}$ value of -21.5‰ at the end of experiment. CH_4 concentrations continuously increased from 0.72 mmol/kg in the first sample at 275°C to 26.6 mmol/kg in last sample at 361°C (Fig. 1a). Similar to CH_4 , C_{2+} alkane concentrations also increased with time except for total C_4H_{10} which decreased in the final sample at 361°C (Fig. 1a). Dissolved *n*- and *i*- C_4H_{10} were present at similar concentrations in each sample (Table 1). The summed total of C_1 – C_4 alkane concentrations increased from 1.3 mmol/kg to 33.2 mmol/kg in the first and last samples, respectively. In general, the concentration of each *n*-alkane decreased with increasing carbon number (Fig 1a). Increases in the C_1/C_{2+} ratio from 1.2 to 4.3 (Figs. 2a and 2b) reflect the rapid increases of abundance of CH_4 relative to longer chain *n*-alkanes. Alkene concentrations were highest at the lower temperature earlier time period with values of 0.064 mmol/kg (C_2H_4), 0.071 mmol/kg (C_3H_6), and 0.049 mmol/kg (C_4H_8) and subsequently decreased with time and increasing temperatures (Fig. 1b). Relative to their corresponding alkanes, alkenes were present at substantially lower concentrations (Table 1). Molecular hydrogen (H_2) concentrations increased from 0.10 to 0.64 during the course of the experiment (Fig 1c). The resulting H_2/CH_4 ratio decreased with time from 0.14 to 0.024. Carbon dioxide (CO_2) was the most abundant dissolved gas present with concentrations increasing 164 mmol/kg in the first sample at 275°C to 229 mmol/kg in the final sample at 361°C (Fig. 1c). The high CO_2 concentrations likely reflect dissolution of sedimentary carbonate, decarboxylation of organic matter, and oxidation of reduced carbon species (Seewald, 2001).

The carbon isotopic composition of methane ($\delta^{13}C_{CH_4}$) increased with time from -42.0‰ to -24.2‰ (Fig. 1d). The carbon isotopic compositions of C_2 – C_4 alkanes also increased with time and ranged between -27.3‰ – -20.3‰ ($\delta^{13}C_{C_2}$), -28.0‰ – -20.4‰ ($\delta^{13}C_{C_3}$), -26.1‰ – -18.2‰ ($\delta^{13}C_{nC_4}$), and -30.3‰ – -16.9‰ ($\delta^{13}C_{iC_4}$) (Figs. 1d and 1e). In general, carbon isotope fractionation between the C_1 – C_4 alkanes and sedimentary organic matter was larger during the lower temperature early stages of sediment heating and smaller with increasing carbon number (Fig. 2c). The carbon isotope fractionations between CH_4 and substrate organic matter, defined by $\alpha^C_{CH_4-org} = (\delta^{13}C_{CH_4} + 1)/(\delta^{13}C_{org} + 1)$, ranged between 0.980–0.998. The $\delta^{13}C$ of the alkenes C_2H_4 and C_3H_6 showed no systematic variations with time and/or temperature and ranged between -20.7‰ – -2.3‰ and -19.3‰ – -13.7‰ , respectively (Fig. 1e). The $\delta^{13}C$ values of C_2 – C_3 alkenes were always higher than those of homologous alkanes at each sampling period. The carbon isotopic composition of dissolved CO_2 ($\delta^{13}C_{CO_2}$) decreased from -13.7‰ to -16.6‰ and was accompanied by a large increase in concentration (Fig. 1e). The carbon isotope fractionations between CH_4 and

CO₂ ($\alpha_{\text{CH}_4\text{-CO}_2}^{\text{C}}$) got smaller from 0.971 to 0.992 with time. Isotope mass balance within the reaction cell cannot be assessed due to a lack of information regarding the ¹³C content of solid inorganic carbon and the other organic molecules such as higher molecular weight hydrocarbons and O- and S-bearing molecules (Seewald *et al.*, 1990, 1994).

The hydrogen isotopic compositions of CH₄ ($\delta\text{D}_{\text{CH}_4}$) increased with temperature from -322‰ at 275°C to -278‰ at 320°C, and -264‰ at 361°C (Fig. 1f). The resulting hydrogen isotope fractionation between CH₄ and H₂O ($\alpha_{\text{CH}_4\text{-H}_2\text{O}}^{\text{H}}$: 0.679–0.736) was significantly lower than values estimated for CH₄-H₂O isotope equilibrium at the given temperatures (0.879–0.888) (Horibe and Craig, 1995) (Fig. 3b). The isotope disequilibrium between CH₄ and H₂O has also been observed in experiments simulating abiotic and microbial methanogenesis (Fu *et al.*, 2007; McCollom *et al.*, 2010; Okumura *et al.*, 2016) and is consistent with negligible isotope exchange between CH₄ and H₂O on the time scale of a year under hydrothermal conditions (Reeves *et al.*, 2012). The hydrogen isotopic compositions of C₂H₆ ($\delta\text{D}_{\text{C}_2}$) increased with time from -248‰ to -179‰ (Fig. 1f). The $\delta\text{D}_{\text{C}_2}$ values were consistently higher than the $\delta\text{D}_{\text{CH}_4}$ values in each sample. The hydrogen isotopic compositions of molecular hydrogen ($\delta\text{D}_{\text{H}_2}$) increased with temperature from -422‰ to -367‰ (Fig. 1f). The resulting hydrogen isotope fractionations between H₂ and H₂O ($\alpha_{\text{H}_2\text{-H}_2\text{O}}^{\text{H}}$: 0.578–0.633) were consistent with values predicted for H₂-H₂O isotope equilibrium at the experimental temperatures (0.574–0.641) (Horibe and Craig, 1995) (Fig. 3c), suggesting that equilibrium was attained within a week under the hydrothermal condition.

DISCUSSION

Hydrocarbon composition

The production of low molecular-weight hydrocarbons (LHCs) during the thermal alteration of sedimentary organic matter involves numerous primary and secondary reactions. During the experiments presented, direct evidence for secondary reactions is provided by decreasing concentrations of alkenes with time and decreases in the concentration of C₄ alkanes at the end of the 361°C stage of the experiment (Figs. 1a and 1b). Decomposition of C₂₊ aqueous hydrocarbons results in the production of shorter straight-chain hydrocarbons and carbon dioxide (Seewald, 2001). From a thermodynamics perspective, C₂H₆ decomposition at H₂ concentrations of <1 mM and temperatures of >275°C that characterized the experiments in this study should result in CH₄ generation and C₁/C₂ ratio higher than 10⁷ (e.g., Kawagucci *et al.*, 2013). The difference in C₁/C₂₊ ratios predicted from thermodynamics and observed in OTS fluids confirms that organic

matter decomposition during OTS was kinetically controlled.

A semi-log plot of C₁–C₄ *n*-alkane concentrations against carbon numbers (Fig. 2a) has been proposed as a tool to identify abiotic origin of hydrocarbons (Etiope and Sherwood-Lollar, 2013) because chain growth by stepwise polymerization results in a linear Schulz-Flory distribution. Results of the OTS at 275°C showed greater CH₄ enrichment relative to the Schulz-Flory trend (Fig. 2a) and likely reflects molecular heterogeneity of the substrate organic matter (e.g., lots of methyl branches) and kinetic heterogeneity of the breaking (e.g., faster cleavage of methyl branches). In turn, the Schulz-Flory distribution test (linear regression) for each four sample at 320–361°C shows good linearity ($r^2 \geq 0.95$) (Fig. 2a). It was pointed out that a pseudo-Schulz-Flory distribution could be produced in thermogenic LHCs by random bond breaking of substrate macro organic molecular (Giggenbach, 1997). Because of absence of abiotic hydrocarbon generation under the OTS condition, the random bond breaking likely accounts for the pseudo-Schulz-Flory distribution of LHCs during the OTS at higher temperatures.

Carbon isotopic composition

The extent of carbon isotope fractionation between CH₄ and sedimentary organic matter during the OTS ($\alpha_{\text{CH}_4\text{-org}}^{\text{C}} = 0.980\text{--}0.998$) is slightly greater than those observed in a previous experiment simulating Guaymas Basin sediment alteration ($\alpha_{\text{CH}_4\text{-org}}^{\text{C}} = 0.995\text{--}0.998$) (Seewald *et al.*, 1994). Values of $\delta^{13}\text{C}_{\text{CH}_4}$ for thermogenic CH₄ are determined from ¹³C content of precursor organic carbon and kinetic isotope effects. Compound- and position-specific isotope heterogeneity (Blair *et al.*, 1987; Hayes *et al.*, 1990; Corso and Brenna, 1997) can result in $\delta^{13}\text{C}$ values for thermogenic CH₄ that are substantially different than bulk $\delta^{13}\text{C}_{\text{org}}$ values even if there are minor kinetic isotope effects during C-C bond breakage. For example, environmental acetate generally showed ~20‰ ¹³C depletion in its methyl carbon compared with the carboxyl carbon (Blair *et al.*, 1987; Blair and Carter, 1992; Sugimoto and Wada, 1993). Similarly, position-specific isotope analyses of C₅–C₁₅ *n*-alkanes suggested >10‰ ¹³C depletion in terminal methyl carbons compared with the internal carbons (Corso and Brenna, 1999; Gilbert *et al.*, 2013).

The systematic approach of $\alpha_{\text{CH}_4\text{-org}}^{\text{C}}$ to a value of unity along with increasing CH₄ abundance during the OTS experiment is consistent with relatively ¹³C-enriched carbon contributing to late-stage CH₄ generation. This model can also explain smaller carbon isotope fractionations in C₂₊ alkanes (Figs. 1d and 2c). The greater fractionation in the OTS experiment relative to previous experiments examining hydrothermal alteration of Guaymas Basin sediment (Seewald *et al.*, 1994) may re-

flect the sampling of scheme utilized during this study that focused on the earlier stages of sediment alteration at lower temperatures that resulted in the greater release of ^{13}C -depleted CH_4 .

A kinetic isotope effect of CH_4 generation from thermal decomposition of C_2 – C_6 alkanes calculated theoretically is 0.984–0.987 ($\alpha^{\text{C}}_{\text{CH}_4\text{-precursor}}$) at 327°C and gets greater at lower temperature (Tang *et al.*, 2000). An experiment that simulated CH_4 generation through thermal degradation of $n\text{-C}_{18}\text{H}_{38}$ under anhydrous conditions at 400–500°C also showed a significant kinetic isotope effect of 0.972–0.975 ($\alpha^{\text{C}}_{\text{CH}_4\text{-C}_{18}}$) associated with the production of CH_4 (Sackett, 1978). The magnitude of this fractionation is small in the presence of montmorillonite ($\alpha^{\text{C}}_{\text{CH}_4\text{-C}_{18}} \leq 0.997$) (Sackett, 1978) suggesting that the extent of isotope effect is influenced by mineral catalysis. In the case of hydrothermal fluid-sediment interaction like the OTS, the reaction of aqueous LHCs may be catalyzed by water and aqueous sulfur species due to additional accessibility of alternative reaction pathways (Seewald, 2001) that similarly decline kinetic isotope effect during the production of CH_4 fluid-sediment interaction. Additionally, speciation of precursor organic carbon can influence kinetic isotope effect on CH_4 generation because of difference in bond enthalpies among C–C, C–N, C–O, and so on (Smith *et al.*, 1985).

Hydrogen isotope composition

Mechanisms controlling the D content of LHCs are more complex than those for ^{13}C because larger numbers of atoms are involved (e.g., four hydrogens per a carbon in CH_4). Possible sources of hydrogen in thermogenic CH_4 include H_2O or sedimentary organic matter. In the case of methane generation from a methyl group carbon in the sedimentary organic matter, the cleavage requires one hydrogen binding from either H_2O or sedimentary organic matter in addition to three native carbon-bound hydrogens. In general, the (D values of marine sedimentary organic molecules (–400‰–80‰) are lower than that of seawater (+0‰) (Sauer *et al.*, 2001; Sessions *et al.*, 2004; Li *et al.*, 2009). If the relative contribution of these sources is the sole factor controlling thermogenic $\delta\text{D}_{\text{CH}_4}$ values, a greater contribution of hydrogen derived from sedimentary organic matter would result in more negative $\delta\text{D}_{\text{CH}_4}$ values. The $\delta\text{D}_{\text{CH}_4}$ shift toward more positive values with time during the OTS experiment (Fig. 1f) can be explained by this assumption in addition to the temporal decreasing of contribution from the native methyl group-derived CH_4 . This is because native internal carbons in sedimentary organic matter (non-methyl group carbon) requires two or more hydrogens addition from H_2O or sedimentary organic carbon to form CH_4 , and thus H_2O -derived D-enriched signature would be more enhanced in the CH_4 accumulated in later stage. Other factors may also regu-

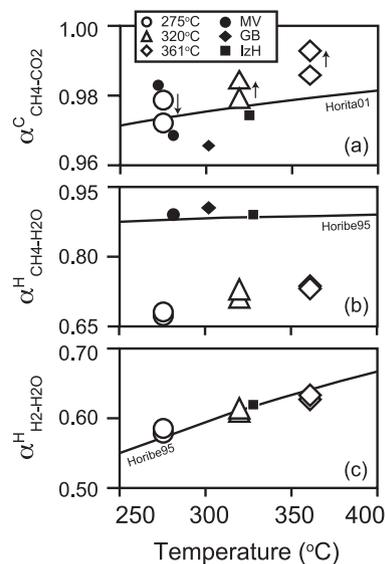


Fig. 3. Comparison of carbon and hydrogen isotope fractionations between OTS fluids and theoretical values. Each panel shows (a) CH_4 and CO_2 for carbon, (b) CH_4 and H_2O for hydrogen, and (c) H_2 and H_2O for hydrogen. Curves in each panel are theoretical equilibrium fractionation factors (Horibe and Craig, 1995; Horita, 2001). Symbols are same with Fig. 2. Arrows in panel (a) represent temporal trend of the change for OTS.

late the hydrogen isotope composition of CH_4 . For example, kinetic isotope effects and compound- and position-specific heterogeneity of the hydrogen isotope composition in bulk sedimentary organic matter may also contribute to the D content of CH_4 as discussed for the ^{13}C content. Hydrogen isotope exchange between water and precursor organic molecules is also a factor. Although laboratory experiments have shown that exchange between CH_4 and water is kinetically inhibited at the temperatures of the OTS experiment, exchange between C_{2+} n -alkanes occurs readily (Reeves *et al.*, 2012). Accordingly, the hydrogen exchange of C_{2+} n -alkanes and subsequent LHC degradation to CH_4 may contribute to the isotopic composition of CH_4 . Nevertheless, current analytical limitation does not allow us to identify which compound/group of substrate organic matter contributes for LHCs generation and to quantify how much δD values are in each precursor compound/position.

Comparison with natural hydrocarbons

The geochemical characteristics of LHCs in the OTS fluids are distinguishable from those in the natural hydrothermal fluids venting at sediment-associated hydrothermal fields including OT sites (Pearson *et al.*, 2005; Cruse and Seewald, 2006; Proskurowski *et al.*, 2006; Ishibashi *et al.*, 2014; McDermott *et al.*, 2015; Kawagucci,

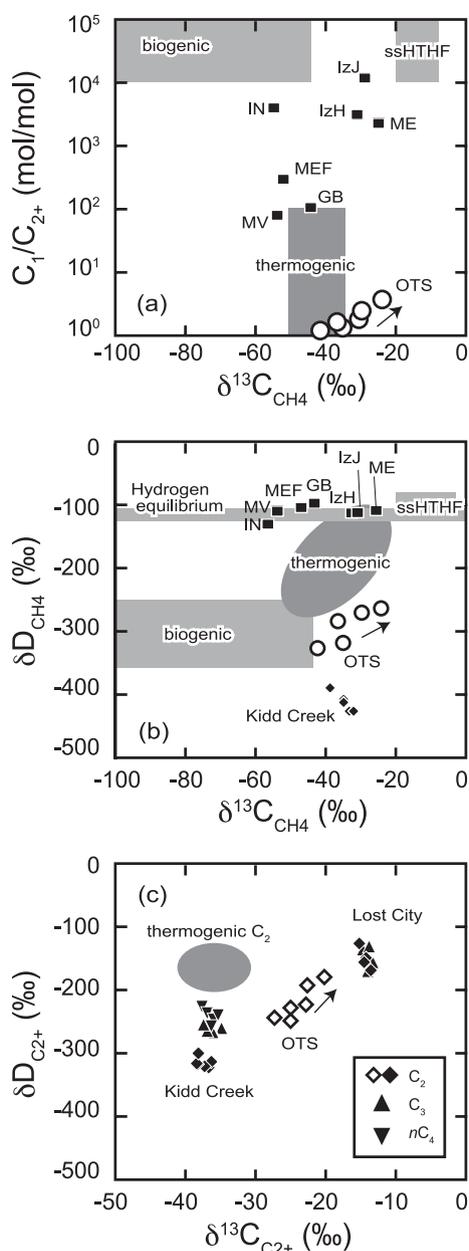


Fig. 4. Diagnostic cross plots for LHCs origins. Each panel shows (a) So-called Bernard plot, (b) C-D plot for methane, and (c) C-D plot for C_{2+} hydrocarbons. Open circles and diamonds are OTS data. Filled symbols in panels a-b represent LHCs in natural geofluids of sediment-associated hydrothermal fluids (squares), sediment-non-associated fields (circles), Kidd Creek geofluid (diamonds (Sherwood Lollar *et al.*, 2002)). Filled symbols in panel c represent LHCs in Kidd Creek geofluid (Sherwood Lollar *et al.*, 2002) and Lost City fluid (Proskurowski *et al.*, 2008). Dark grey zones represent thermogenic LHCs previously referred in literatures (Schoell, 1988; Whiticar, 1999; Sherwood-Lollar *et al.*, 1994; Burruss and Laughrey, 2010). Light grey zones represent biogenic methane (Okumura *et al.*, 2016 and references therein) or LHCs at sediment-starved high-temperature hydrothermal fields (ssHTHF) (Kawagucci *et al.*, 2013 and references therein). Arrows in each panel represent temporal trend of the change for OTS.

2015; Toki *et al.*, 2016; Miyazaki *et al.*, 2017a, b). When compared with results from the OTS experiment, natural hydrothermal fluids show higher C_1/C_{2+} ratio (Figs. 2a and 4a), more diverse $\delta^{13}C_{CH_4}$ values among the fields (Figs. 4a and 4b), higher $\delta^{13}C_{C_2}$ values (Fig. 2c), and higher δD_{CH_4} values (Fig. 4b). With increasing thermal maturity of LHCs, thermodynamically favorable C_{2+} degradation to CH_4 leads to increasing C_1/C_{2+} ratios (Fig. 4a) (see Subsubsection “Carbon isotopic composition”). The C_{2+} degradation and the C_1/C_{2+} increase in natural fluids is likely enhanced when the fluid leaves from sedimentary organic source. The variable $\delta^{13}C_{CH_4}$ values among the fields may be reflected to variable stages of the maturity as seen in the OTS result. Moreover, the lower $\delta^{13}C_{CH_4}$ values ($<-40\text{‰}$) with higher C_1/C_{2+} ratio ($>10^2$) in several hydrothermal fields suggest biogenic methane contribution in addition to thermogenic LHCs (Lilley *et al.*, 1993; Cruse and Seewald, 2006; Kawagucci *et al.*, 2011; Toki *et al.*, 2016). The high δD_{CH_4} values of the natural fluids are similar to values predicted for the hydrogen isotope equilibrium between CH_4 and H_2O (Proskurowski *et al.*, 2006; Kawagucci *et al.*, 2013) although the isotope equilibrium was not observed during the OTS experiment and other hydrothermal experiments (Figs. 3b and 4b) (Fu *et al.*, 2007; McCollom *et al.*, 2010; Reeves *et al.*, 2012). Higher C_1/C_{2+} ratios and equilibrium hydrogen isotopic compositions for LHCs in the natural fluids, which are consistent with the thermodynamic prediction, may reflect longer residence time under hydrothermal condition and/or the presence of natural catalysts in solid and liquid phases within subsurface fluid conduits.

Comparison between the OTS results and petroleum LHCs (Schoell, 1988; Sherwood Lollar *et al.*, 1994; Burruss and Laughrey, 2010) provides additional information on how diverse the “thermogenic signature” is. The diversity results from huge difference in temperature and maturation time between the OTS ($\geq 275^\circ C$ for $>10^6$ years) and natural petroleum (probably $<275^\circ C$ for $>10^6$ years). On a plot of relative abundance of C_{2+} alkanes instead of concentrations along with carbon number, natural gases show a steeper slope than the OTS fluids (Fig. 2b). The depletions in C_{2+} hydrocarbons relative to CH_4 may reflect C_{2+} decomposition during thermal maturation. In general, $\delta^{13}C_{CH_4}$ values from the OTS show some overlap with thermogenic natural gases (Figs. 2c and 4a). The $\delta^{13}C_{C_2-C_3}$ values for alkanes in thermogenic natural gases are lower than observed during the OTS experiment (Fig. 2c). The δD values of C_1-C_2 alkanes of the OTS fluids are lower than those of natural gases during the early stages of the experiments, but are similar during the later stages of OTS alteration (Figs. 2b and 4b).

CONCLUSIONS

The OTS thermogenic LHCs can be explained by simultaneous occurrence of thermal generation and decomposition of LHCs and heterogeneity in bulk sedimentary organic matter with respect to its chemical and isotopic composition. The OTS experiment contributes to our understanding about geochemical processes associated with hydrothermal activity in sediment-associated fields and the origin of subsurface LHCs. On the other hand, there are some shortcomings in experimental setting of OTS. For example, OTS took only ~1200 hours with frequent temperature changes although extent of the maturation is a key factor controlling compositional and isotopic characteristics of thermogenic LHCs. Another shortcoming is no information about the heterogeneity of sedimentary organic matter. Experimental simulation for fluid-sediment interaction with longer timescale than OTS and the compound-/position specific analyses for solid-phase organic source will help to cover broad spectrum and mechanisms of thermogenic signature possibly occurring subsurface environment and to improve accuracy of the geochemical diagnosis for hidden subsurface processes.

Acknowledgments—The InterRidge, a non-profit organization concerned with promoting all aspects of mid-ocean ridge research, provided the Postdoctoral fellowship in 2010 to SK for the internationally collaborative experiment in this study. We wish to thank Sean Sylva and Uta Konno for their professional assistance on the hydrothermal experiment and chemical analysis. SK would like to also thank Prof. Gretchen Bernasconi-Green for providing space and opportunity to prepare the manuscript as an academic visitor of ETH Zurich in 2016.

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