Study of thermochemical sulfate reduction mechanism using compound specific sulfur isotope analysis

Alexander Meshoulam a, Geoffrey S. Ellis b, Ward Said Ahmad a, Andrei Deev c, Alex L. Sessions d, Yongchun Tang c, Jess F. Adkins d, Liu Jinzhong e, William P. Gilhooly III f, Zeev Aizenshtat g, Alon Amrani a,⇑

⇑Corresponding author. Tel.: +972 2 6585477; fax: +972 25662581.
E-mail address: alon.amrani@mail.huji.ac.il (A. Amrani).

a Institute of Earth Sciences, Hebrew University, Jerusalem 91904, Israel
b U.S. Geological Survey, Denver, CO 80225, USA
c Power, Environmental and Energy Research Institute (PEERi), Covina, CA 91722, USA
d Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
e Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
f Department of Earth Sciences Indiana University–Purdue University Indianapolis, IN 46202, USA
g Institute of Chemistry, Hebrew University, Jerusalem 91904, Israel

Received 26 November 2015; accepted in revised form 13 May 2016; Available online 26 May 2016

Abstract

The sulfur isotopic fractionation associated with the formation of organic sulfur compounds (OSCs) during thermochemical sulfate reduction (TSR) was studied using gold-tube pyrolysis experiments to simulate TSR. The reactants used included n-hexadecane (n-C₁₆) as a model organic compound with sulfate, sulfite, or elemental sulfur as the sulfur source. At the end of each experiment, the S-isotopic composition and concentration of remaining sulfate, H₂S, benzothiophene, dibenzothiophene, and 2-phenylthiophene (PT) were measured. The observed S-isotopic fractionations between sulfate and BT, DBT, and H₂S in experimental simulations of TSR correlate well with a multi-stage model of the overall TSR process. Large kinetic isotope fractionations occur during the first, uncatalyzed stage of TSR, 12.4‰ for H₂S and as much as 22.2‰ for BT. The fractionations decrease as the H₂S concentration increases and the reaction enters the second, catalyzed stage. Once all of the oxidizable hydrocarbons have been consumed, sulfate reduction ceases and equilibrium partitioning then dictates the fractionation between H₂S and sulfate (∼17%).

Experiments involving sparingly soluble CaSO₄ show that during the second catalytic phase of TSR the rate of sulfate reduction exceeds that of sulfate dissolution. In this case, there is no apparent isotopic fractionation between source sulfate and generated H₂S, as all of the available sulfate is effectively reduced at all reaction times. When CaSO₄ is replaced with fully soluble Na₂SO₄, sulfate dissolution is no longer rate limiting and significant S-isotopic fractionation is observed. This supports the notion that CaSO₄ dissolution can lead to the apparent lack of fractionation between H₂S and sulfate produced by TSR in nature. The S-isotopic composition of individual OSCs record information related to geochemical reactions that cannot be discerned from the δ³⁴S values obtained from bulk phases such as H₂S, oil, and sulfate minerals, and provide important mechanistic details about the overall TSR process.

© 2016 Elsevier Ltd. All rights reserved.

Keywords: Thermochemical alteration; Organic matter; Sulfur compounds; Sulfate dissolution; Isotopes

http://dx.doi.org/10.1016/j.gca.2016.05.026
0016-7037/© 2016 Elsevier Ltd. All rights reserved.
1. INTRODUCTION

Thermochemical sulfate reduction (TSR) involves a complex reaction network that ultimately results in oxidation of organic carbon (OC) to CO$_2$ and reduction of sulfate to H$_2$S (Machel et al., 1995; Worden and Smalley, 2001). Experimental and field observations have shown that TSR is a kinetically controlled process with an onset temperature between 100 and 140°C, and that temperature is the most critical factor controlling the rate and extent of TSR (Machel, 1987, 2001; Heydari and Moore, 1989; Goldstein and Aizenshtat, 1994; Goldhaber and Orr, 1995; Worden et al., 1995 and references therein).

In one of the first laboratory simulations of TSR, Toland (1960) noted that organic compounds were not oxidized when only sulfate was present; however, the presence of even minute amounts of H$_2$S (or other reduced sulfur species) were able to initiate sulfate reduction. Subsequent studies supported this view that the presence of reduced sulfur is essential for initiating TSR reactions, and showed that the rate of TSR is directly proportional to the amount of reduced sulfur present in the system (Goldhaber and Orr, 1995; Machel, 2001; Cross et al., 2004; Zhang et al., 2008 and references therein). After temperature, the pH of the aqueous solution is probably the next most important factor controlling TSR reactions (Zhang et al., 2012). The dependence of the extent of TSR on pH conditions has been previously noted, with several laboratory studies of TSR having used highly acidic conditions to promote sulfate reduction (Kiyosu and Krouse, 1990; Goldhaber and Orr, 1995). At low pH conditions aqueous sulfate predominantly occurs as bisulfate (HSO$_4^-$), and quantum chemistry molecular modeling calculations have shown that bisulfate ions are much more reactive than stable aqueous sulfur ions (SO$_4^{2-}$) (Ma et al., 2008). The decades-held belief that TSR initiation requires the presence of reduced sulfur was disproven by a series of TSR simulation experiments using aqueous sulfate solutions (CaSO$_4$) buffered to pH conditions <4 (Zhang et al., 2012). It was further proposed that in natural environments where pH conditions are likely to be buffered to values >4, TSR reactions predominantly involve [MgSO$_4$] contact ion pair (CIP) rather than SO$_4^{2-}$ or HSO$_4^-$ (Ma et al., 2008; Zhang et al., 2012). While reduced sulfur species are not required to initiate the TSR reaction, the presence of H$_2$S does enhance the rate of TSR (Zhang et al., 2008). Consequently, a two-stage reaction scheme was proposed to explain this situation. This model postulates that initial sulfate reduction is slow and non-autocatalytic until a threshold concentration of H$_2$S is reached, at which point a faster H$_2$S-catalyzed sulfate reduction reaction becomes dominant (Zhang et al., 2008, 2012). It was suggested that H$_2$S reacts with hydrocarbons to form labile organic sulfur compounds (e.g., thiols, sulfides, polysulfides, etc.) that in turn catalyze TSR (Amrani et al., 2008; Zhang et al., 2008). In addition to the importance of intermediate oxidation-state sulfur species in the catalyzed TSR reaction, Xia et al. (2014) noted the significant role that intermediate oxidized organic compounds (e.g., organic acids, ketones, alcohols, etc.) play at this stage. Further, these authors proposed that once all of the C$_2+$ hydrocarbons have been oxidized, the intermediate oxidized organic compounds are no longer available to participate in the catalytic sulfate reduction reaction, and a slow, non-autocatalytic, third stage of TSR commences (Xia et al., 2014).
showed a relatively large fractionation between OSCs and the parent sulfate.

The demonstrated utility of compound-specific sulfur isotope (CSSI) analysis for identifying reactive classes of compounds involved in TSR indicates that this technique has potential for providing additional information related to the TSR reaction network. In the present study, we attempt to further constrain details of the TSR reaction mechanism(s) by observing S-isotope fractionations among aqueous sulfate, H₂S, BTs, and DBTs during controlled TSR reactions. A series of laboratory pyrolysis experiments were performed involving n-hexadecane as an organic model compound representing petroleum, and two inorganic sulfur species (CaSO₄ and Na₂SO₄) with distinct δ³⁴S values. Compound-specific and bulk sulfur isotope methods were then applied to the products to determine the sulfur isotope fractionations associated with specific organic and inorganic S compounds. The results provide insights into the overall TSR process that can be used to refine existing models of TSR reaction kinetics and geochemical proxies for determining the extent of TSR reaction.

2. EXPERIMENTAL

2.1. Reagents and standards

Solvents used in this study (CH₃Cl₂, hexane, etc.), purchased from BioLab (Jerusalem, Israel), were analytical grade and distilled before use. Sulfur hexafluoride (SF₆, > 99.995% purity) was purchased from Praxair (PA, USA). The sulfur isotope reference materials NBS-127 (BaSO₄; δ³⁴S = 21.1‰), IAEA-S-1 (Ag₂S; −0.3‰), and IAEA-SO-6 (BaSO₄; −34.1‰) were purchased from the National Institute of Standards and Technology (NIST) and used for calibration of in-house standards. All other chemicals were purchased from Sigma–Aldrich (St. Louis, MO) and are analytical grade (>97% purity).

2.2. Pyrolysis experiments

The TSR experiments were conducted in sealed gold tubes with an internal diameter of 4.6 or 7.6 mm, wall thicknesses of 0.2 mm, and lengths of either ∼25 or 70 mm, giving approximate reactor volumes of 1.0 mL. Mg²⁺ plus talc and silica was used as a mineral buffer at elevated temperatures to keep the in situ pH in a narrow range (pH ~ 3, Zhang et al., 2008). The approach used to regulate in situ chemical conditions in this study relies on chemical reactions that are known to proceed rapidly at the temperature and pressure conditions of the experiments (Saccocia and Seyfried, 1990; Seewald et al., 2000). Additional details regarding the mineral buffer approach are given by Zhang et al. (2008).

Each gold tube was loaded with 30 mg of talc, 30 mg of silica, and 450 mg of a distilled water solution containing 5.6 wt% MgCl₂, 10 wt% NaCl, and 0.56 wt% CaSO₄ or Na₂SO₄ depending on the form of solid sulfate used in the experiment. Five mg of hexadecane (n-C₁₆) was added as the organic reagent. Sulfate was added as CaSO₄·2H₂O, 10 mg or 126 mg, to a total sulfate (solid and solution) of 0.093 ± 0.001 mmol and 0.77 ± 0.02 mmol respectively, or as Na₂SO₄ (106 mg, or 0.77 ± 0.02 mmol total sulfate) depending on the particular experiment. Control experiments contained no sulfate (Table 1).

One end of each tube was crimped and sealed using an argon arc welder. Prior to loading the samples, the open-ended tubes were heated to 600 °C (exposed to air) to remove any residual organic material. After loading the reagents into the gold tubes, the tubes were flushed with Ar for 3 min to remove air. The open end of the tube was crimped and welded. Individual sealed gold tubes were subsequently placed in separate stainless-steel autoclaves and inserted into a pyrolysis oven. Pyrolysis experiments were conducted under isothermal conditions at a temperature of 360 °C and ranging from 10 to 180 h. Temperature was controlled to within 1 °C of the set point, and was monitored using a pair of thermocouples (one secured to the outer wall of each autoclave and a second one placed inside). Constant hydrostatic confining pressure was maintained at approximately 24.1 MPa (3500 psi) by a water pump to prevent rupturing of the gold tubes at elevated temperatures and to eliminate possible variations in the reactions as a function of pressure. When the desired reaction time was reached, the stainless-steel autoclave was rapidly cooled to room temperature by an automated cooling system. Once the autoclaves were depressurized, the gold tubes could be recovered for detailed analysis of their contents.

2.2.1. Recovery of samples after pyrolysis

To remove any potential organic contaminants from the exterior of the gold tubes, they were submerged in dichloromethane (DCM) for a minimum of 5 min and then rinsed with an additional aliquot of DCM and allowed to air dry. Following this cleaning procedure, the tubes were scored in three places and then frozen in liquid nitrogen for 5 min. Upon removal from the liquid nitrogen, the welded ends of each of the tubes were cut off and the body of each tube then cut into four equal pieces along the pre-scored lines. The four pieces of the tube were quickly placed into a 20 mL screw-cap vial with a Teflon® lined cap containing 5 mL of DCM and allowed to soak overnight (12–20 h). The vials containing the gold tube pieces were then sonicated for approximately 1 h, and then placed into an ice bath for a minimum of 1 h to minimize loss of volatile components. The vials were then opened for a minimal amount of time to allow for the removal of the pieces of gold tubing and their transfer to a second 20 mL screw-cap vial with a Teflon® lined cap containing 5 mL of DCM. The gold pieces in this second vial were treated in the same manner as the first vial (i.e., soaked overnight, sonicated 1 h, ice bath 1 h). Subsequently, the second vial was opened and each piece of gold tubing was removed, cut open lengthwise, and rinsed with additional DCM to remove all solid residues from the gold. The rinse solvent and solid residues were collected with the 5 mL of solvent in the second vial, which was then combined with the contents of the first vial.
Table 1
Quantities of the reagents used for the gold-tube pyrolysis experiments.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Pyrolysis time (h)</th>
<th>C16 (mg)</th>
<th>C15 (mmol)</th>
<th>Tale (mg)</th>
<th>Silica (mg)</th>
<th>Solutiona (mmol)</th>
<th>Sulfur (solid)b (mmol)</th>
<th>Sulfur in solutionc (mmol)</th>
<th>Total Sd (mmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited</td>
<td>10–180</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.075</td>
<td>0.018</td>
<td>0.093</td>
</tr>
<tr>
<td>CaSO4</td>
<td>10–180</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.75</td>
<td>0.018</td>
<td>0.77</td>
</tr>
<tr>
<td>Excess</td>
<td>10–180</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.069</td>
<td>0</td>
<td>0.069</td>
</tr>
<tr>
<td>Na2SO4</td>
<td>10–180</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.10</td>
<td>0</td>
<td>0.10</td>
</tr>
<tr>
<td>Na2SO3</td>
<td>10–180</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.10</td>
<td>0.018</td>
<td>0.11</td>
</tr>
<tr>
<td>Elemental S</td>
<td>10–89</td>
<td>5.0</td>
<td>0.022</td>
<td>30</td>
<td>30</td>
<td>450</td>
<td>0.10</td>
<td>0</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*a* Mineral buffer water solution containing 5.6 wt% MgCl2 and 10 wt% NaCl. When sulfate was the sulfur source, 0.56 wt% Na2SO4 or CaSO4 was also added to the solution.

*b* Sulfur source added to the gold tube as a solid (CaSO4, Na2SO4, Na2SO3 and elemental S).

*c* Soluble sulfate concentration in the mineral buffer solution added to the gold tube.

*d* Sum of soluble and solid sulfur in each tube.

2.3. GC–MS and GC–FPD analysis

A GC coupled to a Quadrupole mass spectrometer (GC/MS Agilent 7890/5750) was used to identify individual OSCs. About 1 μl of sample was injected into the GC at a split ratio of 10:1 and a constant temperature of 320 °C. Helium was used as the carrier gas at a constant flow rate of 1.5 mL/min. We used two oven temperature programs: (1) 60 °C for 5 min, 60–320 °C at 10 °C/min, and 320 °C for 10 min for a direct comparison with GC–MC–ICPMS and GC coupled to flame photometric detector (FPD) conditions; and (2) 50 °C for 5 min and then heated in a rate of 5 °C min⁻¹ up to 320 °C where it was held for 20 min for the GC–MS. Both GC–MS and GC–FPD were equipped with a DB5-MS capillary column 30 m in length, 0.25 mm in diameter, and with a 0.25 μm film thickness (Agilent). The MS source was operated at 300 °C in electron impact mode at 70 eV.

Peaks of specific compounds (BT, DBT, 2-Phenylthiophene, Thiophenol, etc.) were identified against the retention times and MS spectra of authentic standards. Phenylthiophene, Thiophenol, etc.) were identified against the retention times and MS spectra of authentic standards. Quantification of the gold tube products was made using calibration curves in the range of 1–320 mg. A calibration standard (IAEA) was: 60 °C for 5 min, 60 to 320 °C at 10 °C/min, and 320 °C for 10 min for a direct comparison with GC–MC–ICPMS and GC coupled to flame photometric detector (FPD) conditions; and (2) 50 °C for 5 min and then heated in a rate of 5 °C min⁻¹ up to 320 °C where it was held for 20 min for the GC–MS. Both GC–MS and GC–FPD were equipped with a DB5-MS capillary column 30 m in length, 0.25 mm in diameter, and with a 0.25 μm film thickness (Agilent). The MS source was operated at 300 °C in electron impact mode at 70 eV.

Peaks of specific compounds (BT, DBT, 2-Phenylthiophene, Thiophenol, etc.) were identified against the retention times and MS spectra of authentic standards. Quantification of the gold tube products was made using calibration curves in the range of 1–50 pmol μL⁻¹. Precision of the quantification was estimated by performing duplicate analyses of a few samples to represent the entire sample set. The standard deviation of the duplicates is in the range of 0.2 to 4.4 nmol (RSD 4 to 26%) depends on the sample concentration.

2.4. GC-MC-ICP-MS analysis of δ34S of specific compounds

2.4.1. Instrumental set-up

The compound-specific S-isotope analyses were conducted with a GC coupled to a multi-collector inductively coupled plasma mass spectrometer (GC-MC-ICPMS) based on the system reported by Amrani et al. (2009). We used two different GC-ICP-MS systems in this study. The first, housed in the Division of Geological and Planetary Sciences at the California Institute of Technology, consists of an Agilent 6890 GC that is coupled to a Thermo Scientific Neptune multi-collector (MC) ICP-MS via a heated transfer line (Amrani et al., 2009, 2012). The second, operated by the Earth Sciences Institute at the Hebrew University of Jerusalem Israel, consists of a Clarus 580 GC (Perkin Elmer) or Trace GC (Thermo Fischer), equipped with a Agilent DB5-MS, 30 m, 0.25 mm, 0.25 μm thickness capillary column and coupled to a Thermo Scientific Neptune plus MC-ICP-MS (Said-Ahmad and Amrani, 2013; Gvirtzman et al., 2015). One μl of sample solution was injected into the inlet at a constant temperature of 320 °C. Helium was used as carrier gas at a constant flow rate of 1.5 mL/min. The oven temperature program of the GC was: 60 °C for 5 min, 60 to 320 °C at 10 °C/min, and maintained at 320 °C for 20 min. Both GC-MC-ICPMS systems showed similar performance and similar results (Said-Ahmad and Amrani, 2013; Gvirtzman et al., 2015). SF6 gas (in helium) was used for calibration and injected at the beginning and end of each sample analysis. The SF6 (+2.8 ± 0.5‰ or −1.9 ± 0.5‰) was calibrated against an in-house standard mixture that consisted of: 2-methyl BT (+14.4‰), 2-adamantane thiol (+17.4‰), DBT (+12.9‰ or +3.3‰), octyl sulfide (−0.4) and 4, 6, dimethyl DBT (−8.7). These in-house standards were individually calibrated against IAEA standards (see Section 2.1) EA-IRMS and/or by MC-ICPMS as detailed in Amrani et al. (2009) and Said-Ahmad and Amrani (2013) and Gvirtzman et al. (2015). Calibration of the SF6 against the in-house standard mixture was done every 3–5 samples.

Results of isotopic analyses are expressed in conventional δ34S notation as per mil (‰) deviations in the 34S/32S ratio from the Vienna Canyon Diablo Troilite (VCDT) standard:

\[ \delta^{34}S = \left( \frac{^{34}R_{\text{sample}}}{^{34}R_{\text{std}}} \right) - 1 \]  

where, \(^{34}R\) is the integrated \(^{34}S/^{32}S\) ion-current ratio of the sample and standard peaks. Data processing employed algorithms that are implemented in Visual Basic code.
2.5. Sulfate and hydrogen sulfide quantification and S-isotope analysis

2.5.1. Quantification

For each experiment conducted in the gold tubes, a duplicate was run in parallel to collect the residual sulfate and H₂S. H₂S from the gold tube was bubbled through a 5 wt% AgNO₃ solution and precipitated as solid Ag₂S. The solid was cleaned using distilled water in order to remove any nitrate, washed with acetone, dried and weighed. In several cases, H₂S was also quantified using a GC (Agilent 7890A), equipped with a flame ionization detector (FID) and two thermal conductivity detectors (TCDs). H₂S was measured by TCD after the gold tube gas was initially held at 50 °C for 3 min, ramped from 70 °C to 180 °C at 25 °C/min, and then held at 180 °C for 5 min, where it was held at 90 °C for the inorganic gas analysis. This device was calibrated before the gold tube gas analysis by analyzing a standard gas mixture. The composition of the standard gas was: methane (3%), ethane (3%), propane (1%), CO₂ (5%), and H₂S (5%).

The solid was cleaned using distilled water in order to remove any nitrate, washed with acetone, dried and weighed. In several cases, H₂S was also quantified using a GC (Agilent 7890A), equipped with a flame ionization detector (FID) and two thermal conductivity detectors (TCDs). H₂S was measured by TCD after the gold tube gas was initially held at 50 °C for 3 min, ramped from 70 °C to 180 °C at 25 °C/min, and then held at 180 °C for 5 min, where it was held at 90 °C for the inorganic gas analysis. This device was calibrated before the gold tube gas analysis by analyzing a standard gas mixture. The composition of the standard gas was: methane (5%), ethane (3%), propane (1%), CO₂ (5%), and H₂S (5%), balanced with N₂. The reproducibility of this method was within 10% (RSD).

The residual sulfate was washed from the gold tube into a 20 mL glass vial. An aqueous solution of 5 wt% BaCl₂ was added in excess to the glass vial and then heated to 70 °C overnight. The solution was filtered through a Buchner funnel using 47 mm filter (Whatman®) and the white precipitate was washed with distilled water and weighed. The analytical error for this method was estimated at 0.005 mmol to 0.01 mmol. In some cases the residual sulfate was also quantified using ion chromatography (IC) for comparison. The samples were filtered through a syringe filter (nominal pore size 0.20 µm) and injected into the IC with no further purification. The analytical error of the IC quantification was estimated to be 0.03 mmol (4.1% relative), based on the difference between the measured and known concentration of a standard sample.

2.5.2. Bulk sulfur isotope analysis

The δ³⁴S values of both inorganic sulfide and sulfate were measured using an Elemental Analyzer (Flash 1112 series) connected through a Conflow III interface to an Isotope Ratio Mass Spectrometer (IRMS) (Delta Plus, ThermoFisherScientific). The sulfur isotope reference materials (see Section 2.1) were used for calibration of in-house organic and inorganic standards and Ag₂S and BaSO₄ samples from the pyrolysis experiments. The precision of the measurement of standards were better than 0.3‰.

3. RESULTS

3.1. TSR simulation experiments

Three sets of experiments were performed representing the following experimental conditions as detailed in Table 1: (1) experiments with a limited amount of CaSO₄ and excess hydrocarbon to simulate a closed system for sulfate, (2) experiments with an excess amount of CaSO₄ and limited hydrocarbon to simulate an open system for sulfate, and (3) experiments with an excess amount of Na₂SO₄ as the sulfate source rather than CaSO₄ to study the effect of dissolution rate on S-isotopic fractionation during TSR.

3.1.1. Limited CaSO₄ experiments

These experiments were performed with a limited amount of CaSO₄ (0.093 mmol) for periods of time ranging from 10 to 180 h at 360 °C (Table 1). Fig. 1a clearly shows the reduction of sulfate and formation of H₂S. Sulfate was almost completely consumed during the course of the reaction under these conditions. At early TSR stages, the amounts of BT and DBT produced were small (0–4 nmol of BT and 0–0.2 nmol of DBT), but after 20 h significant amounts of BT, DBT, and H₂S production were observed. The amount of DBT after 40 h remained relatively constant (~10 nmol), while BT reached a maximum amount of about 30 nmol after 89 h and then started to degrade (Fig. 1b).

Experiments were conducted with initial CaSO₄ reactant of three distinct δ³⁴S values (+12.8‰, +2.4‰ and −5.3‰) to follow the S-isotope fractionation of OSC with more confidence (Table 2). Another experiment was performed to measure the residual sulfate fractionations and concentrations (initial δ³⁴S = 19.6‰). The results are presented as the difference between the δ³⁴S values of reactant sulfate and product according to the following equation:

\[ \Delta^{34}S = \delta^{34}S_{\text{product}} - \delta^{34}S_{\text{initial sulfate}} \]  

The results of these three experiments were in good agreement (Table 2), and Fig. 1c presents the average δ³⁴S data from all three experiments. We chose to focus on BT and DBT as representative of OSCs produced via TSR because of their relatively high abundance, differential thermal stability, and ease of chromatographic separation (Fig. 2), the latter of which allowed for more reliable δ³⁴S measurements.

The δ³⁴S value of sulfate was almost constant during the course of the reaction and did not change significantly (0.5‰) relative to the initial sulfate. The δ³⁴S value of the newly formed H₂S was initially (20 h) 7.1‰ lower than that of initial sulfate, and then rapidly converged to the δ³⁴S of initial sulfate (Fig. 1c).

Large S-isotopic differences between the initial sulfate and the OSCs in the early stages of the TSR experiments were consistently observed in all three experiments (Fig. 1c). A fractionation of 18.8‰ was observed between BT and the initial sulfate during the first 10 h (Fig. 1c). After 20 h BT and DBT had similar δ³⁴S values, about 10.6‰ lower than the initial sulfate, while H₂S at this time was depleted in ³⁴S by about 7.1‰. This isotopic difference
gradually decreased as the pyrolysis time progressed, with H$_2$S being the fastest to approach the $\delta^{34}$S of the source sulfate, while BT and DBT changed at slower rates. BT was consistently $^{34}$S-enriched relative to DBT (3 to 5‰) and never reached the $\delta^{34}$S of the H$_2$S and sulfate, but was about 2‰ $^{34}$S-depleted.

3.1.2. Excess CaSO$_4$ experiments

In these experiments, the CaSO$_4$ (0.77 mmol) was in large excess, 8-fold, relative to the “limited” CaSO$_4$ experiments. Consequently only about 16% of the CaSO$_4$ was consumed after 180 h (Fig. 3a), while in the “limited” experiments almost all the CaSO$_4$ was consumed. Significant amounts of H$_2$S, BT, and DBT were observed only after 40 h of reaction (Fig. 3b). The amounts of BT and DBT were higher than those of the limited experiments by 2- and 15-fold, respectively. BT was produced faster than DBT and at 40 h reached its maximum concentration, while DBT reached its maximum production at 180 h. Unlike the limited sulfate experiments, the amount of BT decreased significantly at later TSR stages. In this set of experiments, we also clearly identified another representative compound, 2-phenylthiophene (PT) that has a lower thermal stability than BT (Fig. 2). This compound (PT) can aid our understanding of the system because the lower thermal stability leads to more instantaneous reactions with H$_2$S, which is then reflected in its $\delta^{34}$S value. PT’s production was significant only after 40 h, and its concentration was much lower than BT and DBT reaching a maximum of 14.2 nmol after 89 h.

Experiments with two different initial CaSO$_4$ $\delta^{34}$S values (12.8‰ and 2.4‰) were conducted in order to check the reproducibility of the results. Another experiment was performed to measure the residual sulfate fractionations and concentrations (initial $\delta^{34}$S = 19.6‰). The reported results are the average fractionation values of these two experiments from initial sulfate (Fig. 3c; Table 2). No significant S-isotopic fractionation was observed between sulfate and H$_2$S throughout all stages of the reaction, and they both had $\delta^{34}$S values similar to the initial CaSO$_4$. BT and DBT showed similar trends relative to the limited-CaSO$_4$ experiments, but in this case the S-isotopic values of BT did not reach a plateau even at the latest reaction time. The initial $\delta^{34}$S values of BT and DBT were lower than in the limited-CaSO$_4$ experiment. PT experienced a more rapid S-isotopic convergence to the initial sulfate value than either the BT or DBT. Its value became heavier than BT or DBT and reached the initial sulfate value after 180 h.

3.1.3. Experiments with excess Na$_2$SO$_4$

These experiments were conducted in order to simulate TSR with an excess of the fully soluble Na$_2$SO$_4$ (0.77 mmol) to study the effect of sulfate dissolution rate on S-isotopic fractionation. Two distinct Na$_2$SO$_4$ reagents with initial $\delta^{34}$S values of –5.3‰ and +1.0‰ were chosen for these experiments in order to verify the reproducibility of the results (Table 3). Compared to the excess-CaSO$_4$ experiments, the consumption of Na$_2$SO$_4$ was similar, although a bit higher (about 0.09 mmol) and the H$_2$S yields were similar (Fig. 4a).

Significant formation of OSCs began after 20 h (Fig. 4b). BT and PT reached their maximum concentrations after 40 h (60 and 75 nmol, respectively) while DBT reached its maximum concentration of 355 nmol after 89 h. These maximum OSC concentrations were significantly higher than those observed for the CaSO$_4$ experiments. However, the thermal degradation of OSCs was also very intensive, and after 180 h only DBT, the most thermally stable compound of the three, remained in the
Table 2
δ¹³S values for the individual gold-tube pyrolysis experiments with distinct CaSO₄ reagents.

<table>
<thead>
<tr>
<th>Pyrolysis time (h)</th>
<th>Initial calcium sulfate (CaSO₄) = -5.3‰</th>
<th>Initial calcium sulfate (CaSO₄) = 2.4‰</th>
<th>Initial calcium sulfate (CaSO₄) = 12.8‰</th>
<th>Initial calcium sulfate (CaSO₄) = 19.6‰</th>
<th>Δ³⁴S = δ³⁴S(product) − δ³⁴S(initial sulfate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BT (%)</td>
<td>DBT (%)</td>
<td>BT (%)</td>
<td>DBT (%)</td>
<td>2-PT (%)</td>
</tr>
<tr>
<td>Limited CaSO₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-22.6</td>
<td>-</td>
<td>-6.7</td>
<td>-</td>
<td>-7.4</td>
</tr>
<tr>
<td>20</td>
<td>-15.2</td>
<td>-16.2</td>
<td>-11.5</td>
<td>-</td>
<td>4.1</td>
</tr>
<tr>
<td>40</td>
<td>-9.0</td>
<td>-12.6</td>
<td>-2.9</td>
<td>-3.7</td>
<td>7.8</td>
</tr>
<tr>
<td>89</td>
<td>-6.5</td>
<td>-11.4</td>
<td>-</td>
<td>-</td>
<td>10.4</td>
</tr>
<tr>
<td>180</td>
<td>-5.6</td>
<td>-11.5</td>
<td>-1.6</td>
<td>-3.1</td>
<td>10.9</td>
</tr>
<tr>
<td>Excess CaSO₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-12.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-6.4</td>
<td>-8.5</td>
<td>-2.2</td>
</tr>
<tr>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-1.0</td>
<td>-5.9</td>
<td>3.1</td>
</tr>
<tr>
<td>89</td>
<td>-</td>
<td>-</td>
<td>-1.2</td>
<td>-6.2</td>
<td>1.2</td>
</tr>
<tr>
<td>180</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
</tr>
</tbody>
</table>

'–' Could not be detected or not measured.

Another measurement of -3.5‰ for H₂S was taken from initial CaSO₄ of 2.4‰.
system. The initial S-isotopic fractionation of H$_2$S from the initial sulfate, which could be measured after 20 h, was 12.4‰, and after 89 h it had increased to about 14‰. The remaining sulfate became gradually 34S-enriched up to 3.9‰ relative to the initial sulfate after 180 h. In contrast, the experiments with CaSO$_4$ did not change the $\delta^{34}$S values of the sulfate during the reaction (Figs. 1 and 3).

The S-isotopic fractionation for OSCs at the early stages was the largest observed of all TSR experiments (Fig. 4c) and reached 22.2‰ for BT after 10 h. PT and DBT were measured after 20 h and their fractionation relative to the initial sulfate was 17.5‰ and 18.0‰, respectively. Unlike the experiments with CaSO$_4$, OSCs did not converge on the $\delta^{34}$S values of sulfate as the reaction progressed beyond 20 h. BT did become 34S-enriched for reaction times between 10 and 20 h, but did not change much at 40 h, and later it was completely degraded and disappeared from the system. DBT’s fractionation relative to the initial sulfate started at 17‰, increased to 20.2‰, and then returned to 17‰ to the end of the reaction.

The intensity of the reaction of Na$_2$SO$_4$ relative to that of CaSO$_4$ is evident in Fig. 5. In the Na$_2$SO$_4$ experiments (Fig. 5c), $n$-C$_{16}$ and its breakdown products ($n$-C$_{14}$ to $n$-C$_9$) were completely consumed by the longest experimental time (180 h), thus limiting the TSR reaction and the formation of additional H$_2$S (Fig. 5). Fused-ring aromatic compounds (e.g., naphthalene) become a dominant hydrocarbon with increased reaction time under all of the experimental conditions studied. The concentrations of these aromatic compounds increases from the limited-CaSO$_4$ experiment (Fig. 5a) to the most reactive Na$_2$SO$_4$ conditions (Fig. 5c) with the excess-CaSO$_4$ experiment in between (Fig. 5b), reflecting the intensity of the TSR reaction. A similar order can be seen for the increased formation of elemental S among the different sets of experiments probably because of the decreasing amounts of hydrocarbons available to reduce it to H$_2$S.

3.2. Non-TSR Pyrolysis experiments

In order to better understand the TSR mechanism, we also studied secondary reactions of TSR products (elemental S and SO$_3$) with $n$-C$_{16}$. The molar S quantities, time
3.2.1. n-C16 pyrolysis experiments with elemental sulfur (S8)

These experiments were conducted to determine the fractionation between reduced S species and OSCs. It is important to note that the reaction with elemental S and hydrocarbons is so intense at 360°C that elemental S is rapidly converted to H2S. Consequently, this experiment may actually represent the fractionation associated with the reaction of hydrocarbons with H2S rather than elemental S. Measured values for this fractionation, when combined with the total fractionation for OSC formation via sulfate reduction, allows for the calculation of the net sulfur isotopic fractionation associated with the reduction of sulfate (or sulfite) to elemental S or H2S using the OSCs \( \delta^{34}\text{S} \) values.

In these experiments, elemental S (0.1 mmol) and n-C16 were reacted under identical experimental conditions as in the TSR experiments. The only sulfur source in these experiments was elemental S.

The results showed a rapid formation of BT and DBT (after 10 h), and a temporal pattern that was different from the TSR experiments (Fig. 6a). In the TSR experiments, DBT continuously increased in concentration with reaction time while BT was either constant (limited-sulfate experiment) or reduced (excess-sulfate experiments) with extent of reaction. In contrast to the elemental S experiments, DBT remained constant at about 10 nmole and BT increased up to about 70 nmol (Fig. 6a). The total concentrations of these compounds were in the range of the excess-sulfate TSR experiments. The fractionations of BT and DBT from the initial elemental S (+1.2‰) were 0.5 to 2.5‰, respectively (Table 4). BT was consistently 34S-enriched relative to DBT by about 0.5–1.5‰, and there were no apparent effects of the reaction time on the fractionations.

3.2.2. n-C16 pyrolysis experiments with sodium sulfite (Na2SO3)

The rate-limiting step in TSR is thought to be the cleavage of the first S-O bond in sulfate leading to the formation of sulfite from sulfate (Goldstein and Aizenshtat, 1994; Ma et al., 2008). These experiments were conducted in order to measure the isotopic fractionation related to the reaction of sulfite with organic matter (Table 5). The results of these experiments are presented in Fig. 6. Significant fractionation between BT and DBT and initial sulfite were observed over the course of the reaction, up to 9.0‰ for DBT (Fig. 6b). However, no fractionation between H2S and the original sulfite was measured, contrary to the observations from the limited-sulfate experiments.

4. DISCUSSION

4.1. Isotope fractionation during TSR

4.1.1. Kinetic isotope fractionation

Results of the present study support the two-stage model that was suggested in earlier work by Zhang et al. (2008). Fig. 7 illustrates these two stages and their associated chemical reactions, based on the S-isotopic patterns of individual OSCs observed in the present study. The first reaction in the initial stage of TSR involves cleavage of an S-O bond in the aqueous sulfate ion (Eq. (3); Ma et al., 2008), which is accompanied by a large kinetic isotopic effect (Harrison and Thode, 1957; Goldstein and Aizenshtat, 1994).

\[
\text{HSO}_4^- + \text{C}_x\text{H}_y \rightarrow \text{HSO}_4^- + \text{C}_x\text{H}_{y-2} + \text{H}_2\text{O}
\]  

(3)
Table 3: $\Delta^{34}S$ values for the individual gold-tube pyrolysis experiments with Na$_2$SO$_4$.

<table>
<thead>
<tr>
<th>Na$_2$SO$_4$ experiments</th>
<th>$\Delta^{34}S_{\text{DBT}}$ (%)</th>
<th>$\Delta^{34}S_{\text{H}_2\text{S}}$ (%)</th>
<th>$\Delta^{34}S_{\text{residual}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium sulfate (Na$_2$SO$_4$)=1‰</td>
<td>-12.4 ± 1.2</td>
<td>-15.2</td>
<td>-13.9</td>
</tr>
<tr>
<td>Sodium sulfate (Na$_2$SO$_4$)=5.3‰</td>
<td>-10.3</td>
<td>26.6</td>
<td>-13.9</td>
</tr>
<tr>
<td>Sodium sulfate (Na$_2$SO$_4$)=27.5‰</td>
<td>-22.2</td>
<td>-20.2</td>
<td>-17.3</td>
</tr>
<tr>
<td>Sodium sulfate (Na$_2$SO$_4$)=12.4‰</td>
<td>-17.8</td>
<td>-9.3</td>
<td>-15.2</td>
</tr>
</tbody>
</table>

Harrison and Thode (1957) empirically determined a fractionation factor of about 22% for the chemical reduction of sulfate to H$_2$S over a temperature range of 18–50°C. These authors suggested that the rate-limiting step is the SO$_3^{2-}$ to SO$_2^{2-}$ reduction and support this with theoretical calculations. Grinenko et al. (1969) performed TSR experiments at the range of 100 to 290°C and reported fractions of 18.7‰ to 8.6‰, respectively with a clear temperature dependence. Both Grinenko et al. (1969) and Harrison and Thode (1957) studies used highly acidic and reducing reagents (e.g., HI, H$_3$PO$_2$, and HCl) or H$_2$ but no hydrocarbons in their experiments. More recent laboratory experiments demonstrated fractionations of up to 20.8‰ at 150–200°C and under open-system conditions, using amino acids as the reductant (Watanabe et al., 2009). Oduro et al. (2011) conducted both closed-system pyrolysis (175–298°C in Carius tubes) and open-system pyrolysis (258°C and 298°C) experiments and demonstrated fractionations of up to ~15.6‰ and 19.2‰, respectively, using glycine as the carbon source. These previous studies are difficult to compare to our results because of the different reagents (amino acids, H$_2$ etc.), chemical conditions (e.g., pH), temperatures and type of pyrolysis (open or closed) used. Other TSR experiments, closer in their operating conditions to the present work, were conducted in a closed system over temperatures ranging from 250 to 340°C, and reported maximum fractionations of 8 to 10‰ with no clear dependence on temperature (Kiyosu, 1980). Later work by Kiyosu and Krouse (1990) suggested that the kinetic isotopic effect (KIE) during TSR is a function of temperature:

$$10^3(z - 1) = 3.32 \times 10^6 \frac{T}{T^2} - 4.19$$

where, $z$ is the fractionation factor for sulfate and $T$ is the temperature in Kelvin. Using Eq. (4), $z$ is calculated to be 1.0046 (at $T = 633$ K), which translates to 4.6‰ at our experimental temperature. According to these authors, this reduction in the fractionation relative to their early work by 4–5‰ (Kiyosu, 1980), was caused by the fact that in the later work H$_2$S was detected only after the entire pool of sulfate was consumed. They suggested that the reduced S was in another intermediate form before it was converted to H$_2$S (Kiyosu and Krouse, 1990). In the present study, both H$_2$S and sulfate were present in the system, and is therefore more comparable to the earlier work (Kiyosu, 1980) than the later study (Kiyosu and Krouse, 1990). The previously observed fractionation of 8–10‰ (Kiyosu, 1980) is closer to the values measured for sulfate-sulfide fractionation at the early stages of both the limited-CaSO$_4$ experiment (7.1‰) and the Na$_2$SO$_4$ (12.4‰) experiment, indicating that these initial fractionations are probably due to the kinetic isotopic effect.

4.1.2. Organosulfur species formation

Compared to the fractionations observed in the generated H$_2$S, significantly larger fractionations were recorded by the early formed BT in the limited-CaSO$_4$ and the Na$_2$SO$_4$ experiments, with magnitudes of 18.8‰ and 22.2‰, respectively (Figs. 1c and 4c).
observed after 10 h of reaction when H2S was yet to be detected. In contrast, pyrolysis experiments with n-C16 and elemental S form OSCs with only 1–3‰ 34S depletion relative to their initial S source (Fig. 6a). The δ34S values of BT and DBT were similar, but DBT was consistently about 1–2‰ depleted and the BT was closer to the source elemental S (Fig. 6a). A detailed discussion of the δ34S values of OSCs formed during TSR reactions is provided in Section 4.2.

In similar gold-tube pyrolysis experiments (360 °C) with adamantane (a 10-carbon hydrocarbon with a cage-like structure) and elemental S, a 34S depletion of 0.5–3.4‰ for the newly formed thiaadamantanes and BTs was observed (Gvirtzman et al., 2015). Previous experiments with different reduced S species (H2S(g), elemental S, and (NH4)2S(aq)) with 1-tetradecene at lower temperatures (200 °C) are in agreement with these results and show small fractionations (0.5 to 4‰) for OSC formation (mainly thiophenes, Amrani et al., 2006).

These experimental results indicate that there is only minor fractionation in the formation of OSCs from reduced S species such as H2S and elemental S at high temperature. This fractionation (usually < 4‰) cannot explain the large S-isotope fractionation between source sulfate and OSC, up to ~22‰, in the initial stages of the present TSR experiments (Fig. 4c). If the δ34S values observed in the OSCs represent the very early sulfate-H2S fractionation (plus an additional 2–3‰ for the formation of OSC from H2S), then a large disagreement exists between the current work and the earlier studies of Kiyosu (1980) and Kiyosu and Krouse (1990). Other mechanisms (in addition to the KIE) need to be investigated to assess their potential impact on observed S-isotope fractionations in TSR reactions.

4.1.3. Closed-system distillation

To determine if our isotopic data can be explained by closed-system distillation ("Rayleigh distillation"), the following equations can be used to predict fractionation between sulfate and H2S as a function of the fractional extent of reaction (f) as determined by the consumption of sulfate:

\[
\delta_{RS} = \delta_{initial} - \alpha \ln(1 - f) \\
\delta_{ip} = \delta_{initial} - \alpha \left[1 + \ln(1 - f)\right] \\
\delta_{AP} = \delta_{initial} + \alpha \left(1 - \frac{1}{f}\right) \ln(1 - f)
\]

where, \(\delta_{RS}\) is the residual sulfate isotopic composition, \(\delta_{initial}\) is the initial sulfate value, \(\delta_{AP}\) is the accumulated product value (H2S), \(\delta_{ip}\) is the instantaneous product (H2S) value, and \(\alpha\) is the relevant fractionation factor. Calculations were made using two distinct fractionation factors (\(\alpha\)). First, \(\alpha = 1.011\) based on the measured H2S fractionation relative to source sulfate at the earliest time that it could be detected (20 h) in the Na2SO4 experiment. Second, \(\alpha = 1.020\) based on the BTs fractionation relative to source sulfate after 10 h (22.2‰) in the Na2SO4 experiment. This value accounts for the fractionation related to the formation of BT by elemental S/H2S incorporation into n-C16 (2‰).

The results of the calculations for the CaSO4 experiments do not fit the Rayleigh distillation model for \(\alpha = 1.020\) (not shown) and \(\alpha = 1.011\) (Fig. 8a,b).

However, Rayleigh distillation may be a reasonable model to explain the early stages of the Na2SO4 experiments using \(\alpha = 1.011\), but not at the later stages (Fig. 8c). We therefore conclude that both the CaSO4 and Na2SO4 systems are influenced by additional factors apart from closed-system distillation as is discussed below.
4.1.4. CaSO₄ dissolution

The differences among some of the results observed for the CaSO₄ and Na₂SO₄ experiments can be explained by the slow dissolution rate of CaSO₄ under our experimental conditions. In both the “limited” and “excess” CaSO₄ experiments there is a large amount of solid-phase CaSO₄ present for most of the reaction times. Under the same experimental conditions, Na₂SO₄ is always fully soluble and thus immediately available for TSR. Indeed, for natural systems it has been suggested that the isotopic fractionation during TSR is largely controlled by the rate of dissolution of sulfate minerals, which can be slower than the rate of the dissolved sulfate consumption via reduction by organic molecules (Ohmoto and Rye, 1979; Powell and Macqueen, 1984; Machel et al., 1995). Therefore, dissolution of CaSO₄ may be the rate-limiting step in the reduction of sulfate during the TSR process in nature. Consequently, most reports of natural occurrences of TSR find minimal sulfur isotope fractionation among sulfate, hydrogen sulfide, and bulk oils (Krouse, 1977; Worden and Smalley, 1996; Cai et al., 2003).

The notion that sulfate dissolution rates affect apparent isotopic fractionations in natural occurrences of TSR is supported by the observations from the experiments performed in this study. The temperature, pH, and sulfate concentration all control the amount of reactive sulfate (HSO₄⁻) available in solution in these experiments (Ma et al., 2008). The limited-CaSO₄ experiments initially contained 0.018 mmol of CaSO₄ in solution plus an additional 0.076 mmol of sulfate solid, for a total of 0.094 mmol of sulfate in the system (see Section 2). At this concentration, there is solid sulfate initially present in the experiments, and the rate of TSR is slow enough that sulfate dissolution does not limit the overall reaction process. In this case, significant sulfur isotopic fractionation is observed between the source sulfate and the generated H₂S and OSCs (Fig. 1c). However, once a certain portion of the soluble sulfate is consumed, the system starts to become sulfate limited and the apparent fractionation rapidly diminishes. This sulfate limitation begins to be apparent after about 20 h in the limited-CaSO₄ experiments.

The excess-CaSO₄ experiments initially contained 0.77 mmol of total sulfate (0.018 mmol in solution plus 0.75 mmol of solid sulfate, see Section 2 and Table 1), nearly one order of magnitude greater than in the limited experiments. At this high sulfate concentration, the rate
of TSR is expected to be commensurately faster. This is supported by the larger amount of H$_2$S generated and greater extent of sulfate reduction observed in the excess versus limited-SO$_4$ experiments (Figs. 1a and 3a). In both the limited- and excess-sulfate experiments, OSCs show significant $^{34}$S-depletion at the earliest stages of TSR, and then their $\delta^{34}$S values increased rapidly and reached a plateau, 5–10‰ lower than the source sulfate (Fig. 3c). However, H$_2$S in the limited-sulfate experiment exhibited a similar isotopic pattern; whereas, the H$_2$S generated in the excess-sulfate experiments has a nearly constant $\delta^{34}$S value that is equivalent to that of supplied sulfate, even in the earliest H$_2$S observation (20 h). This is explained by the significantly faster rate of TSR in the excess compared to the limited-sulfate experiments. At the lower total sulfate concentrations (limited CaSO$_4$), the TSR reactions in the short term experiments (<40 h) follow the slow, non-autocatalytic pathway. However, the excess-sulfate experiments contain a sufficiently large amount of reactive sulfate (HSO$_4^-$) that the fast, autocatalytic TSR reaction becomes dominant the pathway at a very early stage (<20 h). Consequently, the dissolved sulfate is rapidly consumed and the dissolution of solid sulfate becomes rate limiting, leading to no apparent S-isotope fractionation between sulfate and sulfide. The slow, non-autocatalytic TSR reaction can be inferred to have occurred in the very initial stages (<<20 h) of the excess sulfate experiments by the $\delta^{34}$S values require a $^{34}$S-depleted source, which can logically be assumed to be the H$_2$S generated from non-autocatalytic TSR.

The clearest evidence for the effect of sulfate solubility on S-isotope fractionation in TSR reactions is provided by comparison of the results of the sparingly soluble CaSO$_4$ experiments with those involving fully soluble Na$_2$SO$_4$ (Figs. 1c, 3c, and 4c). At the initial reaction times, the Na$_2$SO$_4$ experiments show fractionations between sulfate and OSCs similar to those observed in the CaSO$_4$ experiments. However, at the later reaction times the $\delta^{34}$S values of the OSCs do not increase toward sulfate, but rather remain significantly depleted. Likewise, the H$_2$S generated by TSR reactions in the Na$_2$SO$_4$ experiments was consistently $^{34}$S-depleted relative to the sulfate at all reaction times (Fig. 4c). The significant S-isotope fractionation observed in all of the TSR products generated in the Na$_2$SO$_4$ experiments lends unequivocal support to the notion that rate-limiting dissolution of solid sulfate in TSR reactions involving CaSO$_4$ can obscure the actual S isotope effects associated with sulfate reduction. This can explain the apparent lack of S-isotope fractionation often observed in natural systems, and accounts for some of the deviation from Rayleigh distillation behavior observed in the experimental results of the present study.

### 4.1.5. Equilibrium isotope effects

In experiments with Na$_2$SO$_4$, the isotopic fractionation between H$_2$S and residual sulfate after 20 h was 13.4‰.
Na$_2$SO$_3$ experiments, the residual sulfate became more dominant in the chromatogram of the later reaction times. This indicates that the main reactive hydrocarbons for the Na$_2$SO$_4$ experiments are abundant after 89 h of pyrolysis increased to 17.0‰ and 18.4‰ after 180 h (Fig. 4c and Table 3). Note that these fractionations were calculated based on the residual sulfate in the system after each experiment and not to the initial sulfate in the CaSO$_4$ experiments. The residual sulfate fractionations were calculated based on the residual sulfate in the system after each experiment.

The magnitude of fractionation at the later stages of the Na$_2$SO$_4$ experiments is similar to that reported by Ohmoto and Lasaga (1982). They suggested the following reaction scheme to explain the equilibrium isotopic effect (EIE) in hydrothermal sulfate-sulfide systems with no organic compounds present:

$$\text{HSO}_4^- + \text{H}_2\text{S} + \text{H}^+ \rightleftharpoons \text{H}_2\text{SO}_3 + \text{H}_2\text{O} \quad (\text{fast})$$

$$\text{HSO}_4^- + \text{H}_2\text{S} + \text{H}^+ \rightarrow \text{H}_2\text{SO}_3 + \text{H}_2\text{O} \quad (\text{slow})$$

Ohmoto and Lasaga (1982) propose that the fractionation factor for this equilibrium is described by:

$$1000 \ln (x) = \frac{6.463 \times 10^6}{(T)^2} + 0.56$$

Using this equation, the fractionation between sulfate and sulfide predicted in our system would be 16.8‰, close to the range of fractionations (17.0 to 18.4‰) observed at the later reaction times (Fig. 4c). The chromatograms of the extractable residual organic matter in the Na$_2$SO$_4$ experiments reveal that n-C$_{16}$ and other secondarily formed straight-chain hydrocarbons and single-ring aromatic compounds were completely consumed (Fig. 5c). Moreover, elemental S became more dominant in the chromatogram of the Na$_2$SO$_4$ experiments providing additional support for the absence of sufficient oxidizable hydrocarbons (Fig. 5). This indicates that the main reactive hydrocarbons for the TSR reaction were absent at these reaction times. However, in the CaSO$_4$ experiments, the BT production stopped or became very slow (Fig. 4a). Therefore the system at this stage, with no hydrocarbons to react with sulfur, is similar to the system described by Ohmoto and Lasaga (1982) and exhibiting a similar EIE between sulfate and sulfide.

We suggest that the fractionations measured in the Na$_2$SO$_4$ experimental system were governed by both kinetic and equilibrium isotope effects at different stages. When reactive organic compounds are abundant in the system, sulfate reduction is occurring and the dominant fractionation mechanism is kinetic. When the sulfate reduction has slowed down or stopped, equilibrium is attained between sulfate and sulfide and the isotopic fractionation is governed by equilibrium effects. This can also explain why the Rayleigh distillation model was able to fit the early stages of TSR in the Na$_2$SO$_4$ experiments, but did not accurately predict S-isotopic compositions of the TSR products at the later stages (>40 h) when TSR had significantly slowed or stopped.

### 4.2. Isotope fractionation during OSC formation

#### 4.2.1. Relative reaction rates and $\delta^{34}$S values of OSCs

In the CaSO$_4$ experiments, the initial large S-isotope fractionation between OSCs (BT and DBT) and the source sulfate rapidly disappears and the $\delta^{34}$S values converge to that of H$_2$S and sulfate (Figs. 1c and 3c). However, the rates of the convergence differ with BT $\delta^{34}$S changing faster than that of DBT. BT degrades faster than DBT during all experiments because of its lower thermal stability. Another possible reason for the change in the relative abundance of BT and DBT is a decrease in the respective formation rates as a result of the limited availability of suitable precursor compounds. Aromatic precursors (e.g., alkyl-benzenes) are known to react with sulfur at elevated temperatures and produce BTs, while fused aromatic rings and biphenyls produce DBTs (Aizenshtat et al., 1995; Asif et al., 2009). With increasing thermal maturation and TSR, there are more fused aromatic compounds present and consequently more opportunities for DBT formation than BT (Radke et al., 1982). At every reaction time, the concentrations of BT and DBT are controlled by their relative formation and degradation rates.

No significant S-isotope fractionation is apparent during the thermal degradation of either BT or DBT. In the excess-CaSO$_4$ experiments, the BT concentration from 89 to 180 h decreases by nearly 80% while its $\delta^{34}$S composition changes by $<1.5$‰ (Figs. 1b and 3b). In the Na$_2$SO$_4$ experiments, a drop in the DBT concentration from 354 to

### Table 5

Results ($\delta^{34}$S values) for the individual gold-tube pyrolysis experiments with Na$_2$SO$_3$ and n-C$_{16}$.

<table>
<thead>
<tr>
<th>Initial sodium sulfite (Na$_2$SO$_3$)</th>
<th>$-1.3$‰</th>
<th>$\Delta^{34}$S = $\delta^{34}$S(product) − $\delta^{34}$S(initial sulfite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrolysis time (h)</td>
<td>BT (%$\delta^{34}$S)</td>
<td>DBT (%$\delta^{34}$S)</td>
</tr>
<tr>
<td>Na$_2$SO$_3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-7.8</td>
<td>-10.3</td>
</tr>
<tr>
<td>20</td>
<td>-5.5</td>
<td>-8.8</td>
</tr>
<tr>
<td>40</td>
<td>-5.3</td>
<td>-8.6</td>
</tr>
<tr>
<td>89</td>
<td>-5.2</td>
<td>-7.2</td>
</tr>
<tr>
<td>180</td>
<td>-3.0</td>
<td>-4.7</td>
</tr>
</tbody>
</table>
153 nmol is accompanied by no change in the $\delta^{34}$S (Figs. 4b and 4c). The steady-state $\delta^{34}$S of BT and DBT is controlled by the balance of isotope effects on synthesis and degradation. Our data are consistent with little fractionation on degradation, but we cannot prove it is zero. We hypothesize that the steady-state values are therefore mainly controlled by fractionations during synthesis, which should reflect the reactive inorganic S species. The newly formed OSCs carry the $\delta^{34}$S value of the reduced inorganic S species (e.g., H$_2$S produced during TSR) as evidenced by the experiments with elemental S (Fig. 6b). In the experiments with CaSO$_4$, the H$_2$S converges to the $\delta^{34}$S value of the source sulfate very quickly (0–20 h). The $\delta^{34}$S value of OSC at any given reaction time will be the result of a mixture of early formed OSC that has $^{34}$S-depleted values and newly formed OSC with relatively $^{34}$S-enriched values inherited from the inorganic reduced S species produced by TSR at each step. The degree of mixing of sources will be determined by the residence time of BT and DBT in the system, which in turn is related to the relative thermal degradation rate as well as the formation rate during these experiments.

4.2.2. Sulfur sources for OSCs during TSR

Significant quantities of OSCs are known to be formed via reactions of reduced S species with petroleum hydrocarbons during TSR. Hydrogen sulfide is generally assumed to be the predominant species that forms OSCs, because of its high abundance relative to all other reduced S species in petroleum reservoirs (Orr, 1974; Powell and Macqueen, 1984; Hanin et al., 2002; Cai et al., 2003, 2009).

However, other possible S sources for OSC formation during TSR may be intermediate oxidation-state S species such as elemental S, S$_x$S$_2$, SO$_3$, and S$_2$O$_3$ (Goldstein and Aizenshtat, 1994). These intermediate S species readily react with hydrocarbons to form OSC, and H$_2$S is also formed either through direct reduction of the intermediate S or by subsequent thermal cracking of the OSC (Aizenshtat et al., 1995; Lewan, 1998). A recent study has shown that tri-sulfur ions (S$_3$) are formed during heating experiments of aqueous sulfate solutions, suggesting that this may be an important intermediate in the reduction of sulfate (Truche et al., 2014). The mechanism for S$_3$ ion formation is unknown; however, once formed it can be reduced in the presence of protons to sulfide or form thiophenes, although this was shown only under basic conditions (Zhang et al., 2015). If the reaction of S$_3$ or other intermediate S species with organic compounds have S-isotopic fractionations distinct from that of H$_2$S-HC this would be expected to be recorded in the $\delta^{34}$S values of the OSCs. At this stage we cannot examine the role of S$_3$ in TSR and its possible S-isotopic signature, because we cannot produce or purchase S$_3$ reagent. We therefore examined two model compounds (elemental S and sulfite) of different oxidation states (0 and +4) to be representative of intermediate and reduced S species. The experiments with elemental S and C$_{16}$ yielded relatively small fractionation of the newly formed OSCs, while the experiments with sulfite have very distinct fractionations (up to 9.0‰) at the early stages of the reaction (Fig. 6b).

Sulfite is likely to react with organic molecules at the earliest stages of TSR, because this species forms immediately after the cleavage of the first S-O bond in sulfate, which is required for the TSR reaction (Ma et al., 2008). This first S-O bond cleavage of sulfate was suggested as the rate-limiting step in TSR leading to the formation of
34S-depleted sulfite (SO3^2−) via a KIE (Harrison and Thode, 1957; Kiyosu, 1980).

Sulfite is highly reactive with organic compounds, and can be quickly reduced to the S2− oxidation state (Fig. 7), as is evident in the present experiments with n-C16 and Na2SO3 and in a previous study in which SO3^2− was completely consumed in ~20 h and yielded H2S (Amrani et al., 2008). Therefore, only the initial reaction time (10 h) may uniquely represent the S-isotope fractionation associated with the formation of OSCs from the reaction of sulfite and organic compounds at our experimental conditions (first stage, Fig. 7). The fractionation in the Na2SO3 experiments is initially as large as 9.0‰ (Fig. 6b). The details of the mechanism of SO3^2− reaction with hydrocarbons at elevated temperatures is not well understood, but it likely involves reactions with SO2, which has the same oxidation state as SO3^2− and may attain equilibrium with it under our experimental conditions (Fig. 7).

As the reaction progresses, the δ34S of the OSCs quickly become 34S-enriched and we hypothesize that the dominant reaction in the system shifts from SO3^2− + n-C16 to H2S + n-C16, with a much smaller fractionation in the range of 1–3‰ (Fig. 6a). When SO2 and H2S are present they can form elemental sulfur (Drozdova and Steudel, 1995 and references therein) which at elevated temperatures (similar to our system) will form highly reactive polysulfides that can readily react with organic matter to form OSC (Goldstein and Aizenshtat, 1994). As seen from the elemental sulfur experiments the OSCs formed by this reaction are only 1–3‰ 34S-depleted relative to their source elemental S (Fig. 6b). The reduction of SO3^2− to H2S has minimal apparent fractionation associated with it, as is evident in our experiments starting with Na2SO3 (Fig. 6b). This is thought to result from rapid equilibration among all intermediate (or reduced) S species present, and the fact that most of the sulfite is reduced within the first few hours of the experiments. The 34S-enriched OSCs generated at later reaction stages (>20 h) mix with the early 34S-depleted OSCs, causing δ34S values of the bulk OSCs to gradually converge to the composition of the initial sulfite (Fig. 6b). We therefore conclude that the formation of OSCs via SO3^2− reduction by hydrocarbons is accompanied by a significant S-isotope fractionation in the range of ~10‰. We propose that this relatively large fractionation explains the large 34S depletions recorded by OSCs and H2S during the initial stages of our TSR experiments (Figs. 1, 3, 4 and 7).

4.3. S-isotope fractionations throughout the TSR process

Based on differences in reaction rates and availability of reactants, a multi-stage model of the overall TSR process has been proposed that involves distinct reaction mechanisms at different stages of TSR (Zhang et al., 2008, 2012; Xia et al., 2014). If reaction mechanisms vary over the duration of TSR, it is reasonable to expect that these could be reflected in distinct S-isotopic fractionations throughout the TSR process, as presented in Fig. 7. The δ34S composition of the initial and generated S-containing species in the present experimental work can be used to evaluate this proposition (Fig. 9). The results from the experiments containing Na2SO4 are best suited for this task because there is no limitation on the availability of sulfate (as in the limited-CaSO4 experiments) nor complication from sulfate dissolution, which can obscure the reaction-specific fractionations (Fig. 3c). In the first non-catalytic stage of TSR (0–20 h), the formation of OSCs associated with HSO4^− reduction is accompanied by significant isotopic fractionation that...
reaches values as great as 22.2‰ as recorded in BT (Fig. 4c). The maximum fractionation observed for H₂S generated during this initial stage of TSR is 12.4‰. This value is close to that reported by Kiyosu (1980) (8–10‰) for the kinetic isotopic fractionation for sulfate reduced to sulfide.

At 20 h reaction time, the difference between the d³⁴S₀ of BT and H₂S has dropped to 4.7‰ (Fig. 4c). This difference between H₂S and the coexisting BT is larger than expected for fractionation related to the formation of OSCs from H₂S or elemental S. Therefore, it can be inferred that other S species are more important in the formation of OSCs during the initial non-catalytic phase of TSR. The fractionation of 4.7‰ observed in the early stages of the Na₂SO₄ experiments is identical within analytical uncertainties (to that recorded in the SO₃²⁻/Co experiments (4.3‰, Fig. 6b), suggesting that SO₃²⁻ rather than H₂S is the S source for OSC formation at reactions times of 20 h. This finding is consistent with the work of Kiyosu and Krouse (1990) who observed a 4–5‰ fractionation for SO₃²⁻/Co (or SO₂) produced from the reduction of sulfate. This is because the concentration of H₂S is much higher than that of the less stable and short-lived SO₃²⁻. Similarly, as TSR progresses, SO₃²⁻ (or SO₂) has increasing probability of reacting with H₂S rather than (or at least, in addition to) organic compounds, producing elemental S according to the following reaction (Eq. (10) and Fig. 7):

\[
\text{SO}_2 + 2\text{H}_2\text{S} \rightarrow 3\text{S} + 2\text{H}_2\text{O} \tag{10}
\]

This process yields elemental S that can then react with hydrocarbons to form OSCs with a small fractionation of 1–3‰ (Fig. 6b). Furthermore, cracking of thermally labile OSCs releases H₂S that can further react with hydrocarbons or SO₂ leading to homogenization of the S-isotope pool among all organic and inorganic S species. Fig. 9 summarizes the isotopic fractionations during the different TSR stages as we propose.

4.4. Geochemical implications

The S-isotopic results presented herein are consistent with a multi-stage reaction mechanism for the overall TSR process as previously proposed (Zhang et al., 2008, 2012; Xia et al., 2014). The initial non-catalytic stage of TSR involves the reduction of sulfate to sulfite at a slow
rate. The OSCs formed during the earliest portion of this stage have distinctive, low $\delta^{34}S$ values due to their formation by reduction of sulfite. The progression of the initial phase of TSR is reflected in the gradual $^{34}S$-enrichment in the OSCs as new molecules are generated from reactions of hydrocarbons with sulfur in lower oxidation states (e.g., S$^0$, H$_2$S). It has been suggested that the breaking of S-O bonds in aqueous sulfate ions during the first step of sulfate reduction is the rate-limiting step in the overall TSR process (Harrison and Thode, 1957; Kiyosu, 1980; Ma et al., 2008). However, the results of the present study show that other factors such as the availability of reactants (e.g., sulfate dissolution) can be rate-limiting during TSR. More accurately, the initial reduction of sulfate to sulfite controls the onset of the overall TSR process. The rate of sulfate reduction significantly increases during the second, autocatalytic phase of TSR as shown in previous studies (Amrani et al., 2008; Zhang et al., 2008, 2012) and confirmed by the present experimental results. This stage of TSR is clearly identified by the rapid convergence of the $\delta^{34}S$ values of the generated H$_2$S and OSCs toward that of the supplied sulfate. TSR experiments involving sparingly soluble CaSO$_4$ confirm field observations (Orr, 1974; Machel, 2001) that the rate of sulfate reduction can be sufficiently rapid such that sulfate dissolution becomes the rate-limiting step in the overall TSR process. In these instances, no S-isotopic fractionation is observed between generated sulfide and source sulfate.

The $\delta^{34}S$ values obtained in the present study provide supporting evidence for the interpretation of the sulfur isotopic composition of individual OSCs in natural crude oils. Recent studies of oils from the Smackover Formation that had been exposed to TSR found S-isotopic differences as great as 30‰ between BT and DBT within individual oil samples (Amrani et al., 2012; Gvirtzman et al., 2015). Amrani et al. (2012) suggested that the $\delta^{34}S$ values of BTs and DBTs in TSR-affected oils are controlled by the S-isotopic composition of the reduced S source, and differences in the relative thermal stabilities of the compounds. Extreme differences between the $\delta^{34}S$ values of BTs and DBTs are explained by the fact that BTs are more refractorypenultimate stage of TSR are 12.4‰, respectively. The interpretation is predicated on the assumptions that (1) fractionation associated with the formation of OSCs (e.g., BTs and DBTs) from the reaction of reduced S species such as H$_2$S with organic compounds is minor (Amrani, 2014), and (2) fractionations during the formation of individual OSCs (e.g., BT and DBT) are similar at the same temperature.

The present study provides experimental evidence that supports these interpretations, and provides additional insights into the details of the reaction mechanisms. Specifically, the fractionation between reduced S sources (e.g., elemental S) and generated OSCs is relatively small (<4‰); however, OSCs generated in association with the reduction of more oxidized sulfur species (i.e., SO$_4^{2-}$ and SO$_3^{2-}$) have significantly larger S-isotopic fractionations. Consequently, the $\delta^{34}S$ of individual OSCs can be traced to the S source (e.g., SO$_4^{2-}$ versus H$_2$S) providing a sensitive tool for assessing the extent of TSR that an oil has experienced, particularly during the first and early part of the second stage of TSR. Moreover, the residence time of these molecules in the system—and thus the rate at which the $\delta^{34}S$ values of OSC adjust towards those of new sources (e.g., SO$_4^{2-}$) is dependent on the thermal stability of the molecules. For example, in Smackover oils exposed to variable amounts of TSR, the $\delta^{34}S$ values of BTs increase much more quickly than those of DBTs (Amrani et al., 2012).

The sulfur isotopic compositions of individual organosulfur compounds in natural crude oils has the potential to provide critical information that cannot be determined from $\delta^{34}S$ of bulk phases alone (e.g., whole oil, sulfate minerals, and H$_2$S). However, the accurate interpretation of molecular-level results in complex mixtures, such as natural crude oils, requires controlled experimental studies to identify the factors responsible for producing these isotopic signatures. The present study provides some insights into the primary controls on the $\delta^{34}S$ values of OSCs in petroleum exposed to TSR. These values can offer diagnostic information on the extent of TSR that has occurred in a reservoir, as well as help to refine and constrain predictive models of TSR occurrence. It should be noted though, that extrapolation of high-temperature, short-term experimental results to low-temperature, long-term reactions that occur in natural environments must be made cautiously. Further work is needed to fully understand the effects of TSR on the S-isotopic composition of individual OSCs in petroleum.

5. CONCLUSIONS

The main conclusions from this study are:

1. The observed S-isotopic fractionations between sulfate and BT, DBT, and H$_2$S in experimental simulations of TSR correlate well with the two-stage model (Zhang et al., 2008) of the overall TSR process. This fractionation decreases as the H$_2$S concentration increases and the reaction enters the second, catalyzed stage, indicating that different reaction mechanisms are involved in these two distinct stages of TSR.

2. Under the experimental conditions studied, the maximum fractionations observed for H$_2$S and OSC generated during the initial stage of TSR are 12.4‰ and 22.2‰, respectively.

3. OSCs produced from the reaction of n-C$_{16}$ with elemental S have S-isotopic fractionations in the range of 0.5 to 4‰, and show little variation over all reaction times. Similar experiments with sulfite (Na$_2$SO$_3$) instead of elemental S show initial fractionations as large as 9.0‰ that rapidly disappear with progressive reaction time. In both cases (SO$_4^{2-}$ and S$^2-$), the coexisting H$_2$S has $\delta^{34}S$ values similar to the initial S source.

4. There is S-isotopic evidence for the involvement of SO$_4^{2-}$ as an intermediary in the early uncatalyzed stage of TSR.

5. The $\delta^{34}S$ compositions of the OSCs 2-PT, BT and DBT exhibit different responses as TSR progresses in the experimental systems studied. The observed fractionation...
between the individual OSCs and the coexisting H$_2$S correlates with the respective thermal stabilities of the OSCs. DBT is the most thermally stable and the slowest to adopt the $\delta^{34}$S value of the coexisting H$_2$S throughout the TSR process, whereas 2-PT is the least stable and fastest to incorporate the $\delta^{34}$S value of H$_2$S.

6. The aqueous solubility of CaSO$_4$ can be a limiting factor that controls the S-isotopic fractionation between sulfate and sulfide during TSR. This supports the notion that CaSO$_4$ dissolution can lead to the apparent lack of fractionation between sulfate and sulfide produced by TSR in nature.

7. $\delta^{34}$S values of the products of the early stages of the TSR experiments involving Na$_2$SO$_4$ are governed by the KIE, whereas EIE is observed at later stages once all of the readily oxidizable hydrocarbons have been consumed.

8. The S-isotopic composition of individual OSCs record information related to geochemical reactions that cannot be discerned from the $\delta^{34}$S values obtained from bulk phases such as H$_2$S, oil, and sulfate minerals, which can provide important mechanistic details about the overall TSR process.

ACKNOWLEDGMENTS

Alexander Meshoulam thanks the Ministry of National Infrastructures Energy and Water Resources of Israel for MSc grant. Alon Amrani thanks the Israeli Science Foundation (ISF) Grant Number 1269/12 for partial support of this study. Liu Jinzhong acknowledges the support by the Chinese National Scientific Foundation number 41173069 and 41321001. We are also thank Gilad Antler (Cambridge University, UK) for bulk S analysis of some of the starting materials for interlaboratory comparison. We also grateful to Li Gao (PEERI), Bob Dias (U. S. Geological Survey) and three anonymous referees for helpful comments on an earlier version of this manuscript. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES


*Associate editor: Josef P. Werne*