Sulfur cycling and sulfur stable isotopes in subsurface sediments from R/V JOIDES Resolution IODP-385 drilling expedition in the Guaymas Basin between September and November, 2019

Website: https://www.bco-dmo.org/dataset/994391
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Project
» Pathways and regulation of transformation of low molecular weight carbon compounds in subseafloor sediments from the Guaymas Basin (Gulf of California) (Guaymas Basin Sediments)

Contributors	Affiliation	Role
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Abstract
Microbial sulfur cycling plays a significant role in organic matter degradation in marine sediments, while sulfur biogeochemistry and its coupling with carbon and iron cycling remain poorly constrained in hydrothermal sediment. Here, we investigated carbon-sulfur-iron diagenesis in deep subsurface sediments of the Guaymas Basin, Gulf of California. Sediments down to 370 meters below the seafloor had a low average carbon-to-sulfur ratio (C/S ≈ 1.6), particularly at sites impacted by active hydrothermal circulation (1.3–0.67). These values are well below the typical value of 2.8 for marine sediment and could reflect carbon release and relative sulfur enrichment driven by high geothermal gradients and sill intrusion. Elemental sulfur content correlates positively with reactive iron, indicating iron oxides facilitate elemental sulfur accumulation. High sulfur isotope fractionations of 60–65‰ contribute to 34S-depleted pyrite (~ −40‰) in the organic-rich sediments. These results provide insight into the control of temperature and iron redox chemistry on sulfur dynamics in hydrothermal systems.

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Coverage

Location: Guaymas Basin, Gulf of California
Spatial Extent: **N**:27.633 **E**:-111.25 **S**:27.167 **W**:-111.916
Temporal Extent: 2019-09-15 - 2019-11-15

Methods & Sampling

Subsurface sediment samples were collected from four drilling sites in the Guaymas Basin, Gulf of California, during IODP Expedition 385 “Guaymas Basin Tectonics and Biosphere” using the research vessel R/V JOIDES Resolution between September and November of 2019. Rates of methanogenesis were determined at four sites. Sites 1545 (27º38.230’N, 111º53.329’W) and 1546 (27º37.884’N, 111º52.781’W) were located roughly 52 km and 51 km, respectively, northwest of the axial graben of the northern spreading segment. Both sites

are highly sedimented and a 75-meter thick inactive (~thermally equilibrated) basaltic/doleritic/gabbroic sill was present at site 1546 between ~355 to 431 meters below the seafloor (mbsf). Site U1545B is considered a reference site since it was free of sill intrusions and unaffected by active hydrothermal circulation. The geothermal gradient in hole U1545B was 227ºC/km. The geothermal gradient in hole U1546C, 221ºC/km, was similar to that measured in hole U1545B. Sites U1547 and U1548 were located inside the periphery of an active, sill-associated hydrothermal mound located about 27 km northwest of the axial graben of the northern spreading segment. Temperatures in hole U1547B (27º30.413'N, 111º40.734'W, water depth 1585.6m) exceeded 50°C in the upper 50 mbsf. The geothermal gradient in the U1547B hole was between 529ºC. The geothermal gradient in the U1548C hole was between 958ºC. Site U1549 was located near a cold seep sustained by a deeply buried, thermally equilibrated sill intrusion at several hundred meters depth. The geothermal gradient at hole U1549B was 194ºC/km. Site U1550 (27°15.170′N, 111°30.445′W, water depth 2001.2) was located near a cold seep sustained by a deeply buried, thermally equilibrated sill intrusion at several hundred meters depth. The geothermal gradient at hole U1550B was 135ºC/km. These sites are described in more detail in Teske et al. (2021).

To preserve sediment for solid-phase sulfur analysis and incubation experiments, sectioned core samples were placed in N_2-filled gas-tight bags, and subsequently transferred to anoxic glass bottles and stored at 4°C until further subsampling. Porewater concentrations of sulfate, methane and sulfide, and solid phase parameters, including total organic carbon and total sulfur, were analyzed onboard using established IODP protocols (Teske, 2021). These data were obtained from the IODP database at https://web.iodp.tamu.edu/OVERVIEW/ (Teske, 2021). Briefly, methane concentrations were determined using a gas chromatograph (Agilent 7890A), sulfate concentrations were analyzed by ion chromatography (Metrohm 850 Professional IC), and sulfide samples were fixed with zinc acetate solution and measured spectrophotometrically (Cline, 1969). For total carbon (TC) and total sulfur (TS) contents, samples were freeze-dried and powdered, and ~15 mg was accurately weighed. Analysis was conducted using an elemental analyzer (Thermo Finnigan FlashEA 1112 CHNS). Inorganic carbon (IC) content was measured using a Coulometrics 5012 CO_2 coulometer. Freeze-dried and powdered sediments was reacted with 6.5 mL of 2 mol L^{-1} HCl in a glass vial to liberate CO_2. Total organic carbon (TOC) content was quantified by the subtraction of IC from TC content. The statistical ANOVA of TOC to TS (C/S) ratios at the six sites was performed using Origin 2025 software (OriginLab Corporation). Significance was determined at a threshold of $p < 0.05$.

For solid-phase sulfur species extraction, ~1.5 g subsamples were transferred to centrifuge tubes containing 5% zinc acetate solution. After centrifugation to remove the supernatant, elemental sulfur (ES) was first extracted via sustained agitation for 15 hours with 30 mL 100% methanol (Zopfi et al. 2004). Dissolved ES was quantified via reversed-phase liquid chromatography (Agilent, 1260 Infinity III) with a C-18 column (Agilent ZORBAX Eclipse XDB-C18), using 100% methanol as the eluent. The pump speed was set to 1 mL min^{-1}, and absorbance at 265 nm was measured via UV detection. The detection limit for this method is <1 µmol L^{-1}, and the analytical precision (relative standard deviation, RSD) was better than 0.7%.

The separated solid residue was subsequently treated with a cold chromium distillation procedure (Kallmeyer et al. 2004, Røy et al. 2014), where acid volatile sulfur (AVS) was released with 6 mol L^{-1} HCl, and chromium reducible sulfur (CRS, mainly pyrite) was sequentially extracted with an acidified chromium chloride solution ($CrCl_2$). The sulfide liberated from these solid-phase sulfur species was trapped by 5% (w/v) zinc acetate to form ZnS precipitate and then the concentration of each species was determined spectrophotometrically (Cline, 1969).

Reactive iron was extracted using a citrate-dithionite buffer (Raiswell et al. 1994). 0.2 g sediment subsample was extracted with 50 mL 50 g L^{-1} sodium dithionite in pH 4.8 buffer at room temperature for 2 hours. The concentration of iron released was determined spectrophotometrically using the ferrozine method (Stookey 1970). The degree of pyritization (DOP) was used to determine the effects of iron limitation on pyrite formation and the calculation formula was as follows (Berner 1970):

DOP = Pyrite Fe / (Pyrite Fe + Reactive Fe)

For porewater sulfate sulfur isotope analysis, a thawed pore fluid volume (give volume) was fixed with saturated barium chloride solution to precipitate sulfate as barium sulfate. The $BaSO_4$ was then rinsed with 6 mol L^{-1} HCl and Milli-Q water. After determination, the precipitated zinc sulfide from CRS was subsequently converted to Ag_2S by addition of silver nitrate and ammonium hydroxide to the recovery vessel. Cleaned and dried $BaSO_4$ and Ag_2S was mixed with excess V_2O_5 and the stable sulfur isotopic ratio was measured on an isotope ratio monitoring mass spectrometer (IRMS; Thermo Delta V Plus) coupled to a Flash elemental analyzer. Standard deviations were better than 0.3‰ (n ≥3), estimated using one International Atomic Energy Agency

(IAEA-3) standard (–32.30‰) and two national (China) first level sulfur isotope standards (–0.07‰ and 22.15‰), respectively. The stable sulfur isotope values, $\delta^{34}S$, were calculated using the following formula:

$$\delta^{34}S = [\{(^{34}S/^{32}S)_{sample}/(^{34}S/^{32}S)_{standard}\} - 1] \times 1000$$

The units of $\delta^{34}S$ are per mil (‰) and are reported relative to the Vienna Canyon Diablo Troilite (VCDT) standard.

For the determination of potential rates of sulfate reduction (SR) and anaerobic oxidation of methane (AOM), 10 g sediment subsamples were weighed in a N_2-filled glove box and transferred into 120 mL glass vials. Next, 40 mL artificial seawater medium was added and the vials were closed with blue butyl rubber stoppers and crimped. The seawater media for sediment slurry incubations were prepared as follows: 200 mg KH_2PO_4, 250 mg NH_4Cl, 25 g NaCl, 0.5 g $MgCl_2 \times 6H_2O$, 0.5 g KCl and 150 mg $CaCl_2 \times 2H_2O$, dissolved with 1 L Mill-Q water in a glass bottle (Heuer 2017). Sediment samples collected from above the sulfate-methane transition zone (SMTZ) were supplemented with 5 mmol $L^{-}1$ sulfate in the artificial seawater medium, whereas samples from below the SMTZ were maintained without the addition of Na_2SO_4. After autoclaving, 5 mL sterile-filtered 154 mM Na_2S and 1 M $NaHCO_3$ was added to the media to assure anoxia and to modulate the pH, respectively.

After pre-incubation, ~3 mL sediment slurry was introduced into a modified cut-end Hungate tube sealed with a gray chlorobutyl stopper and a screw cap. 100 µL of radiolabeled ^{35}S-Na_2SO_4 solution (~167 kBq) and ^{14}C-CH_4 solution (~17 kBq) was injected into the quadruplicate sediment samples (one killed control and three live samples) for SR and AOM rate measurements, respectively. Samples were incubated concurrently under in situ temperature for 20 days. After incubation, microbial activities of SR and AOM were terminated by injecting 3 mL 20% (w/v) zinc acetate and 3 mL 2 mol L^{-1} NaOH, respectively.

Zinc acetate-fixed slurry samples were transferred to falcon tubes and then centrifuged. The supernatant was obtained to count unreacted ^{35}S-SO_4^{2-} radioactivity, and the pool of total reduced sulfur species in the remaining sediment was recovered by the cold chromium distillation (Røy et al. 2014). The extracted sulfide was trapped with 5% (w/v) zinc acetate solution to measure ^{35}S-H_2S radioactivity. The sulfate reduction rates were calculated from the following formula:

$$SRR = \{(^{35}S\text{-}H_2S) / [(^{35}S\text{-}H_2S) + (^{35}S\text{-}SO_4^{2-})]\} \times [SO_4^{2-}] \times 1.06 / t \times 1{,}000{,}000$$

where SRR is the sulfate reduction rate presented in pmol cm^{-3} day^{-1}; (^{35}S-H_2S) is the measured ^{35}S-H_2S radioactivity (decays per minute, dpm); (^{35}S-SO_4^{2-}) is the radioactivity of unreacted ^{35}S-SO_4^{2-} (dpm); [SO_4^{2-}] is the total sulfate concentration of slurry (i.e. sediment porewater sulfate plus added sulfate times the porosity); 1.06 is the correction factor for the expected isotopic fractionation; t is incubation time in days; 1,000,000 is the unit conversion factor. The units of sulfate reduction are pmol cm^{-3} d^{-1}.

For AOM rate measurements, ^{14}C-CO_2 production from ^{14}C-CH_4 was quantified with the acid digestion method (Joye et al. 2004, Zhuang et al. 2019). Briefly, homogenized sediment slurries were transferred to a 250 mL glass bottle and purged with air to remove unreacted ^{14}C-CH_4. Then 5 mL of 30% (v/v) sulfuric acid was added to the bottle and then liberated ^{14}C-CO_2 was trapped with 3-methoxypropylamine. AOM rates were calculated using the following equation:

$$AOM = \{(^{14}C\text{-}CO_2) / [(^{14}C\text{-}CO_2) + (^{14}C\text{-}CH_4)]\} \times [CH_4] \times 1.06 / t \times 1{,}000$$

where AOM is the anaerobic oxidation of methane calculated in pmol cm^{-3} day^{-1}; (^{14}C-CO_2) is the ^{14}C-CO_2 counts (dpm); (^{14}C-CH_4) is the total injected ^{14}C-CH_4 (dpm); [CH_4] is the methane concentration of sediment slurry (µmol $L^{-}1$); 1.01 is the carbon isotopic fractionation correction factor; t is incubation duration in days; 1,000 is the unit conversion factor. The units of anaerobic oxidation of methane are pmol cm^{-3} d^{-1}.

The reported microbial activity rates reflected the potential metabolic capacity of the *in situ* microbial community within the sediment, constrained by ambient geochemical conditions and substrate availability.

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Related Publications

Berner, R. A. (1970). Sedimentary pyrite formation. American Journal of Science, 268(1), 1–23. https://doi.org/10.2475/ajs.268.1.1
Methods

Cline, J. D. (1969). Spectrophotometric Determination of Hydrogen Sulfide in Natural Waters. Limnology and Oceanography, 14(3), 454–458. doi:10.4319/lo.1969.14.3.0454
Methods

Grasshoff, K., Kremling, K., & Ehrhardt, M. (Eds.). (1999). Methods of Seawater Analysis. doi:10.1002/9783527613984
Methods

Joye, S. B., Boetius, A., Orcutt, B. N., Montoya, J. P., Schulz, H. N., Erickson, M. J., & Lugo, S. K. (2004). The anaerobic oxidation of methane and sulfate reduction in sediments from Gulf of Mexico cold seeps. Chemical Geology, 205(3-4), 219–238. doi:10.1016/j.chemgeo.2003.12.019
Methods

Kallmeyer, J., Ferdelman, T. G., Weber, A., Fossing, H., & Jørgensen, B. B. (2004). A cold chromium distillation procedure for radiolabeled sulfide applied to sulfate reduction measurements. Limnology and Oceanography: Methods, 2(6), 171–180. doi:10.4319/lom.2004.2.171
Methods

Raiswell, R., Canfield, D. E., & Berner, R. A. (1994). A comparison of iron extraction methods for the determination of degree of pyritisation and the recognition of iron-limited pyrite formation. Chemical Geology, 111(1–4), 101–110. https://doi.org/10.1016/0009-2541(94)90084-1
Methods

Røy, H., Weber, H. S., Tarpgaard, I. H., Ferdelman, T. G., & Jørgensen, B. B. (2014). Determination of dissimilatory sulfate reduction rates in marine sediment via radioactive 35S tracer. Limnology and Oceanography: Methods, 12(4), 196–211. Portico. https://doi.org/10.4319/lom.2014.12.196
Methods

Teske, A., Lizarralde, D., Höfig, T. W., Aiello, I. W., Ash, J. L., Bojanova, D. P., Buatier, M. D., Edgcomb, V. P., Galerne, C. Y., Gontharet, S., Heuer, V. B., Jiang, S., Kars, M. A. C., Khogenkumar Singh, S., Kim, J., Koornneef, L. M. T., Marsaglia, K. M., Meyer, N. R., Morono, Y., … Zhuang, G. (2021). Expedition 385 methods. Guaymas Basin Tectonics and Biosphere. Internet Archive. https://doi.org/10.14379/iodp.proc.385.102.2021
Methods

Zhuang, G., Xu, L., Liang, Q., Fan, X., Xia, Z., Joye, S. B., & Wang, F. (2019). Biogeochemistry, microbial activity, and diversity in surface and subsurface deep-sea sediments of South China Sea. Limnology and Oceanography, 64(5), 2252–2270. Portico. https://doi.org/10.1002/lno.11182
Results

Zopfi, J., Ferdelman, T. G., & Fossing, H. (2004). Distribution and fate of sulfur intermediates—sulfite, tetrathionate, thiosulfate, and elemental sulfur—in marine sediments. Sulfur Biogeochemistry - Past and Present. https://doi.org/10.1130/0-8137-2379-5.97
Methods

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Parameters

Parameters for this dataset have not yet been identified

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Instruments

Dataset-specific Instrument Name	Centrifuge tubes
Generic Instrument Name	Centrifuge
Dataset-specific Description	For solid-phase sulfur species extraction, ~1.5 g subsamples were transferred to centrifuge tubes containing 5% zinc acetate solution.
Generic Instrument Description	A machine with a rapidly rotating container that applies centrifugal force to its contents, typically to separate fluids of different densities (e.g., cream from milk) or liquids from solids.

Dataset-specific Instrument Name	Coulometrics 5012 CO2 coulometer
Generic Instrument Name	CO2 Coulometer
Dataset-specific Description	Inorganic carbon (IC) content was measured using a Coulometrics 5012 CO2 coulometer.
Generic Instrument Description	A CO2 coulometer semi-automatically controls the sample handling and extraction of CO2 from seawater samples. Samples are acidified and the CO2 gas is bubbled into a titration cell where CO2 is converted to hydroxyethylcarbonic acid which is then automatically titrated with a coulometrically-generated base to a colorimetric endpoint.

Dataset-specific Instrument Name	Gas chromatograph (Agilent 7890A)
Generic Instrument Name	Gas Chromatograph
Dataset-specific Description	Briefly, methane concentrations were determined using a gas chromatograph (Agilent 7890A), sulfate concentrations were analyzed by ion chromatography (Metrohm 850 Professional IC), and sulfide samples were fixed with zinc acetate solution and measured spectrophotometrically.
Generic Instrument Description	Instrument separating gases, volatile substances, or substances dissolved in a volatile solvent by transporting an inert gas through a column packed with a sorbent to a detector for assay. (from SeaDataNet, BODC)

Dataset-specific Instrument Name	Liquid Chromatograph
Generic Instrument Name	High-Performance Liquid Chromatograph
Dataset-specific Description	Dissolved ES was quantified via reversed-phase liquid chromatography (Agilent, 1260 Infinity III) with a C-18 column (Agilent ZORBAX Eclipse XDB-C18), using 100% methanol as the eluent.
Generic Instrument Description	A High-performance liquid chromatograph (HPLC) is a type of liquid chromatography used to separate compounds that are dissolved in solution. HPLC instruments consist of a reservoir of the mobile phase, a pump, an injector, a separation column, and a detector. Compounds are separated by high pressure pumping of the sample mixture onto a column packed with microspheres coated with the stationary phase. The different components in the mixture pass through the column at different rates due to differences in their partitioning behavior between the mobile liquid phase and the stationary phase.

Dataset-specific Instrument Name	Ion Chromatograph (Metrohm 850 Professional IC)
Generic Instrument Name	Ion Chromatograph
Dataset-specific Description	Briefly, methane concentrations were determined using a gas chromatograph (Agilent 7890A), sulfate concentrations were analyzed by ion chromatography (Metrohm 850 Professional IC), and sulfide samples were fixed with zinc acetate solution and measured spectrophotometrically.
Generic Instrument Description	Ion chromatography is a form of liquid chromatography that measures concentrations of ionic species by separating them based on their interaction with a resin. Ionic species separate differently depending on species type and size. Ion chromatographs are able to measure concentrations of major anions, such as fluoride, chloride, nitrate, nitrite, and sulfate, as well as major cations such as lithium, sodium, ammonium, potassium, calcium, and magnesium in the parts-per-billion (ppb) range. (from http://serc.carleton.edu/microbelife/research_methods/biogeochemical/ic....)

Dataset-specific Instrument Name	Spectrometer
Generic Instrument Name	Spectrometer
Dataset-specific Description	Briefly, methane concentrations were determined using a gas chromatograph (Agilent 7890A), sulfate concentrations were analyzed by ion chromatography (Metrohm 850 Professional IC), and sulfide samples were fixed with zinc acetate solution and measured spectrophotometrically.
Generic Instrument Description	A spectrometer is an optical instrument used to measure properties of light over a specific portion of the electromagnetic spectrum.

Dataset-specific Instrument Name	Mass spectrometer (IRMS; Thermo Delta V Plus)
Generic Instrument Name	Thermo Fisher Scientific DELTA V Plus isotope ratio mass spectrometer
Dataset-specific Description	Cleaned and dried BaSO4 and Ag2S was mixed with excess V2O5 and the stable sulfur isotopic ratio was measured on an isotope ratio monitoring mass spectrometer (IRMS; Thermo Delta V Plus) coupled to a Flash elemental analyzer.
Generic Instrument Description	The Thermo Scientific DELTA V Plus is an isotope ratio mass spectrometer designed to measure isotopic, elemental and molecular ratios of organic and inorganic compounds. The DELTA V Plus is an enhanced model of the DELTA V series of isotope ratio mass spectrometers, which can be upgraded from the DELTA V Advantage. The DELTA V Plus can be operated in Continuous Flow or Dual Inlet mode and can accommodate up to 10 collectors, ensuring flexibility to cover many applications. The DELTA V Plus is controlled by an automated, integrated Isodat software suite. A magnet, whose pole faces determine the free flight space for the ions, eliminates the traditional flight tube. The magnet is designed for fast mass switching which is further supported by a fast jump control between consecutive measurements of multiple gases within one run. The sample gas is introduced at ground potential, eliminating the need for insulation of the flow path, ensuring 100 percent transfer into the ion source. The amplifiers register ion beams up to 50 V. The DELTA V Plus has refined optics, enabling greater ion transmission than the DELTA V Advantage. It has a sensitivity of 800 molecules per ion (M/I) in Dual Inlet mode and 1100 M/I in Continuous Flow mode. It has a system stability of < 10 ppm and an effective magnetic detection radius of 191 nm. It has a mass range of 1 - 96 Dalton at 3 kV.

Dataset-specific Instrument Name	Elemental Analyzer (Thermo Finnigan FlashEA 1112 CHNS)
Generic Instrument Name	Thermo Fisher Scientific Flash EA 1112 elemental analyzer
Dataset-specific Description	For total carbon (TC) and total sulfur (TS) contents, samples were freeze-dried and powdered, and ~15 mg was accurately weighed. Analysis was conducted using an elemental analyzer (Thermo Finnigan FlashEA 1112 CHNS).
Generic Instrument Description	The Thermo Finnigan {Thermo Fisher Scientific} Flash EA 1112 elemental analyzer is a laboratory instrument used to determine total carbon, hydrogen, nitrogen, sulphur, and oxygen in a sample. The sample is completely and instantaneously oxidised by flash combustion, which converts all organic and inorganic substances into combustion products. The resulting combustion gases pass through a reduction furnace and are swept into the chromatographic column by the helium carrier gas. The gases are separated in the column and detected by the thermal conductivity detector, which gives an output signal proportional to the concentration of the individual components of the mixture. The instrument was originally manufactured by Thermo Finnigan, which was acquired by Thermo Electron and later Thermo Scientific (part of Thermo Fisher Scientific).

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Deployments

IODP-385

Website	https://www.bco-dmo.org/deployment/869491
Platform	R/V JOIDES Resolution
Start Date	2019-09-16
End Date	2019-11-16
Description	Guaymas Basin Tectonics and Biosphere - International Ocean Discovery Program Expedition 385, General information: https://iodp.tamu.edu/scienceops/expeditions/guaymas_basin_tectonics_bio...

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Project Information

Pathways and regulation of transformation of low molecular weight carbon compounds in subseafloor sediments from the Guaymas Basin (Gulf of California) (Guaymas Basin Sediments)

Coverage: Guaymas Basin (Gulf of California)

NSF Award Abstract:
This research will explore carbon cycling in one of the largest carbon reservoirs on Earth, marine sediments, located at bottom of the ocean. This carbon is recycled gradually over time through interacting geological, chemical, and biological processes. This project will document how each of these processes transforms carbon in marine sediments from the Guaymas Basin (Gulf of California). This setting offers the chance to study carbon cycling across a broad range of chemical and temperature gradients, providing an opportunity to tease apart the factors regulating carbon cycling in marine sediments. This project will investigate the role of ocean sediments in the global carbon cycle. These research objectives represent key science priorities in a time of global environmental change. For outreach activities, the scientist, in collaboration with Jim Toomey Education, would continue the "Adventures of Zack and Molly" educational video series. In this instance, the video would document results from this study and its broader significance. The scientist also would create a learning guide for teachers. Both the video and the learning guide would be disseminated to educators. One graduate and one undergraduate student would be supported and trained as part of this project.

Subsurface sediments in the Guaymas Basin (Gulf of California) offer an accessible window for investigating carbon cycling in a dynamic, yet tractable, marine environment. This work will study how heating of subsurface sediments affects the production, consumption, and fate of low molecular weight dissolved organic carbon. The research will track the fate of key carbon species – including formate, acetate, and methanol – as they are processed through a gauntlet of microbial-mediated processes. Samples were collected during Expedition 385 of the International Ocean Discovery Program in September-October 2019. Some experiments were conducted on the research vessel and additional experiments will be conducted in the laboratory. The study will constrain the magnitudes of transformation and the fate of low molecular weight carbon substrates using a combination of direct rate, pool size, and stable isotopic measurements coupled to thermodynamic modeling and probative laboratory experiments. Key topics for investigation include: (1) What is the dominant production mode for organic compounds in subsurface sediments? (2) What are the dominant pathways of methanogenesis along geochemical and temperature gradients? (3) What are the temperature limits of microbially-driven carbon cycling processes? (4) How does the fate of organic compounds change along geochemical and/or temperature gradients?

This award reflects NSF's statutory mission and has been deemed worthy of support through evaluation using the Foundation's intellectual merit and broader impacts review criteria.

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Funding

Funding Source	Award
NSF Division of Ocean Sciences (NSF OCE)	OCE-2023575

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