Long-term incubations provide insight into the mechanisms of anaerobic oxidation of methane in methanogenic lake sediments

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Abstract

Anaerobic oxidation of methane (AOM) is among the main processes limiting the release of the greenhouse gas methane from natural environments. Geochemical profiles and experiments with fresh sediments from Lake Kinneret (Israel) indicate that iron-coupled AOM (Fe-AOM) sequesters 10-15% of the methane produced in the methanogenic zone (> 20-cm sediment depth). The oxidation of methane in this environment was shown to be mediated by a combination of *mcr* gene-bearing archaea and *pmoA* gene-bearing aerobic bacterial methanotrophs. Here, we used sediment slurry incubations under controlled conditions to elucidate the electron acceptors and microorganisms that are involved in the AOM process over long-term (~18 months). We monitored the process with the addition of ^{13}C-labeled methane and two stages of incubations: (i) enrichment of the microbial population involved in AOM and (ii) slurry dilution and manipulations, including the addition of several electron acceptors (metal oxides, nitrate, nitrite and humic substances) and inhibitors (2-bromoethanesulfonate, acetylene and sodium molybdate) of methanogenesis, methanotrophy and sulfate reduction/sulfur disproportionation. Carbon isotope measurements in the dissolved inorganic carbon pool suggest the persistence of AOM, consuming 3-8% of the methane produced at a rate of 2.0±0.4 nmol g^{-1} dry sediment day^{-1}. Lipid carbon isotopes and metagenomic analyses point towards methanogens as the sole microbes performing the AOM process by reverse methanogenesis. Humic substances and iron oxides, but not sulfate, manganese, nitrate, or nitrite, are the likely electron acceptors used for this AOM. Our observations support the contrast between methane oxidation mechanisms in naturally anoxic lake sediments, with potentially co-existing aerobes and anaerobes, and long-term incubations, wherein anaerobes prevail.

Keywords: Anaerobic oxidation of methane (AOM), lake sediments, dissolved inorganic carbon, stable carbon isotopes, electron acceptors, archaea, methanogens, methanotrophs, lipids.

1. Introduction

Methane (CH_4) is an important greenhouse gas (Wuebbles and Hayhoe, 2002), which has both anthropogenic and natural sources, the latter of which account for about 50% of the emission of this gas to the atmosphere (Saunois et al., 2020). Naturally occurring methane is mainly produced biogenically via the methanogenesis process, which is performed by methanogenic archaea. Traditionally acknowledged as the terminal process anchoring carbon remineralization (Froelich et al. 1979), methanogenesis occurs primarily via the reduction of carbon dioxide by hydrogen in marine sediments and via acetate fermentation in freshwater systems (Whiticar et al. 1986).

Methanotrophy, the aerobic and anaerobic oxidation of methane (AOM) by microbes, naturally controls the release of this gas to the atmosphere (Conrad, 2009; Reeburgh, 2007; Knittel and Boetius, 2009). In marine sediments, up to 90% of the upward methane flux is consumed anaerobically by sulfate, and in established diffusive profiles, that methane consumption occurs within a distinct sulfate-methane transition zone (Valentine 2002). While sulfate-dependent AOM, catalyzed by the archaeal ANaerobic MEthanotrophs (ANMEs) 1-3, is widespread chiefly in marine sediments (Hoehler et al., 1994; Boetius et al., 2000; Orphan et al., 2001; Treude et al., 2005, 2014), methane oxidation in other environments can be coupled to other electron acceptors (e.g. Raghoebarsing et al., 2006; Ettwig et al. 2010; Sivan et al., 2011; Crowe et al. 2011; Norði and Thamdrup 2014; Valenzuela et al., 2017).

In freshwater sediments sulfate is often depleted, and methanogenesis may be responsible for most of the organic carbon remineralization, resulting in thus high concentrations of methane in shallow sediments (Sinke et al., 1992). Indeed, lakes and wetlands, are responsible for 33-55% of naturally emitted methane (Rosentreter et al., 2021). A large portion of this produced methane is oxidized by aerobic (type I) methanotrophic bacteria via oxygen. Aerobic methanotrophy is generally observed in the sediment-water interface (Damgaard et al. 1998) and/or in the water column thermocline (Bastviken 2009). AOM, however, can also consume over 50% of the produced methane (Segarra et al. 2015).

Sulfate can be an electron acceptor of AOM in freshwater sediments, as was shown for example in Lake Cadagno (Schubert et al., 2011, Su et al., 2020). Alternative electron acceptors for AOM in natural freshwater environments and cultures include humic substances, nitrate, nitrite and metals (such as iron manganese and chromium). Natural humic substances and their synthetic analogs were shown to function as terminal electron acceptors for AOM in soils, wetlands and cultures (Valenzuela et al., 2017; 2019; Bai et al., 2019; Zhang et al., 2019; Fan et al., 2020). Nitrate-dependent AOM has been demonstrated in a consortium of archaea and denitrifying bacteria from a canal (Raghoebarsing et al., 2006), in freshwater lake sediments (Norði and Thamdrup 2014) and in a sewage enrichment culture of ANME-2d (Haroon et al., 2013; Arshad et al., 2015). Nitrite is exploited to oxidize methane by the aerobic bacteria *Methylomirabilis* (NC-10), which split the nitrite to N_2 and O_2 and then uses the

produced oxygen to oxidize the methane (Ettwig et al., 2010). ANME-2d were also suggested to be involved in Cr(VI) coupled AOM, either alone or with a bacterial partner (Lu et al., 2016). Iron and/or manganese coupled AOM have also been suggested in lakes (Sivan et al., 2011; Crowe et al. 2011; Norði et al., 2013), sometimes by supporting sulfate-coupled AOM (Shubert et al., 2011; Su et al., 2020; Mostovaya et al., 2021). Iron-coupled AOM was also shown to occur in enriched, denitrifying cultures from sewage where it was performed by ANME-2 (Ettwig et al. 2016), and in a bioreactor with natural sediments (Cai et al., 2018).

The mechanism and role of iron-coupled AOM in lake sediments have been studied with a variety of tools in the sediments of Lake Kinneret. *In-situ* pore water profiles and top core experiments (Sivan et al., 2011), diagenetic models (Adler et al., 2011) and batch incubation experiments with fresh sediment slurries (Bar-Or et al., 2017) suggest that iron coupled-AOM (Fe-AOM) removes 10-15% of the produced methane in the deep methanogenic zone (> 20 cm below the water-sediment interface). Analysis of the microbial community structure suggested that both methanogenic archaea and methanotrophic bacteria are potentially involved in methane oxidation (Bar-Or et al., 2015). Analyses of stable isotopes in fatty acids, 16S rRNA gene amplicons and metagenomics showed that both reverse methanogenesis by archaea and bacterial type I aerobic methanotrophy by Methylococcales play important role in methane cycling (Bar-Or et al., 2017; Elul et al., 2021). Aerobic methanotrophy, which has also been observed in the hypolimnion and sediments of several other lakes that are considered anoxic (Beck et al., 2013; Oswald et al., 2016; Martinez-Cruz et al., 2017; Cabrol et al., 2020), may be driven by the presence of oxygen at nanomolar levels (Weng et al., 2018). Pure cultures of the ubiquitous aerobic methanotrophs Methylococcales have indeed been shown to survive under hypoxia either by oxidizing methane and with nitrate (Kits et al., 2015), by switching to iron reduction (Zheng et al., 2020), or even by exploiting their methanobactins to generate their own oxygen to fuel their methanotrophic activity (Dershwitz et al., 2021). The latter study also showed that the alphaproteobacterial methanotroph *Methylocystis* sp., strain SB2, can couple methane oxidation and iron reduction. However, whether these aerobic methanotrophic bacteria are able to oxidize methane under strictly anoxic conditions and which electron acceptors are available to facilitate that activity are still not known.

In the current study, we used long-term anaerobic incubations to assess the dynamics of methane-oxidizing microbes under anoxic conditions and to quantify the respective availabilities of different electron acceptors for AOM. To that end, we diluted fresh methanogenic sediments from Lake Kinneret with original porewater from the same depth and amended the sediment with ^{13}C-labeled methane. Our experiment design comprised two stages, the first of which included the enrichment of the microbial population involved in AOM, while the second involved an additional slurry dilution and several manipulations with different electron acceptors and inhibitors. We measured methane oxidation rates (based on ^{13}C-DIC enrichment), determined the characteristics of each electron acceptor (via its

turnover), and evaluated changes in microbial diversity over various incubation periods (based on metagenomics and lipid biomarkers). The results from the long-term anaerobic incubations were compared to those of batch and semi-continuous bioreactor experiments.

2. Methods

2.1 Study site

Lake Kinneret (Sea of Galilee) is a warm, monomictic, freshwater lake that is 21 km long and 13 km wide and located in northern Israel. Its maximum depth is ~42 m at its center (station A, Figure S1) while its average depth is 24 m. From March to December, the lake is thermally stratified, and from April to December, the hypolimnion is anoxic. Surface water temperatures range from 15°C in the winter (January) to 32°C in the summer (August), while the lake's bottom water temperatures remain in the range of 14-17°C throughout the year. The sediment from the deep methanogenic zone used in this study (sediment samples taken from a sediment depth of ~20 cm from the water-sediment interface at the lake's center) contains 50% carbonates, 30% clay and 7% iron (Table S1). The dissolved organic carbon (DOC) concentration of the porewater increases with depth, ranging from ~6 mg C L^{-1} at the sediment-water interface to 17 mg C L^{-1} at a depth of 25 cm (Adler et al., 2011). The concentrations of dissolved methane in the sediment porewater increase sharply with sediment depth, reaching a maximum of more than 2 mM at a depth of 15 cm, after which the amounts of dissolved methane gradually decreased with depth to 0.5 mM at a depth of 30 cm (Adler et al., 2011; Sivan et al., 2011; Bar-Or et al., 2015).

2.2 Experimental setup

2.2.1 General

In this study we compared three incubation strategies (A, B and C; Fig. 1) in Lake Kinneret methanogenic sediments (sediment depths > 20 cm), which were amended with original porewater from the same depth, ^{13}C-labeled methane, different potential electron acceptors for AOM (nitrite, nitrate, iron and manganese oxides and humic substances) and activity inhibitors. We inhibited the *mcr* gene with 2-bromoethanesulfonate (BES), methanogenesis and methanotrophy with acetylene, and sulfate reduction and sulfur disproportionation with Na-Molybdate (Nollet et al., 1997; Oremland & Capone, 1988; Lovley & Klug, 1983). Below we describe the three incubation strategies (Fig. 1).

A) Long-term, two-stage slurry incubations with a 1:1 sediment to porewater ratio and high methane content for the first three months (first stage) to ensure the enrichment of the microorganisms involved in AOM. After three months, the slurry was diluted with porewater to a 1:3 ratio (second stage) and different reactants were added to the incubations, which were subsequently monitored for up to 18 months.

B) Semi-continuous bioreactor experiments in which sediments were collected up to three days before the experiment was set up (freshly sampled sediments) and sediment to porewater ratio of 1:4, where porewater was exchanged regularly.

C) Batch incubation experiments with freshly sampled sediments and porewater at a 1:5 ratio, respectively, and amended with hematite. This experimental set-up was described in our previous studies (Bar-Or et al., 2017; Elul et al., 2021).

The sediments for the slurries conducted in the current work were collected during seven sampling campaigns aboard the research vessel *Lillian* between 2017 and 2019 from the center of the lake (Station A, Fig. S1) using a gravity corer with a 50-cm Perspex core liner. The length of the sediment in each core was 35-45 cm. During each sampling campaign, 1-2 sediment cores were collected for the incubations and 10 cores were collected for the porewater extraction. Sediments from the methanogenic zone (sediment depths > 20 cm) were diluted with porewater from the methanogenic zone of parallel cores sampled on the same day. The porewater was extracted on the day of sampling. The sediment cores were sliced while onboard, and sediment samples from the methanogenic zone (> 20 cm) were transferred to a dedicated container. In the lab, sediments were collected with 20-ml cutoff syringes and moved to 50-ml falcon tubes. The porewater was extracted by centrifugation at 9300 g for 15 min at 4°C, filtered by 0.22-µM filters into 250-ml pre-autoclaved glass bottles, crimp-sealed with rubber stoppers, and flushed for 30 min with N_2. The extracted porewater was kept under anaerobic conditions at 4 until its use. The sediments for the incubations were subsamples from the liners and diluted no later than three days after their collection from the lake and treated further according to the experimental strategies described above (setup A or B).

2.2.2 Experiment type A set-up: Long-term two-stage incubations (henceforth referred to as "two-stage" for simplicity)

Experiment A comprised ten two-stage incubation experiments (experiment serial numbers (SN) 1-10; Table 1) with different treatments (electron acceptors/shuttling/inhibitors). In the first stage (pre-incubation slurry), the sediment core was sliced under a N_2 atmosphere and sediments from depths > 20 cm were collected into zipper bags. The sediment was homogenized, and between 80-100 gr transferred into 250-ml glass bottles under continuous N_2 flushing. The sediments were diluted with the extracted porewater to create a 1:1 sediment to porewater slurry with a headspace of 70-90 ml (Fig. 1). The slurries were sealed with rubber stoppers and crimped caps and were flushed with N_2 (99.999%, MAXIMA, Israel) for 30 min. Methane (99.99%, MAXIMA, Israel) was injected using a gas-tight syringe for a final content of 20% in the headspace, where 10% of the injected methane was ^{13}C-labeled methane (99%, Sigma-Aldrich). When significant AOM activity was observed based on the increase of $\delta^{13}C_{DIC}$ after approximately three months (Fig. S2), some of the incubations were further diluted during

171 the second stage of the experiments. The remainder of the incubations continued to be run with
172 porewater exchange while the $\delta^{13}C_{DIC}$ values were monitored every three months.

173 All the experiments were set up similarly (see dates and detailed protocols in the supplementary
174 information): the pre-incubation bottle was opened and subsamples (~18 g each) were transferred with
175 a syringe and a Tygon® tube under a laminar hood and continuous flushing of N_2 gas into 60-ml glass
176 bottles. The subsamples were then diluted with fresh anoxic porewater from the methanogenic zone (as
177 described above) to achieve a 1:3 sediment to porewater ratio (Fig. 1) while leaving 24 ml of headspace
178 in each bottle. The bottles were crimp-sealed, flushed with N_2 gas for 5 min, shaken vigorously and
179 flushed again (3 times). Then ^{13}C-labeled methane was added to all of the bottles as described in Table
180 1. The "killed" control slurries in each experiment were autoclaved twice and cooled, only after which
181 they were amended with the appropriate treatments and ^{13}C-labeled methane.

182 To the diluted (1:3) batch slurries electron acceptors were added either as a powder (hematite –
183 experiment no. 1, magnetite – experiment no. 2, clay and humic substances – experiment no. 7, MnO_2
184 – experiment no. 3) or in dissolved form in double-distilled water (DDW) (KNO_3 – experiment no. 4,
185 $NaNO_2$ – experiment no. 5). In addition, the potential involvement of sulfur cycling in the transfer of
186 electrons was tested in experiment no. 2 via its inhibition with Na-molybdate (Lovley and Klug, 1983).
187 The synthetic analog for humic substances, i.e., 9,10-anthraquinone-2,6-disulfonate (AQDS), was
188 dissolved in DDW (detailed in the supplementary information) and added to the bottles of experiment
189 no. 6 until a final concentration of 5 mM was achieved in each bottle. Amorphous iron ($Fe(OH)_3$) was
190 prepared in the lab by dissolving $FeCl_3$ in DDW that was then titrated with NaOH 1.5 N up to pH 7 and
191 injected to the bottles of experiment no. 2 . The final concentration of each addition is detailed in Table
192 1. The ^{13}C-labeled methane was injected into all of the experimental bottles at the beginning of each
193 experiment (unless described otherwise) by using a gas-tight syringe from a stock bottle filled with ^{13}C-
194 labeled methane gas (which was replaced with saturated NaCl solution). Three different inhibitors were
195 added to three different experiments: Molybdate was added to experiment No. 1 (to one bottle of
196 methane-only treatment, magnetite treatment and amorphous iron treatment) to detect the feasibility of
197 an active sulfur cycle; BES was added to experiment No. 8 at the start of the experiment; and acetylene
198 was added to experiment No. 9, wherein it was injected during the experiment into two bottles at
199 different timepoints after ^{13}C enrichment was observed in the DIC (Table 1).

200 All live treatments were set up in duplicate or triplicate, depending on the amount of the pre-incubated
201 slurry aimed for each experiment, and the results are presented as the average with an error bar. In two
202 experiments, only one "killed" control bottle was set up, and the remainder of the slurry was prioritized
203 for other treatments, because the killed controls repeatedly showed no activity in several previous
204 experiments. The humic substrate experiment used a natural (humic) substance that was extracted from
205 a lake near Fairbanks, Alaska, where the iron reduction was observed in the methanogenic zone. One

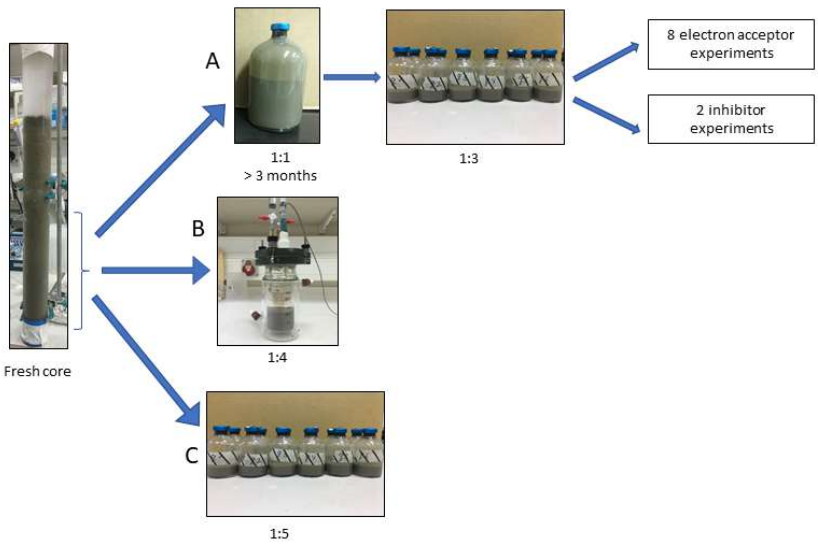
experiment was set up without any additional electron acceptor to assess the rate of methanogenesis in the two-stage slurries. Porewater was sampled anaerobically for $\delta^{13}C_{DIC}$ and dissolved Fe(II) measurements in duplicate (2 ml), and methane was measured from the headspace. Variations in the $\delta^{13}C_{DIC}$ values between the experiments resulted from different amounts of ^{13}C-labeled methane injected at the start of each experiment (geochemical measurements detailed in the analytical methods section below).

2.2.3 Experiment type B setup: Semi-continuous bioreactor

Semi-continuous bioreactors were used to monitor the redox state regularly at close-to-natural *in-situ* conditions for 15 months in freshly collected sediments. Two 0.5-L semi-continuous bioreactors (Fig. 1) (LENZ, Weinheim, Germany) were set up with freshly sampled sediments from the methanogenic zone (25 - 40 cm) and extracted porewater from the same depth from Station A on Lake Kinneret immediately after their collection. Both reactors were filled, headspace-free, with a slurry at a 1:4 sediment to porewater ratio. One bioreactor was amended with 10 mM hematite while the second, which was a control, was not amended. To dissolve ^{13}C-labeled methane in the porewater, 15 ml of porewater were replaced with 15 ml of methane gas (13 ml of $^{12}CH_4$ and 2 ml of $^{13}CH_4$) to produce a methane-only headspace for 24 h, during which time the reactors were shaken repeatedly. After 24 h, the gas was replaced with anoxic porewater, thus eliminating the headspace, which resulted in lower methane concentrations (0.2 mM) than in either the two-stage incubations or the fresh batch experiment (~2 m). The redox potential was monitored continuously using a platinum/glass electrode (Metrohm, Herisau, Switzerland) to verify anoxic conditions and to determine the redox state throughout the incubation period. The bioreactors were subsampled weekly to bi-weekly, and the sample volume (5-10 ml) was replaced immediately by preconditioned anoxic (flushed with N_2 gas for 15 min) porewater from the methanogenic zone. As outlined below, samples were analyzed for dissolved Fe(II), methane and $\delta^{13}C_{DIC}$. Additional subsamples for metagenome and lipid analyses were taken at the beginning of the experiment and on days 151 and 382, respectively.

2.2.4 Experiment type C setup: Fresh batch experiment

Sediments for this experiment were collected in August 2013 at Station A using a protocol similar to that used to collect the sediments for the pre-incubations. Sediments from depths greater than 26 cm were diluted under anaerobic conditions with porewater from the same depth to obtain a ratio of sediment to porewater of 1:5. The resulting slurry was then divided between 60-ml glass bottles (40 ml slurry in each bottle). The sampling and experimental setup are described in detail in our earlier study (Bar-Or et al., 2017). Here we present our results of the $\delta^{13}C_{DIC}$, metagenome and lipid analyses of two treatments: natural (with only ^{13}C-labeled methane) and hematite. The experiment ran for 15 months.



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240 Figure 1: Flow diagram of the experimental design. Three types of experiments were set up to investigate the
241 methanogenic zone sediments (deeper than 20 cm): **A)** Two-stage slurry experiments, with 1:1 ratio of sediment
242 to porewater incubations and then with diluted pre-incubated slurries and porewater (1:3 ratio of sediment to
243 porewater). **B)** Semi-aerobic bioreactor experiment with freshly collected sediment. **C)** Fresh batch experiment
244 – slurry experiment with freshly collected sediments (Bar-Or et al., 2017).

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Table 1: Details of the three types of experiments: two-stage, semi-aerobic bioreactor and fresh batch experiments.

Experiment serial number (SN)	Experiment	Treatment	# of bottles	CH_4 [ml]	$^{13}CH_4$ [ml]	Fe_2O_3 [mM]	Fe_3O_4 [mM]	$Fe(OH)_3$ [mM]	MnO_2 [mM]	NO_2^- [mM]	NO_3^- [mM]	AQDS [mM]	Humic substances [mM]	PCA [mM]	Fe-bearing nontronite (clay) [gr]	Na_2-molybdate [mM]	BES [mM]	Acetylene [µL]	Temp [c°]	Duration [day]	Comments
1	Hematite	$^{13}CH_4$	2		1														20	201	
		13CH4+hematite	2		1	10													20		
2	Magnetite	$^{13}CH_4$	2		1											1			16	447	The methane that was added at the beginning of the experiment was not labelled, so ^{13}C-labeled methane was added after 105 days. Na_2-molybdate was added to one of the bottles on day 365
		$^{13}CH_4$+magnetite	2		1		10									1			16		Na_2-molybdate was added to one of the bottles on day 365
		$^{13}CH_4$+$Fe(OH)_3$	2		1			10								1			16		
		Killed+ $^{13}CH_4$+m.agnetite	1		1		10												16		
3	MnO_2	$^{13}CH_4$	2		1.2														20	201	200 µL $^{13}CH_4$ was added on day 1, then another 1 mL was added on day 24.
		$^{13}CH_4$+MnO2	2		1.2				10										20		200 µL $^{13}CH_4$ was added on day 1, then another 1 mL was added on day 24.
4	Nitrate	$^{13}CH_4$+NO_3^-(high conc.)	2	1	0.5	12					1								20	306	
		$^{13}CH_4$+hematite	2	1	0.5	12													20		
		$^{13}CH_4$+NO_3^-(high conc.)+hematite	2	1	0.5	12					1								20		
		$^{13}CH_4$+NO_3^-(low conc.)+hematite	2	1	0.5	12					0.2								20		
		Killed+ $^{13}CH_4$+NO_3^-(high conc.)+hematite	1	1	0.5	12					1								20		
5	Nitrite	$^{13}CH_4$	3	1	0.5														20	493	
		$^{13}CH_4$+NO_2^-(high conc.)+hematite	2	1	0.5	10				0.5									20		
		$^{15}CH_4$+NO_2^-(low conc.)+hematite	2	1	0.5	10				0.1									20		
		Killed+ $^{13}CH_4$+NO_2^-(high conc.)+hematite	2	1	0.5	10				0.5									20		
6	AQDS	$^{15}CH_4$	3		1														20	264	
		$^{13}CH_4$+AQDS	2		1	10						5							20		
		$^{15}CH_4$+AQDS+hematite	2		1	10						5							20		
		Killed+ $^{13}CH_4$+AQDS	2		1														20		
7	Natural humic acids and clay	$^{13}CH_4$	2		1	10													20	169	The head space of the experiment bottles was flushed with N_2 on day 51 and $^{13}CH_4$ was added. This was done to match the the clay bottles.
		$^{13}CH_4$+hematite	2		1	10													20		
		$^{13}CH_4$+humic acid	2		1								0.5						20		Clay was added on day 43, and the bottles were flushed again with N_2. $^{13}CH_4$ was added again on day 51.
		$^{13}CH_4$+clay	2		1										1				20		
		Killed+ $^{13}CH_4$+hematite	2		1	10													20		
8	Bromoethanesulfonate (BES)	$^{13}CH_4$+hematite	2	9	1	10													20	493	
		$^{13}CH_4$+hematite+BES	2	9	1	10											20		20		
9	Acetylene	$^{13}CH_4$+hematite	4	1	0.5	10												120	20	321	
		$^{13}CH_4$+hematite+acetylene	2	1	0.5	10												120	20		Acetylene was injected to each bottle at different time points during the experiment.
		Killed+ $^{13}CH_4$+hematite	2	1	0.5	10													20		
10	No electron acceptor	No additions	3																20	147	
		$^{13}CH_4$	3		1														20		
	Semi-bioreactor	$^{13}CH_4$		15															16	345	
		$^{13}CH_4$+hematite		15		10													16	677	
	Freshly collected sediment exp.	$^{13}CH_4$			0.05														20	467	
		$^{13}CH_4$+hematite			0.05	20													20		

2.3 Analytical methods

2.3.1 Geochemical measurements

Measurements of $\delta^{13}C_{DIC}$ were performed on a DeltaV Advantage Thermo Scientific isotope-ratio mass-spectrometer (IRMS). Results are reported referent to the Vienna Pee Dee Belemnite (VPDB) standard. For these measurements, about 0.3 ml of filtered (0.22 µm) porewater was injected into a 12-ml glass vial with a He atmosphere and 10 µl of H_3PO_4 85% to acidify all the DIC species to CO_2 (g). The headspace autosampler (CTC Analytics; Type PC PAL) sampled the gas from the vials and measured the $\delta^{13}C_{DIC}$ of the sample on the GasBench interface with a precision of ±0.1 ‰. DIC was measured on the IRMS using the peak height and a precision of 0.05 mM. Dissolved Fe(II) concentrations were determined using the ferrozine method (Stookey, 1970) by a spectrophotometer at a 562-nm wavelength with a detection limit of 1 µmol L^{-1}. A 100-µL headspace sample was taken for methane measurements with a gas-tight syringe and was analyzed by gas chromatograph (Focus GC, Thermo) equipped with a flame ionization detector (FID) and a packed column (Shincarbon ST) with a helium carrier gas (UHP) and a detection limit of 1 nmol methane. Bottles to which acetylene was added were also measured by GC for ethylene to determine the acetylene turnover with the N cycle.

2.3.2 Lipid analysis

A sub-set of samples (Table 3) was investigated for the assimilation of ^{13}C-labeled methane into polar lipid-derived fatty acids (PLFAs) and intact ether lipid-derived hydrocarbons. A total lipid extract (TLE) was obtained from 0.4 to 1.6 g of the freeze-dried sediment or incubated sediment slurry using a modified Bligh and Dyer protocol (Sturt et al., 2004). Before extraction, 1 µg of 1,2-diheneicosanoyl-*sn*-glycero-3-phosphocholine and 2-methyloctadecanoic acid were added as internal standards. PLFAs in the TLE were converted to fatty acid methyl esters (FAMEs) using saponification with KOH/MeOH and derivatization with BF_3/MeOH (Elvert et al., 2003). Intact archaeal ether lipids in the TLE were separated from the apolar archaeal lipid compounds using preparative liquid chromatography (Meador et al., 2014) followed by ether cleavage with BBr_3 in dichloromethane forming hydrocarbons (Lin et al., 2010). Both FAMEs and ether-cleaved hydrocarbons were analyzed by GC-mass spectrometry (GC-MS; Thermo Finnigan Trace GC coupled to a Trace MS) for identification and by GC-IRMS (Thermo Scientific Trace GC coupled via a GC Isolink interface to a Delta V Plus) to determine $\delta^{13}C$ values by using the column and temperature program settings described by Aepfler et al. (2019). The $\delta^{13}C$ values are reported with an analytical precision better than 1‰ as determined by long-term measurements of an *n*-alkane standard with known isotopic composition of each compound. Reported fatty acid isotope data are corrected for the introduction of the methyl group during derivatization by mass balance calculation similar to equation 1 (see below) using the measured $\delta^{13}C$ value of each FAME and the known isotopic composition of methanol as input parameters.

2.3.3 Metagenomic analysis

For the metagenomic analyses, total genomic DNA was extracted from the semi-aerobic bioreactor with hematite addition (duplicate samples), pre-incubation slurries ($^{13}CH_4$-only control, $^{13}CH_4$ + hematite) and their respective initial slurries (t0) by using the DNeasy PowerLyzer PowerSoil Kit (QIAGEN). Genomic DNA was eluted using 50 µl of elution buffer and stored at −20 °C. Metagenomics libraries were prepared at the sequencing core facility at the University of Illinois at Chicago using the Nextera XT DNA library preparation kit (Illumina, USA). Between 19 and 40 million 2 × 150 bp paired-end reads per library were sequenced using Illumina NextSeq500. Metagenomes were co-assembled from the concatenated reads of all of the metagenomic libraries with Spades V3.12 (Bankevich et al., 2012; Nurk et al., 2013) after decontamination, quality filtering (QV= 10) and adapter-trimming with the BBDuk tool from the BBMap suite (Bushnell B, http://sourceforge.net/projects/bbmap/). Downstream analyses, including reading coverage estimates, automatic binning with maxbin (Wu et al., 2014) and metabat2 (Kang et al., 2019) bin refining with the DAS tool (Sieber et al., 2018), were performed within the SqueezeMeta framework (Tamames and Puente-Sánchez, 2019). GTDB-Tk was used to classify the metagenome-assembled genomes (MAGs) based on Genome Taxonomy Database release 95 (Parks et al., 2021). The principal component analysis biplot was constructed with Past V4.03 (Hammer et al., 2001).

2.3.4 Rate calculations

Methanogenesis rates were calculated from temporal changes in methane concentration in a representative pre-incubated slurry experiment (Fig. 2). The amount of methane oxidized was calculated by a simple mass balance calculation according to equations 1 and 2:

$$x \times F^{13}CH_4 + (1 - x) \times FDI^{13}C_i = FDI^{13}C_f \quad (1)$$

$$[CH_4]_{ox} = x \times [DIC]_f \quad (2)$$

The final DIC pool comprises two end members, the initial DIC pool and the oxidized ^{13}C-CH_4. The term *x* denotes the fraction of oxidized ^{13}C-CH_4, while 1-*x* denotes the fraction of the initial DIC pool out of the final DIC pool. $F^{13}CH_4$ is the fraction of ^{13}C out of the total CH_4 at t0 (i-initial), $FDI^{13}C_i$ is the fraction of ^{13}C out of the total DIC at t0, and $FDI^{13}C_f$ is the fraction of ^{13}C out of the total DIC at t-final. $[CH_4]_{ox}$ is the amount (concentration in pore water) of the methane oxidized throughout the full incubation period, and $[DIC]_f$ is the DIC concentration at t-final. It was assumed that the isotopic composition of the labeled CH_4 did not change significantly throughout the incubation period.

3. Results

In ten sets of slurry incubation experiments, we followed the progress of the methane oxidation process in Lake Kinneret methanogenic sediments in type A two-stage long-term incubations. This is by monitoring the changes in $\delta^{13}C_{DIC}$ values and by running metagenomic and specific isotope lipid

analyses. We also followed methane oxidation in a semi-continuous bioreactor system (type B) with freshly collected sediments with or without the addition of hematite (Fig. 3). The results were compared to those of fresh batch slurry incubations (type C) from the same methanogenic zone, presented by Bar-Or et al. (2017) and Elul et al. (2021).

3.1 Geochemical trends in the long-term two-stage experiments

In the second stage (1:3 ratio of sediment to porewater) long-term batch slurry experiments (type A) from the methanogenic zone, methanogenesis occurred with net methanogenesis rates of ~ 25 nmol g dry weight $(DW)^{-1}$ d^{-1} (Fig. 2, Table S2), which are similar to those of fresh incubation experiments (Bar-Or et al., 2017). At the same time there was a conversion of ^{13}C-methane to ^{13}C-DIC in all the non-killed slurries amended with ^{13}C-methane, indicating significant AOM (Figs. 3 and 4). The $\delta^{13}C_{DIC}$ values of the "methane-only" control slurries reached as high values as 743‰. The average AOM rate in the methane-only controls was 2.0±0.4 nmol g DW^{-1} d^{-1} (Table 2). AOM was observed in these geochemical experiments also with the addition of electron acceptors, and the potential of several electron acceptors to perform and stimulate the AOM process is detailed below.

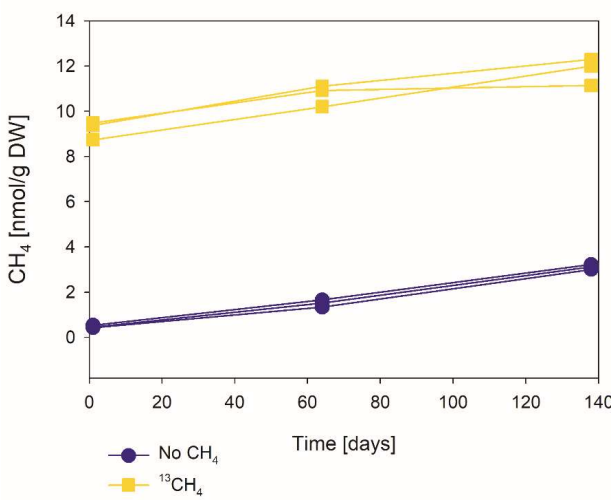


Figure 2: The change of methane concentrations with time of a representative incubated second stage long-term slurry experiment, showing apparent net methanogenesis with average rate of 25 nmol g DW^{-1} d^{-1}.

3.1.1 Metals as electron acceptors

Iron and manganese oxides were added as potential electron acceptors to the second stage long-term slurries. The addition of hematite to three different experiments increased the $\delta^{13}C_{DIC}$ values over time to 694‰, similar to the behavior of the methane-only controls, and in a different pattern than the fresh experiments (Fig. 3). The average AOM rate in those two-stage treatments was 1.0±0.3 nmol g DW^{-1} d^{-1} (Table 3). Magnetite amendments resulted in a minor increase of $\delta^{13}C_{DIC}$ values compared to the

methane-only controls (200‰ and 265‰, respectively, Fig. 4A) with an AOM rate of 1.8 nmol g DW^{-1} d^{-1}. Amorphous iron amendments resulted in only a 22‰ increase in $\delta^{13}C_{DIC}$ and a lower AOM rate (0.1 nmol g DW^{-1} d^{-1}, Fig. 4A and Table 2). The addition of iron-bearing clay nontronite did not cause any increase in the $\delta^{13}C_{DIC}$ values (Fig. 4B), but the concentration of dissolved Fe(II) increased compared to the natural methane-only control (Fig. 5). Based on $\delta^{13}C_{DIC}$ estimates, no AOM was detected 200 days after the addition of MnO_2 whereas the $\delta^{13}C_{DIC}$ values of the methane-only controls increased to over 500‰ (Fig. 4F).

3.1.2 Sulfate as an electron acceptor

The involvement of sulfate in the AOM in the incubations was tested, even in the absence of detectable sulfate in the methanogenic sediments. This is as sulfate could theoretically still be a short living intermediate for the AOM process in an active cryptic sulfur cycle (Holmkvist et al., 2011). It was quantified directly by adding Na-molybdate to the methane-only controls and the amended with magnetite in the second stage long-term incubations (Fig. 4A). This addition did not affect the increasing trend of $\delta^{13}C_{DIC}$ with time, and therefore, the AOM rates remained unchanged, similar to the observation in the fresh batch incubations (Bar-Or et al., 2017).

3.1.3 Nitrate and nitrite as electron acceptors

Nitrate and nitrite involvement in the AOM was tested for the feasibility of an active cryptic nitrogen cycle, even in the absence of detectable amounts of nitrate and nitrite in the sediments (Nüsslein et al., 2001; Sivan et al., 2011). Nitrate was added at two different concentrations (0.2 and 1 mM, Fig. 4C) to the second stage long-term slurries amended with hematite, as these concentrations were shown previously to promote AOM in other settings (Ettwig et al., 2010). The addition of hematite alone increased the $\delta^{13}C_{DIC}$ values by ~200‰ during the 306 days of the experiment. The $\delta^{13}C_{DIC}$ in the bottles with the addition of 1 mM nitrate, with and without hematite (Fig. 4C; the data points of the two treatments are on top of each other), decreased from 43‰ at the beginning of the experiment to 35‰ after 306 days. The $\delta^{13}C_{DIC}$ in the bottles with the addition of 0.2 mM nitrate and hematite increased by 27‰ at the end of the experiment. Following the addition of 0.5 mM of nitrite, we observed no increase in $\delta^{13}C_{DIC}$ values during the first 222 days (Fig. 4D), after which they increased from 34‰ to 54‰ by the end of the experiment. The AOM rate of the high nitrite concentration treatment was 0.2 nmol g DW^{-1} d^{-1} (Table 2). Following the addition of 0.1 mM nitrite, $\delta^{13}C_{DIC}$ increased only after 130 days to 158‰ on day 493. The AOM rate of the low nitrite concentration treatment was 0.5 nmol g DW^{-1} d^{-1}. In the methane-only controls, the $\delta^{13}C_{DIC}$ value reached a maximum of 330‰.

3.1.4 Organic compounds as electron acceptors

Two of the second stage long-term incubation experiments were amended with synthetic and natural organic electron acceptors to test the potential of organic electron acceptors. The addition of AQDS to slurries with and without hematite caused to a decrease in $\delta^{13}C_{DIC}$ values over the entire duration of the experiment (Fig. 4E). Dissolved Fe(II) increased by 50 µM in these treatments, while in those without AQDS, it exhibited an increase of 20 µM (Fig. S3). We further tested the effect of naturally occurring humic substances by using those isolated from a different natural lake. The results show that the $\delta^{13}C_{DIC}$ values did not change at the beginning of the experiments (Fig. 4B), while a steep increase of ~90 µM in their Fe(II) concentration was observed (Fig. 5). After 20 days, the $\delta^{13}C_{DIC}$ values of these slurries started to increase dramatically from 84‰ to 150‰ with an AOM rate of 1.2 nmol g DW^{-1} d^{-1} (Fig. 4B, Table 2). Dissolved Fe(II) concentrations mirrored the trend of $\delta^{13}C_{DIC}$ with a steep increase during the first 20 days followed by a decrease of 37 µM (Fig. 5).

3.1.5 Metabolic pathways

To elucidate which metabolic processes drive AOM, we analyzed $\delta^{13}C_{DIC}$ following the addition of inhibitors to the second stage long-term slurries: i) BES, a specific inhibitor for methanogenesis (Nollet et al., 1997) and ii) acetylene, a non-specific inhibitor for methanogenesis and methanotrophy (Orembland and Capone, 1988). In both cases and similar to the killed control, labeled ^{13}C-DIC production was completely inhibited following the addition (Fig. 6). Though acetylene can also inhibit nitrogen cycling in some cases, it has been shown to result in the production of ethylene (Oremland and Capone, 1988). In our case, however, no ethylene was detected, supporting the conclusion that only the methanogenesis activity was inhibited.

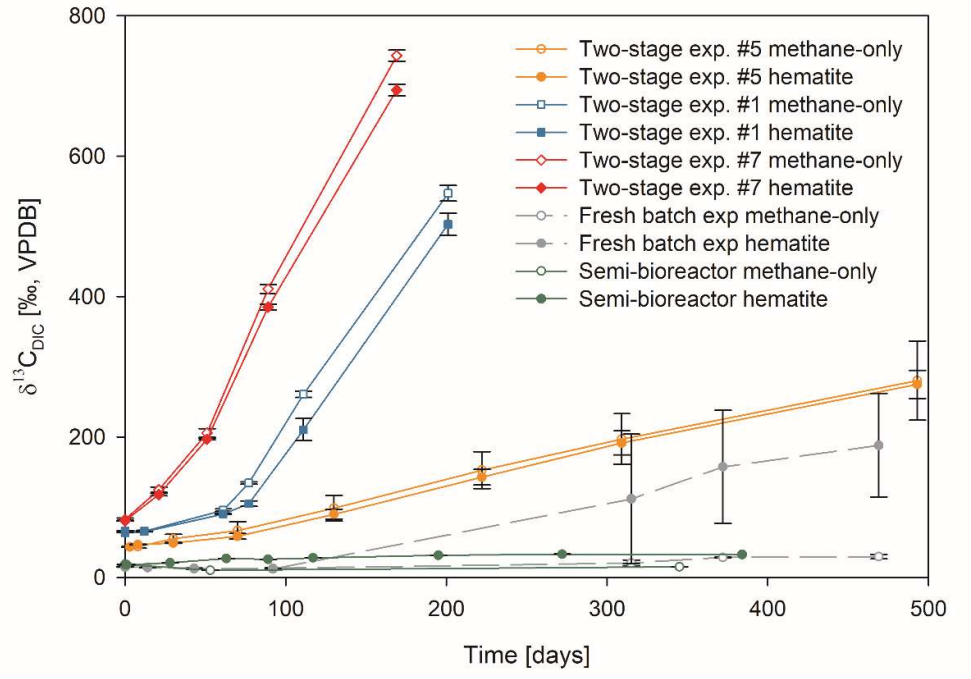
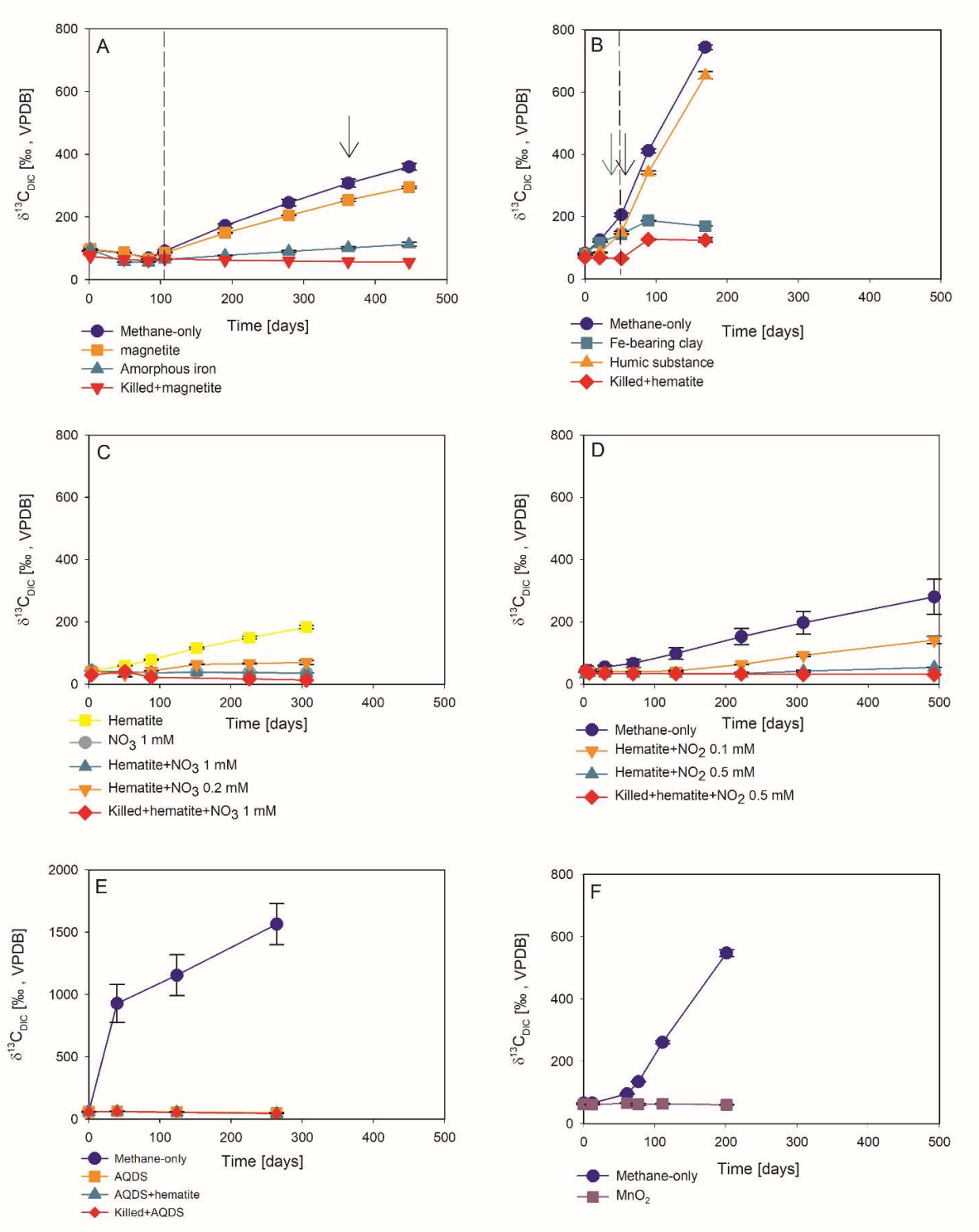


Figure 3: Comparison of $\delta^{13}C_{DIC}$ values among the three types of experiments with ^{13}C -labeled methane addition: A) three two-stage slurry experiments (at the second stage of 1:3 ratio of sediment to porewater); B) the semi-continuous bioreactor experiment; and C) slurry batch experiment with freshly collected sediments (Bar-Or et al., 2017). In each experiment, two treatments are shown, with hematite (filled symbol) and without hematite (empty symbols). The error bars represent the average deviation of the mean of duplicate/triplicate bottles.



399 Figure 4: Potentials of different electron acceptors for AOM in Lake Kinneret in the two-stages long-term slurry
400 experiments (at the second stage of 1:3 ratio of sediment to porewater) with of ^{13}C -labeled methane and the
401 following treatments: (A) with and without the addition of magnetite and amorphous iron ($Fe(OH)_3$). The dashed
402 line represents the specific time of ^{13}C -labeled methane addition. The black arrow represents the addition of Na-
403 molybdate as an inhibitor for sulfate reduction. (B) with clay and natural humic substance. The green arrow
404 represents the time clay was added to the relevant bottles, the dashed line represents the time the headspace of
405 each bottle was flushed again with N_2, and the black arrow represents the second injection of 1 mL of ^{13}C-labeled
406 methane. (C) with the addition of hematite and two different concentrations of nitrate. (D) with the addition of
407 hematite and two different concentrations of nitrite. (E) with the addition of AQDS. (F) with and without the
408 addition of ^{13}C-labeled methane to all of the bottles (see Table 1 for specific experimental details). Error bars
409 represent the average deviations of the data points from their means of duplicate/triplicate bottles.

410 Table 2: AOM rates and AOM role in experiment A second stage slurries amended with ^{13}C-labeled methane and
411 different electron acceptors (assuming methanogenesis rate of 24.8 nmol g DW^{-1} d^{-1}).

Experiment serial number (SN)	Treatment	AOM rate [nmol/g DW X d]	AOM/methanogenesis [%]
10	**methane only**	1.1	4.4
1	**methane only**	1.6	6.4
	methane+hematite	0.5	2.1
2	**methane only**	2.4	8.2
	methane+magnetite	1.8	6.3
	methane+amorphous iron	0.1	0.5
7	**methane only**	1.4	6.4
	methane+hematite	1.3	6.0
	methane+humics	1.2	5.4
5	**methane only**	1.0	4.6
	methane+hematite	1.0	4.6
	methane+hematite+nitrite 0.5 mM	0.2	0.8
	methane+hematite+nitrite 0.1 mM	0.5	2.1

412

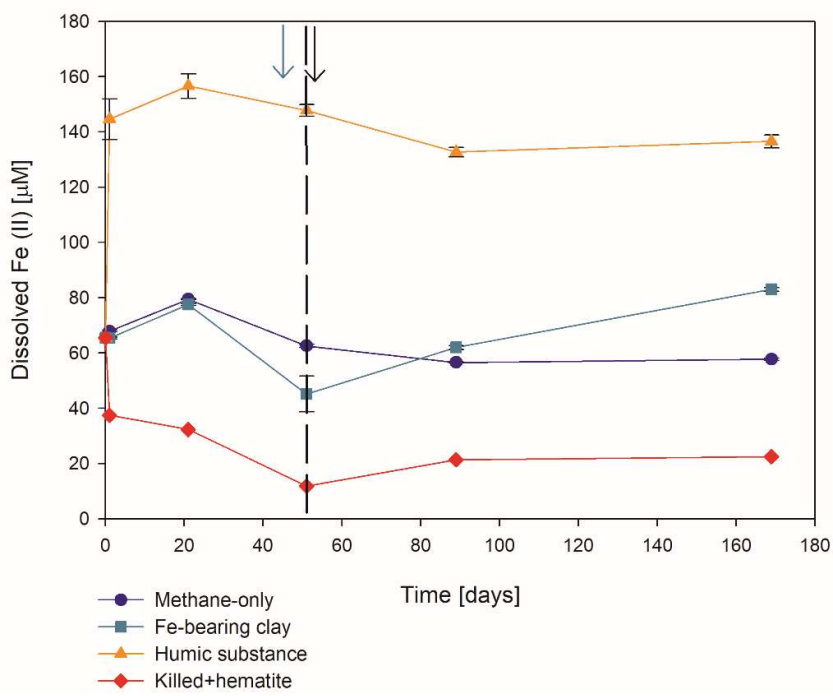


Figure 5: Change in dissolved Fe(II) in the second stage of experiment No. 7 containing clay and natural humic acid. The green arrow represents the time at which clay was added to the specific bottles and those bottles were flushed with N_2, the dashed line represents the time at which the rest of the bottles were flushed, and the black arrow represents the time at which ^{13}C-labeled methane was added again. Error bars represent the average of the absolute deviations of the data points from their means.

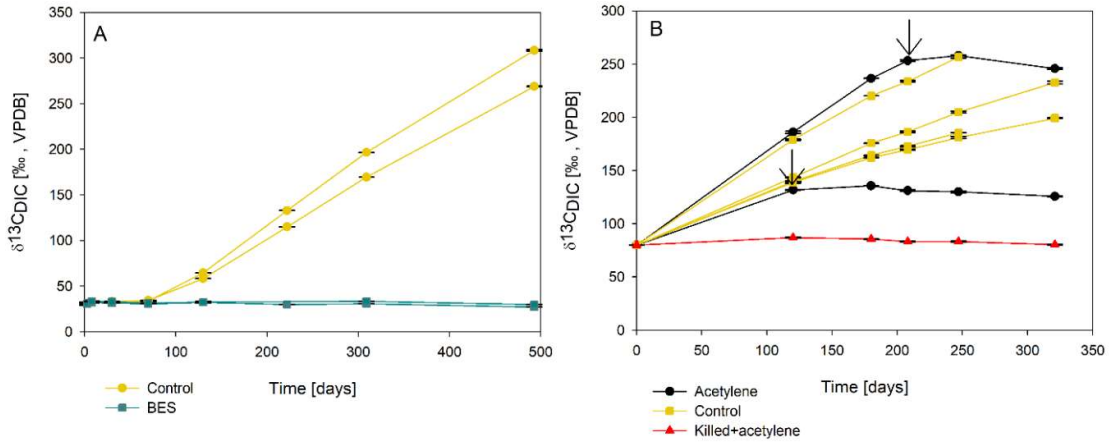


Figure 6: Change in $\delta^{13}C_{DIC}$ values over time in the second stage long-term sediment slurry incubations amended with hematite and ^{13}C-labeled methane. (A) with/without BES and (B) with/without acetylene. Black arrows represent the time at which acetylene was injected into the experiment bottle. The error bars are smaller than the symbols.

3.2 Microbial dynamics

Analyses of taxonomy and coverage of metagenome-assembled genomes suggest that in the pre-incubated two-stage slurries, Bathyarchaeia are the dominant archaea, together with putative methanogens such as Methanofastidiales (Thermococci), Methanoregulaceae (Methanomicrobia) and Methanotrichales (Methanosarcina) (Supplementary coverage table). Bona-fide ANME (ANME-1) were detected with substantial coverage of approximately 1 (the 27th most abundant from among the 195 MAGs detected) in all of the treatments. Among the bacteria, the sulfate reducers Desulfobacterota and Thermodesulfovibrionales (Nitrospirota) were prominent together with the GIF9 Dehalococcoida lineage, which is known to metabolize chlorinated compounds in lake sediments (Biderre-Petit et al., 2016). Some Methylomirabilales (NC10) were found (average coverage of 0.32±0.06), and no Methanoperedens were detected. Methylococcales methanotrophs were found in the natural sediments and the fresh batch and bioreactor incubations (average of 0.34±0.02), in contrast to their average coverage of 0.09±0.04 in the long-term incubations. Methylococcales comprised the *Methyloterricola*, *Methylomonas* and *Methylobacter* genera (Supplementary coverage table). The methylotrophic partners of aerobic methanotrophs, *Methylotenera*, were found in fresh batch and bioreactor incubations, where *Methylomonas* was found, findings that are in line with those of previous studies that showed their association (Beck et al., 2013). Principal component analysis shows the grouping of long-term, pre-incubated slurries, semi-aerobic bioreactor incubations, and fresh batch experiments (Fig. 7), emphasizing the microbial dynamics over time.

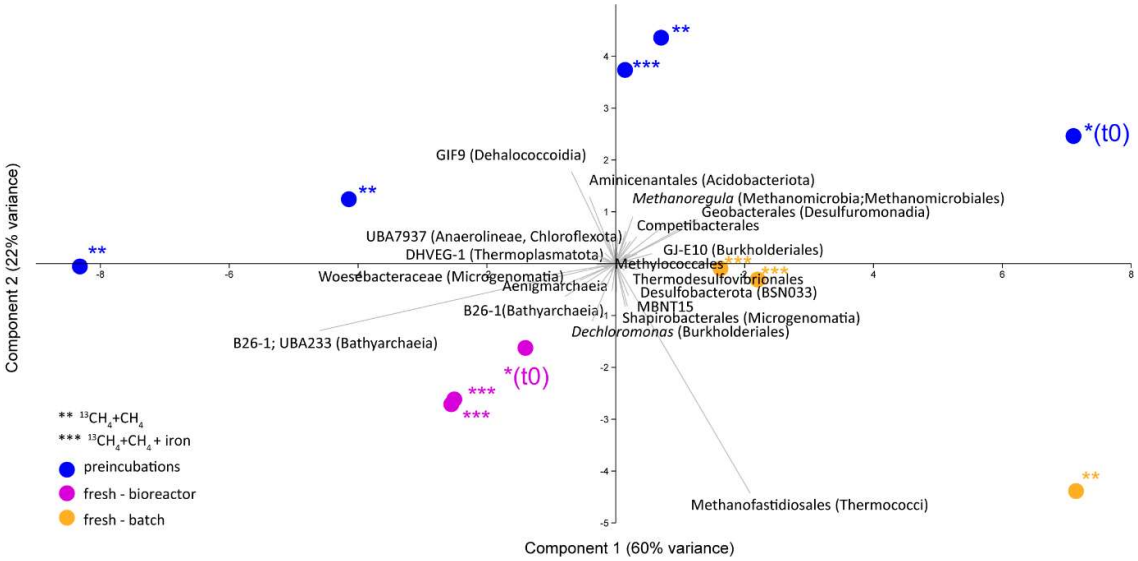


Figure 7: Principal component analysis comparison of three types of samples: long-term pre-incubated slurries (blue – experiment A), semi-continuous bioreactor (pink – experiment B) and fresh batch experiments (orange – experiment C). One asterisk represents t0, two asterisks denote methane-only treatments, three asterisks represent hematite treatment.

3.3 Lipid analysis

The $\delta^{13}C$ values of the archaeol-derived isoprenoid phytane were between −5 and −17‰ in the long-term pre-incubated samples and thus showed ^{13}C-enrichment of 15 to 27‰ relative to the original sediment. This is indicative of methane-derived carbon assimilation by archaea (Table 3). Acyclic biphytane, derived mainly from caldarchaeol, exhibited a less pronounced ^{13}C-enrichment of 5-10‰. For bacterial-derived fatty acids, $\delta^{13}C$-values similarly shifted by up to 10‰ relative to the original sediment. Nonetheless, one would have expected values to be extremely higher if aerobic methanotrophs were active, as was previously indicated by strong ^{13}C-enrichments of up to 1,650‰ in $C_{16:1\omega5c}$ observed in freshly incubated batch samples (Bar-Or et al., 2017).

Table 3: The $\delta^{13}C$ values (in ‰) of fatty acids and isoprenoid hydrocarbons from different experiments compared to values obtained from the original sediment in the methanogenic zone.

			Fatty acids		Hydrocarbons	
Description	Temperature (°C)	Sampling (days)	$C_{16:1\omega9/8/7}$	$C_{16:1\omega5}$	Phytane	Biphytane
Pre-incubated slurry + $^{13}CH_4$+hematite	20	411	-40	-43	-17	-23
Pre-incubated slurry + $^{13}CH_4$ (bottle A)	20	411	-40	-43	-13	-24
Pre-incubated slurry + $^{13}CH_4$ (bottle B)	20	1227	-36	-41	-5	-38
[a] Fresh batch experiment+ $^{13}CH_4$+hematite	20	470	610	1600	-14	-28
Semi-bioreactor+ $^{13}CH_4$+hematite	16	382	n.d.	n.d.	n.d.	n.d.
Original sediment (28-30 cm)	14		-44	-51	-32	-33

[a] Bar-Or et al., 2017
n.d. – Not detected

4. Discussion

4.1 Anaerobic oxidation of methane in the methanogenic sediment incubation experiments

The *in-situ* geochemical and microbial diversity profiles (Bar-Or et al., 2015) and the geochemical (Sivan et al., 2011; Bar-Or et al., 2017; Fig. 3) and metagenomic (Elul et al., 2021) analyses of batch incubations with fresh sediments provided strong support for the occurrence of Fe-AOM in sediments of the methanogenic zone below 20 cm. Such profiles and alongside incubations showed an unexpected presence of aerobic bacterial methanotrophs together with anaerobic microorganisms, such as methanogens and iron reducers (Adler et al., 2011; Sivan et al., 2011; Bar-Or et al., 2015; Bar-Or et al., 2017; Elul et al., 2021). These findings suggested that both *mcr* gene-bearing archaea and aerobic bacterial methanotrophs mediate methane oxidation. In the current study, we have supportive evidence of considerable AOM in the long-term incubations, even after the two treatment stages and considering the low abundance of the microbial populations.

The data from the second stage incubations show a similar increasing trend in the $\delta^{13}C_{DIC}$ values of both natural (methane-only) and the hematite amended treatments (Fig. 3). This deviates from our observations during experiments B and C with fresh sediment, wherein higher $\delta^{13}C_{DIC}$ values were

obtained after the addition of hematite than in the methane-only treatment (Fig. 3 and Bar-Or et al. (2017)). This was particularly dramatic in the batch slurries (experiment C), but it was also observed in the semi-continuous bioreactor (experiment B). We assume that the observed difference in the bioreactors would have been more pronounced if methane concentrations had been higher, but it is still a significant finding. We also note that the difference between the bioreactors results may also be due to the fact that each bioreactor community developed separately. The results of the type A experiments (compared to those of types B and C) suggest that either hematite lacks the potential to stimulate the AOM activity during the two-stage experiments or that there is enough natural Fe(III) in the sediments to sustain the maximum potential of Fe-AOM. Below we characterize the AOM process in the long-term, two-stage incubation experiments.

4.2 Potential electron acceptors for AOM in the long-term two-stage incubation experiments

Measurements of $\delta^{13}C_{DIC}$ show that the additions of magnetite, amorphous iron, clays and manganese oxide in the second stage incubations resulted in a less pronounced increase in the $\delta^{13}C_{DIC}$ values compared to those of the methane-only controls (Fig. 4). A possible explanation for the latter may be that these metal oxides inhibit AOM, either directly or via a preference for organoclastic iron reduction over Fe-AOM, which adds a natural, more negative carbon isotope signal from the organic materials rather than the heavy carbon from the ^{13}C-labeled methane. Using mass-balance estimations in the methane-only and in the amorphous iron treatments and considering the DIC concentrations and $\delta^{13}C_{DIC}$ values of the methane-only treatments at the beginning of the experiment (6 mM and 60‰, respectively) and the values at the end (6.5 mM and 360‰, respectively), about 0.5 mM of the DIC was added by the AOM of methane with $\delta^{13}C$ of ~4000‰. The DIC and $\delta^{13}C_{DIC}$ values of the amorphous iron treatment at the beginning of the experiment were 5.4 mM and 60‰, respectively, and by the end were 6.1 mM and 120‰, respectively. Assuming the same $\delta^{13}C$ of the added methane of 4000‰ and a $\delta^{13}C_{TOC}$ of −30‰ (Sivan et al., 2011), 0.1 mM of the DIC should derive from AOM and 0.6 mM from organoclastic metabolism. This means that adding amorphous iron to the system encouraged iron reduction that was coupled to the oxidation of organic compounds other than methane. Intrinsic microbes, particularly the commonly detected ex-deltaproteobacterial lineages such as Geobacterales, may catalyze Fe(III) metal reduction, regardless of AOM (Xu et al., 2021). Manganese oxides are found in very low abundance in Lake Kinneret sediments (0.1 %, Table S1 and Sivan et al., 2011). Thus, their role in metal-AOM is likely minimal.

Sulfate concentrations in the methanogenic Lake Kinneret sediments have been below the detection limit in years past, similar to their representation in the natural sediments we used for the incubations (< 5 μM, Bar-Or et al., 2015; Elul et al., 2021). Sulfide concentrations have also been reported to be minor (< 0.3 μM, Sivan et al., 2011). However, sulfate could theoretically still be a short-lived intermediate for the AOM process, as pyrite and FeS precipitate in the top sediments, and cryptic

cycling via pyrite or FeS may replenish the sulfate, thus rendering it available for AOM (Bottrell et al., 2000). The addition of Na-molybdate to the second stage slurries, including those amended with and without magnetite, did not change the $\delta^{13}C_{DIC}$ dynamics, which remained similar to those from before the addition of the inhibitor (Fig. 4A). This finding is in line with that in fresh batch sediment slurries (Bar-Or et al., 2017) and suggests that sulfate is not a potent electron acceptor for AOM in this environment. Furthermore, although sulfate-reducing bacteria were abundant, none of the reducers belonged to the known clades of ANME-2d partners, which were connected previously to the Fe-S-CH_4 coupled AOM (Su et al., 2020; Mostovaya et al., 2021).

Nitrate and nitrite concentrations are also undetectable in the porewater of Lake Kinneret sediments (Nüsslein et al., 2001; Sivan et al., 2011), but again may appear as short-lived intermediate products of ammonium oxidation that is coupled to iron reduction (Tan et al., 2021; Ding et al., 2014; Shrestha et al., 2009; Clement et al., 2005). We thus assessed the roles of nitrate and nitrite as electron acceptors in the two-stage slurries. Our results indicate that the addition of nitrate did not promote AOM, likely due to the absence of ANME-2d, which is known to use nitrate (Arshad et al., 2015; Haroon et al., 2013). In the case of nitrite, even low concentrations appeared to delay the increase in $\delta^{13}C_{DIC}$ values, suggesting that organoclastic denitrification outcompetes AOM, and despite the occurrence of Methylomirabilia, the role of nitrite-AOM is not prominent in the two-stage incubations (Figs. 4C, D).

Humic substances may promote AOM by continuously shuttling electrons to metal oxides (Valenzuela et al., 2019). Though humic substances were not measured directly in Lake Kinneret sediments, the DOC concentrations in the methanogenic depth porewater were previously found to be high (~1.5 mM, Adler et al., 2011), suggesting that they may play a role in AOM. Compared to the methane-only treatments, the treatment with the synthetic humic analog AQDS caused an increase in dissolved Fe(II) concentrations, but it did not cause ^{13}C-DIC enrichment. This may be explained by the behavior of AQDS as a strong electron shuttle in organoclastic iron reduction (Lovely et al., 1996), which produces isotopically more negative carbon that masks the AOM signal (Fig. 4E, Fig. S3). Yet, as was done by Valenzuela et al. (2017), the addition of natural humic substances did promote AOM, compared to the rest of the electron acceptors tested, and may thus support AOM (Fig. 4B). In our incubations, the natural humic substances promoted first the oxidation of organic matter by iron reduction, probably by shuttling electrons from the broad spectrum of organic compounds to natural iron oxides (Figs. 4B and 5). When the availability of the iron oxides or the organic matter decreased, humic substances likely took over to facilitate the AOM (Fig. 4B).

Overall, the results of our long-term two-stage experiments indicate that sulfate, nitrate, nitrite and manganese oxides do not support AOM in the methanogenic sediments of Lake Kinneret. The candidate electron acceptors for AOM in the long-term experiments are natural humic substances and/or the

naturally abundant iron minerals. Future experiments can simulate iron limitation and the involvement of iron oxides in the AOM by removing natural iron oxides from the sediments.

4.3 Main microbial players in the long-term two-stage slurries

Methane oxidation in the pre-incubated Lake Kinneret sediments is likely mediated by either ANMEs or methanogens, as the addition of BES and acetylene immediately stopped the AOM (Fig. 6) similar to the results of the killed bottles and the BES treatment in the fresh batch experiment (Bar-Or et a., 2017). Apart from methane-metabolizing, acetylene can inhibit nitrogen cycling, which results in ethylene production (Oremland and Capone, 1988). This was not the case in our incubations, as no ethylene was produced. The increase in $\delta^{13}C$ values in phytane and biphytane (Table 3) also indicates the presence of active archaeal methanogens or ANMEs (Wegener et al., 2008; Kellermann et al., 2012; Kurth et al., 2019).

Using the isotopic compositions of specific lipids and metagenomics, we identified a considerable abundance of aerobic methanotrophs and methylotrophs in the fresh sediments, but not in the long-term slurries (Table 3, Fig. 7). In the natural sediments, micro levels (nano molar) of oxygen could be trapped in clays and slowly released to the porewater (Wang et al., 2018). However, if such micro levels of oxygen still existed during the time of the pre-incubation, they were probably already exhausted. Indeed, the results of our specific lipids and metagenomics analyses suggest that the aerobic methanotrophs lineages play only a minor role in the long-term slurries, probably due to complete depletion of the oxygen. The metagenomic data (Fig. 7, Supplementary coverage table) also indicate that Bathyarchaeia, which may be involved in methane metabolism (Evens et al., 2015), were enriched in the bioreactor incubations, yet their role in Lake Kinneret AOM remains to be evaluated. We also observed changes in the abundance of bacterial degraders of organic matter and necromass: for example, GIF9 Dehalococcoidia, which can metabolize complex organic materials under methanogenic conditions (Cheng et al., 2019; Hug et al., 2013), were most abundant in the long-term incubations (Fig. 7, Supplementary coverage table). Though ANME-1 are likely mediators of AOM in these sediments, methane oxidation via reverse methanogenesis is feasible for some methanogens in Lake Kinneret sediments (Elul et al., 2021).

4.4 Mechanism of methane oxidation in the long-term two-stage incubations

Our results indicate net methanogenesis in the two-stage incubation experiments with an average rate of 25 nmol gr^{-1} dry sediment day^{-1} (Fig. 1 and Table S2), which are similar to those from fresh incubation experiments (Bar-Or et al., 2017). This is despite the overall trend of increasing $\delta^{13}C_{DIC}$ values, a result representing potential methane turnover (Figs. 3 and 4). A likely explanation for the presence of both signals is an interplay between methane production and oxidation, which is possibly triggered by reversal of the methanogenesis pathway in bonafide ANMEs or certain methanogens (Hallam et al.,

2004; Timmers et al., 2017). Due to the overall production of methane and the lack of intense stimulation of AOM by any electron acceptor added, the increase in $\delta^{13}C_{DIC}$ values could theoretically result from the occurrence of carbon back flux during methanogenesis, which is feasible in environments that are close to thermodynamic equilibrium (Gropp et al., 2021). To test this, we used DIC mass balance calculations to determine the strength of back flux in our incubations. Based on equations 1 and 2, the observed level of ^{13}C-enrichment indicates that 3-8% of the ^{13}C-methane should be converted into DIC. These estimates are orders of magnitude higher than the previously reported values of 0.001-0.3% for methanogenesis back flux in cultures (Zehnder and Brock, 1979; Moran et al., 2005), but they are in the same range as the back flux of 3.2 to 5.5% observed in ANME-enrichment cultures (Holler et al., 2011). For the latter, however, modeling approaches from AOM-dominated marine sediment samples and associated ANME enrichment cultures indicated the absence of net methanogenesis (Yoshinaga et al., 2014; Chuang et al., 2019; Meister et al., 2019; Wegener et al., 2021). Thus, it seems unlikely that back flux alone can account for the methane-to-DIC conversion in Lake Kinneret sediments. Moreover, the occurrence of back flux alone in marine methanogenic sediments with similar net methanogenesis rates and abundant methane-metabolizing archaea did not yield considerable ^{13}C-enrichment in the DIC pool following sediment incubations (Sela-Adler et al., 2015; Amiel, 2018; Vigderovich et al., 2019; Yorshansky, 2019) (Table S3). It is, therefore, less likely that the observed DIC values in our study were sustained by methanogenesis back flux alone (without an external electron acceptor) than by active AOM, which, in this case, is probably performed by ANME-1 or by methanogens that perform reverse methanogenesis to some extent.

Conclusions

The previous results of the geochemical and microbial profiles and the fresh sediment incubations from Lake Kinneret sediment constitute evidence of the occurrence of Fe-AOM, which removes about 10-15% of the methane produced in the lake's sediment (Adler et al., 2011; Sivan et al., 2011). Anaerobic archaea appear to be responsible for the methane turnover in these reduced sediments by reverse methanogenesis, but aerobic Methylococcales may oxidize methane in these sediments as well. The co-occurrence of aerobes and anaerobes in the natural environment may be the result of the presence of undetected trace amounts of oxygen that are trapped at those depths in "nano-niches" or even in mineral layers (Wang et al., 2018). This oxygen portion may not be removed by purging at the beginning of our experiments but is rather slowly used by the methanotrophs for their survival. However, after two incubation stages and intensive purging for a prolonged duration, only archaea remained active and were involved in the observed methane turnover, consuming 3-8% of the methane produced. Thus, we propose two modes of methanotrophy in Lake Kinneret sediments: i) methane oxidation performed by Methylococcales species. This mode was observed only in the incubations with freshly collected sediments (batch or bioreactor). ii) methane oxidation through reverse methanogenesis performed most

likely by ANME-1 or specific methanogens. This mode was observed in all incubation types and could be a result of carbon back flux, however, the very high $\delta^{13}C_{DIC}$ signal points to a metabolic reaction. This AOM is most probably coupled to the reduction of iron and/or humic substances, as terminal electron acceptors or as electron shuttles stimulating the Fe-AOM.

Competing interests. The authors declare that they have no conflict of interest.

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