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Ecosystem modeling of chemosynthesis around mound type methane hydrate

Tetsuo YAMAZAKI
Osaka Metropolitan Univ., Sakai, Japan
E-mail address: yamazaki.marine@omu.ac.jp

Naoki NAKATANI
Osaka Metropolitan Univ., Sakai, Japan

Norio TENMA
National Inst. of Advanced Industrial Science and Technology, Tsukuba, Japan

Contents of today's presentation:

1. Need for ecosystem modeling
2. Structure of ecosystem model around mound type methane hydrate
3. Introduction of chemosynthesis around methane seepage
3. Non-steady growth modeling of anaerobic consortium
4. Conditions and results of test calculation

Keywords:

Anaerobic methane oxidation; Anaerobic sulfate reduction; Bacterial mat; Chemosynthesis; Ecosystem model; Methane seepage; Mound type methane hydrate.

How to use ecosystem model for quantitative environmental impact assessment

1. Creation of numerical ecosystem model
2. Measurement of baseline ecosystem
3. Creation of small scale artificial impact on ecosystem
4. Monitoring of ecosystem recovery from damage
5. Simulate ecosystem recovery by numerical model

Primary stage

Scale-up stage

6. Measurement of baseline ecosystem
7. Creation of larger scale artificial impact on ecosystem
8. Monitoring of ecosystem recovery from larger damage
9. Simulate ecosystem recovery from larger damage by numerical model

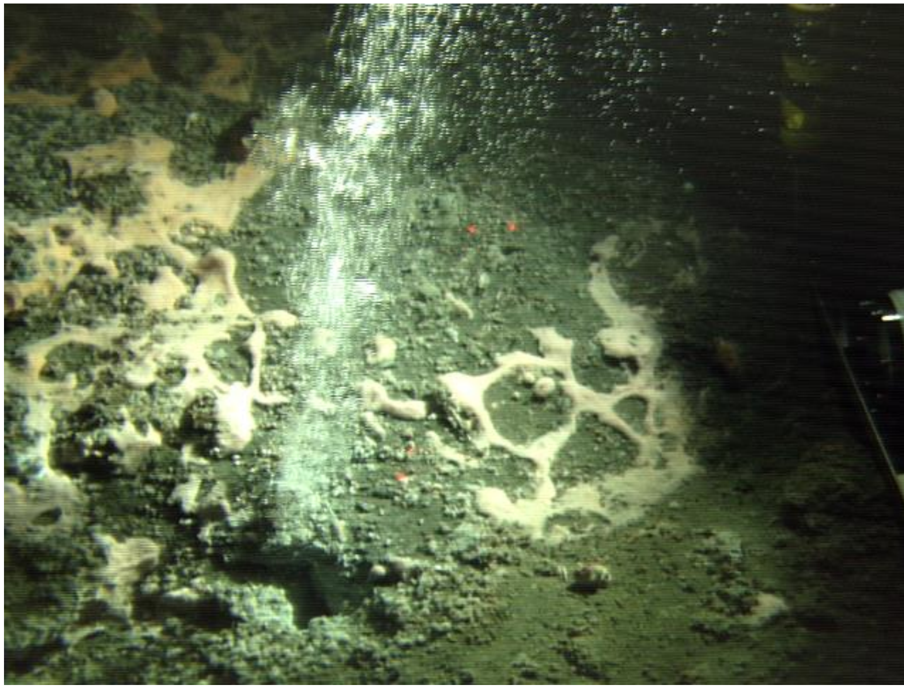
At least one scale-up stage is necessary to blush up ecosystem model. Multi scale-up stages are preferable.

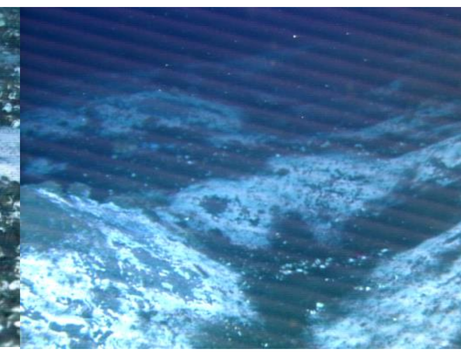
Japan’s experiences of small scale artificial impact on ecosystem (primary stage)

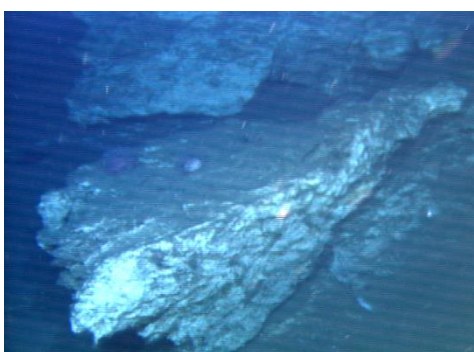
1. JET (Japan Deep Sea Impact Experiment) in manganese nodule area in 1994
   Monitoring after two years and after 17-18 years
2. DIETS (Direct Impact ExperimenT on Seamount) in manganese nodule area on seamount in 1999
   Monitoring after three years
3. Small scale excavation test on massive sulfide mound in 2016
   Monitoring after six years
4. Small scale artificial impact test around massive sulfide mound in 2017
   Monitoring after five years

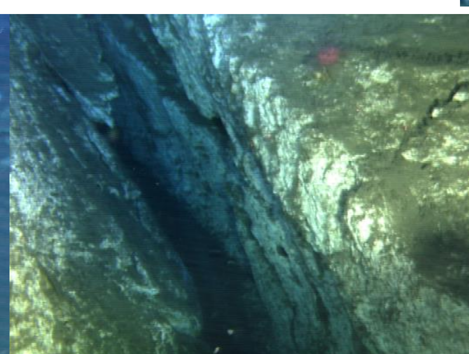
Phenomena observed around methane seepage

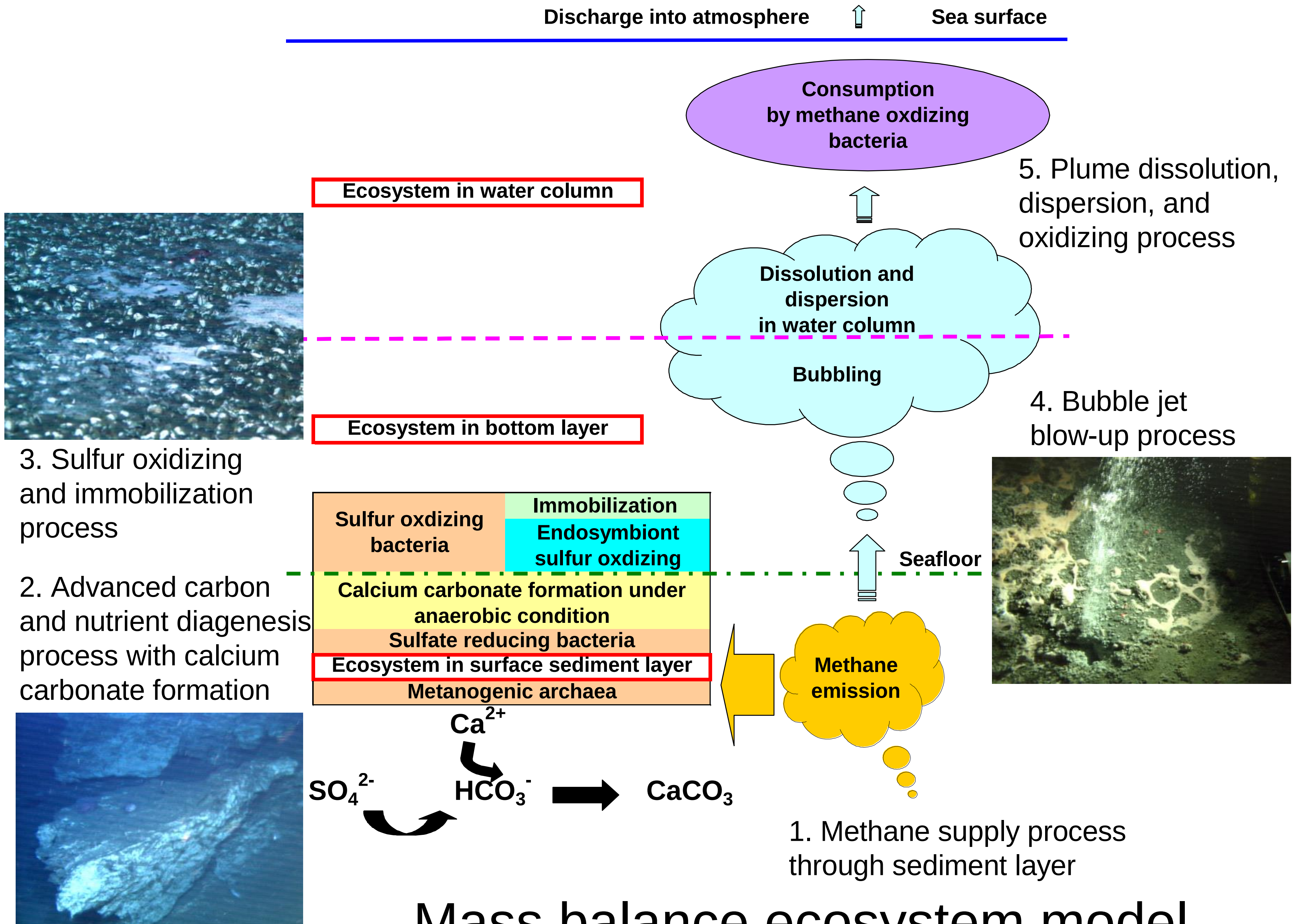
Photos taken by ROPOS during SO148 Cruise in 2000 at Hydrate Ridge, off Oregon











Mass balance ecosystem model around methane seepage

Components of Mass Balance Ecosystem Model around methane seepage

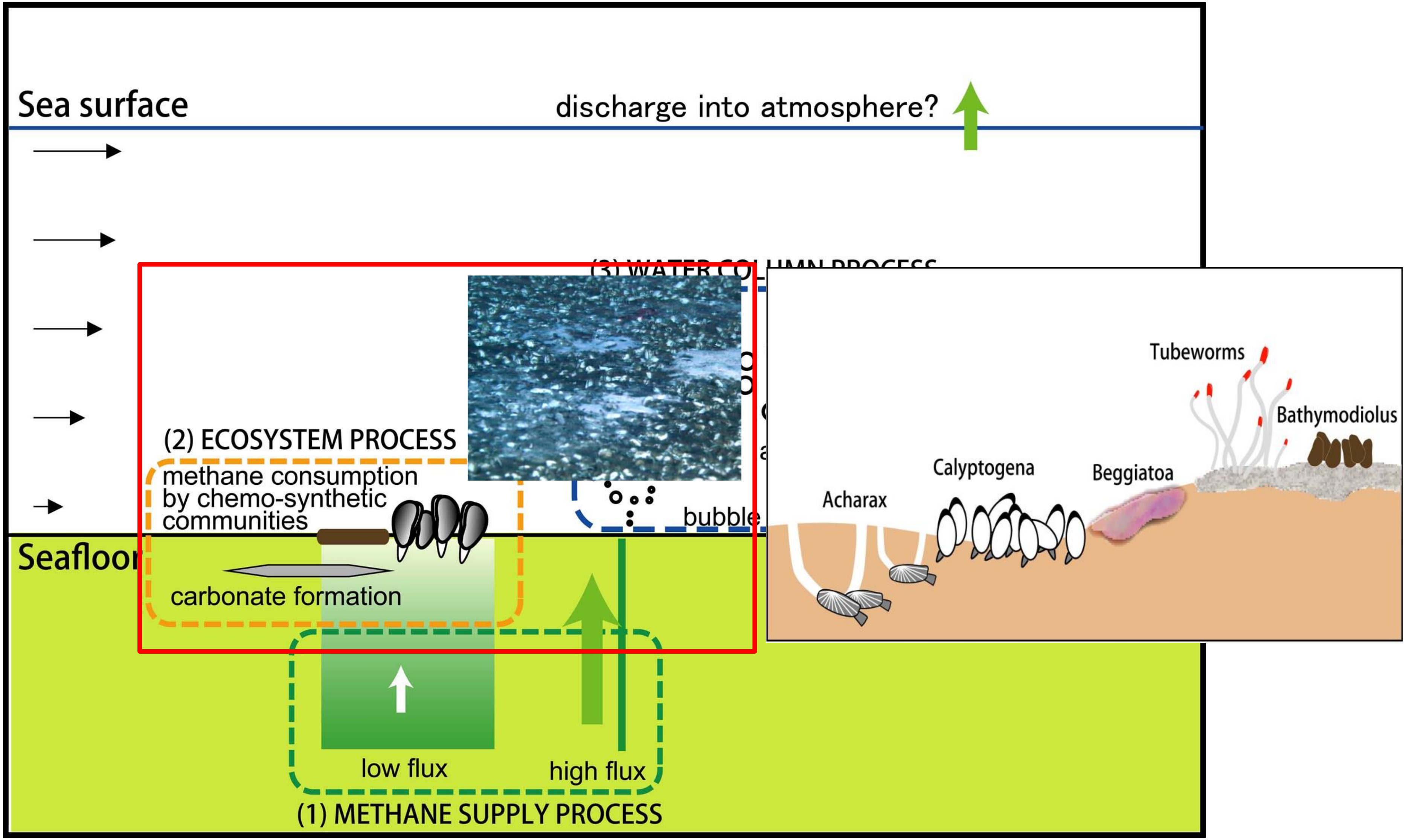
Ecosystem process on seafloor:
Biogeochemical + Geochemical processes
- Anaerobic methane oxidation and anaerobic sulfate reduction
- Calcium carbonate formation
- Sulfur oxidation
- Chemosynthetic immobilization

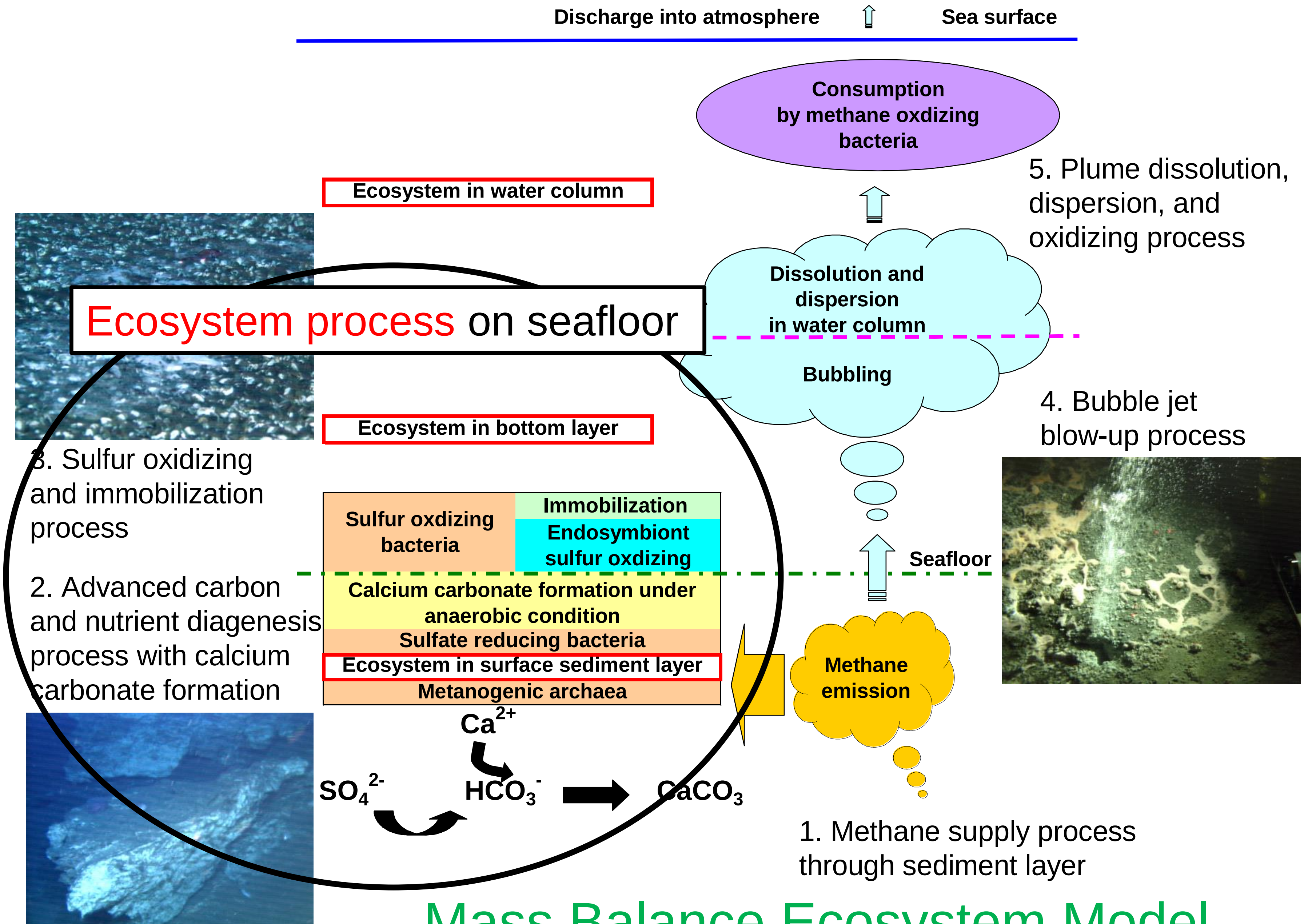
Water column process:
Physical + Biological processes
- Bubble jet blow-up and dissolution
- Plume dispersion
- Methane oxidation

Methane supply process:
Physical + Geochemical processes
- Hydrate formation and dissociation
- Methane dissolution and movement

Detailed information is given from:
Yamazaki, T., Takeuchi, R., Monoe, D., Oomi, T., Nakata, K., and Fukushima, T. (2008). Non-steady Growth Modeling of Anaerobic Consortium of Microorganisms around Methane Seepage, *Proc. 18th Int. Offshore and Polar Eng. Conf.*, Vancouver, pp. 521-526.

Closed-up ecosystem process on seafloor



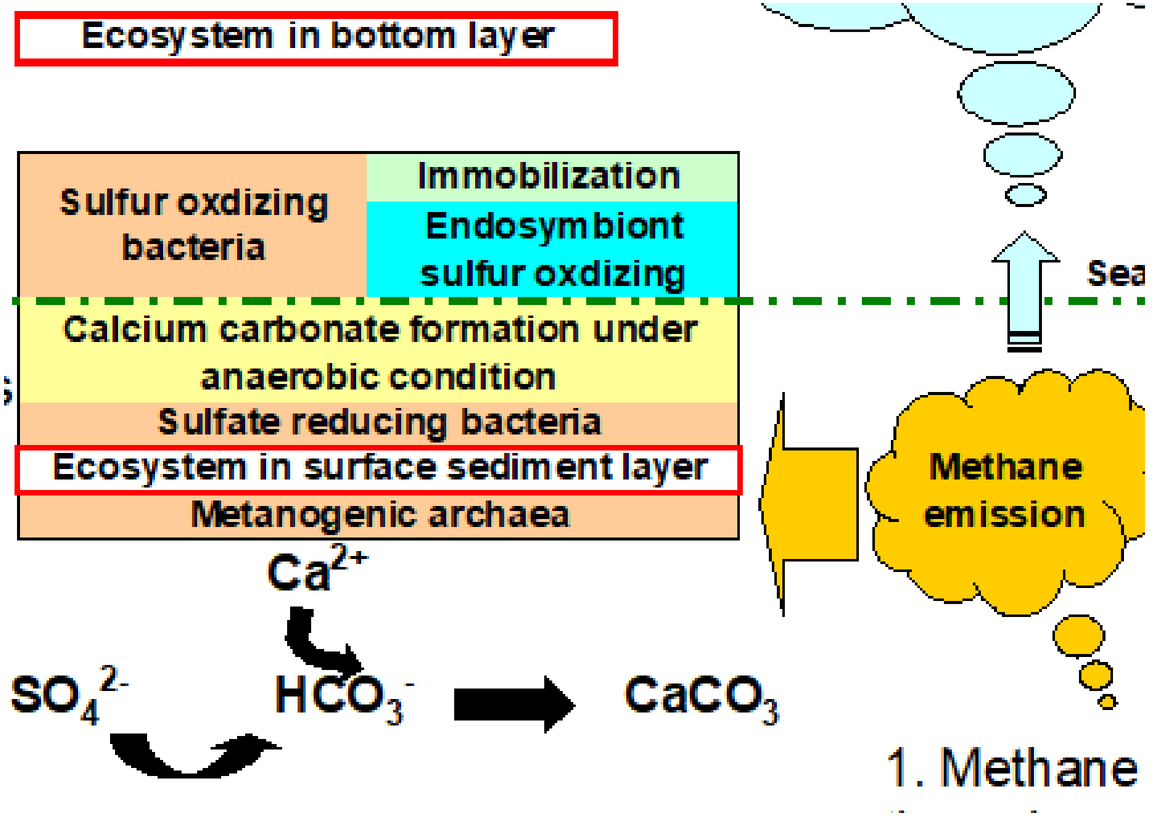


Mass Balance Ecosystem Model around methane seepage

Closed-up biogeochemical and geochemical processes on seafloor

Sulfur oxidizing and immobilization process

Coupled anaerobic oxidation of methane (AOM) and anaerobic sulfate reduction with calcium carbonate formation



Mass Balance Ecosystem Model around methane seepage

Biogeochemical reaction in seafloor ecosystem

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad \text{-- (1)}$$

$$H^+ + 4H_2 + SO_4^{2-} \rightarrow HS^- + 4H_2O \qquad \text{-- (2)}$$

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \qquad \text{-- (3)}$$

$$2HCO_3^- + Ca^{2+} \Leftrightarrow CaCO_3 + CO_2 + H_2O \qquad \text{-- (a)}$$

On the basis of a numerical
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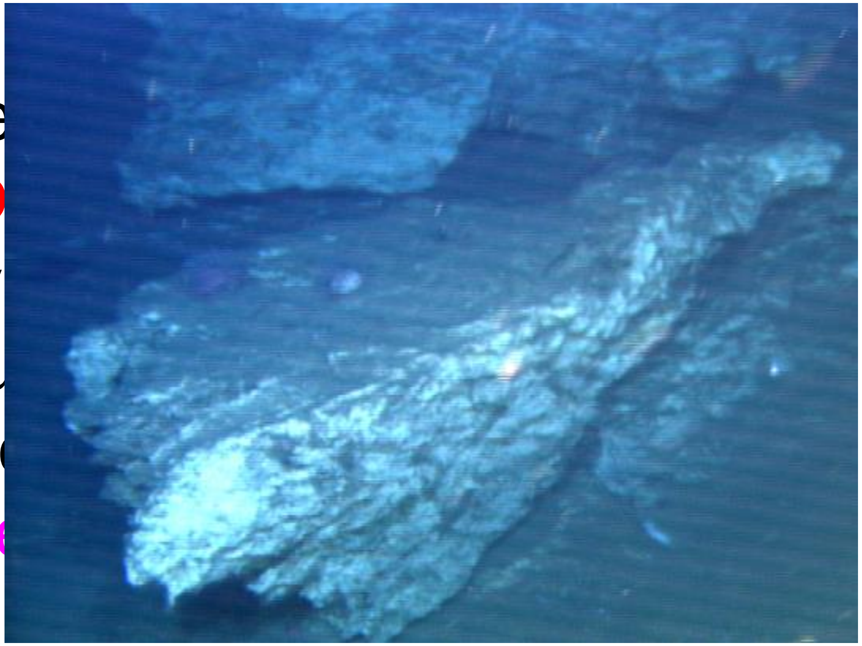


AOM (Anaerobic oxidation of methane) rate: R_{AOM}

$$R_{\mathrm{AOM}} = k_{\mathrm{AOM}} \cdot N_{\mathrm{A}} \cdot [\mathrm{CH}_4] \frac{[\mathrm{SO}_4^{2-}]}{K_{\mathrm{SO4}} + [\mathrm{SO}_4^{2-}]} \cdot F_{\mathrm{tmp}} \quad \text{-- (4)}$$

k_{AOM}: kinetic constant for AOM
$[\mathrm{CH}_4]$: methane concentration (M=mol/l)
$[\mathrm{SO}_4^{2-}]$: sulfate concentration (M=mol/l)
N_{A}: concentration of aggregates of AOM consortium
K_{SO4}: Monod constant (= 1 mM) defining the inhibition of AOM at low sulfate concentrations (Nauhaus et al., 2002)
F_{tmp}: temperature dependent factor added in this modeling

Nauhaus, K, Boetius, A, Krüger, M, Widdel, F (2002). “In vitro demonstration of anaerobic oxidation of methane coupled to sulphate reduction in sediment from marine gas hydrate area,” *Environ Microbiol*, Vol 4, pp 4298-305.

Growth model of consortium of microorganisms

$$\frac{dN}{dt} = R \cdot N \qquad \text{- - (5)}$$

$$N = N_0 \exp\{R(t - t_0)\} \qquad \text{- - (6)}$$

$$R = G - L \cdot N \qquad \text{- - (7)}$$

N: growth of microorganisms
R: growth ratio
N_0: population of microorganisms at $t = t_0$
G: environmentally free growth ratio
L: natural death ratio

Eq. (7) is applied to the consortium.

Growth and death ratios induced from AOM rate

$$G_i = F_i \cdot k_{\mathrm{AOM}}[\mathrm{CH_4}]\frac{[\mathrm{SO_4^{2-}}]}{K_{\mathrm{SO4}}+[\mathrm{SO_4^{2-}}]} \qquad \text{-- (8)}$$

$$L_i = k'_{\mathrm{LOS}} \cdot \left\{\frac{K'_{\mathrm{CH4}}}{(K'_{\mathrm{CH4}}+[\mathrm{CH_4}])}\right\}^{\alpha} \qquad \text{-- (9)}$$

i: suffix for archaea or bacteria

F: cell increase factor with 1 μmol methane consumption

k'_{LOS}: kinetic constant of natural death rate

K'_{CH4}: Monod constant (= 1 mM) defining the inhibition of growth

α: acceleration factor defining the natural death at low methane concentration.

- A steady model was created by the authors. From the test calculation, it is recognized more than 1,000 years is necessary to reach the steady condition.

- Because methane hydrate distributes in shallower sediment layer, accidental leakage of methane may occur while the utilization of methane hydrate as energy resources.

- The final goal of this study is to create a numerical model to estimate ecosystem reactions under non-steady condition and apply the model for the environmental assessment of the methane hydrate exploitation.

- Non-steady growth model is necessary.

Qualified literatures with experimental data

Numerical modeling itself is not difficult, if some qualified literatures with good experimental and/or in-situ observation data are available.

For example:

Boetius A, Ravenschlag K, Schubert CJ, Rickert D, Widdel F, Gieseke A, Amann R, Jorgensen BB, Witte U, and Pfannkuche O (2000). “A marine microbial consortium apparently mediating anaerobic oxidation of methane,” *Nature*, Vol 407, pp 623-626.

Girguis, PR, Cozen, AE, and DeLong, EF (2005). “Growth and population dynamics of anaerobic methane-oxidizing archaea and sulfate-reducing bacteria in a continuous-flow bioreactor,” *Applied & Environmental Microbiology*, Vol 71, pp 3725-3733.

Table 3 Growth functions of microorganisms

	ANME-1	AMNE-2	*D*SRB
LF	160.4exp(0.121t)	124.9exp(0.167t)	274.2exp(0.302t)
HF	321.3exp(0.218t)	230.4exp(0.158t)	613.4exp(0.286t)

Yamazaki, T. et al. (2008). Non-steady Growth Modeling of Anaerobic Consortium of Microorganisms around Methane Seepage, *Proc. 18th Int. Offshore and Polar Eng. Conf.*, Vancouver, pp. 521-526.

Table 4 AOM rates before and after incubation

	before incubation	after incubation
LF	0.30±2.02	9.03±1.94
HF	0.64±3.15	138.35±11.52

Yamazaki, T. et al. (2008). Non-steady Growth Modeling of Anaerobic Consortium of Microorganisms around Methane Seepage, *Proc. 18th Int. Offshore and Polar Eng. Conf.*, Vancouver, pp. 521-526.

Girguis et al. (2005) incubated ANME-1, ANME-2, and *D*SRB. Two different pore water flow rates, such as 19 cm yr^{-1} (LF: low-flow) and 90 cm yr^{-1} (HF: high-flow), were applied to the non-seep 20 cm long sediment core column under 5 mM in methane and 950 µM in hydrogen sulfide concentrations for 27 and 29 weeks.
A linear regression between the ln(cell density) in SSU rRNA copies g^{-1} dry sediment $week^{-1}$ and the time in week were recognized.

Conditions and results of test calculation

Table 5 Parameters assumed for ANME-2 and *D*SRB

	initial population of consortium	cell/aggregate	rRNA/cell
ANME-2	124.9	100	2
*D*SRB	274.2	200	2

(Unit of the population is SSU rRNA copies g^{-1} dry sediment. The rRNA/cell is 16 SSU rRNA gene copy number per one genome.)

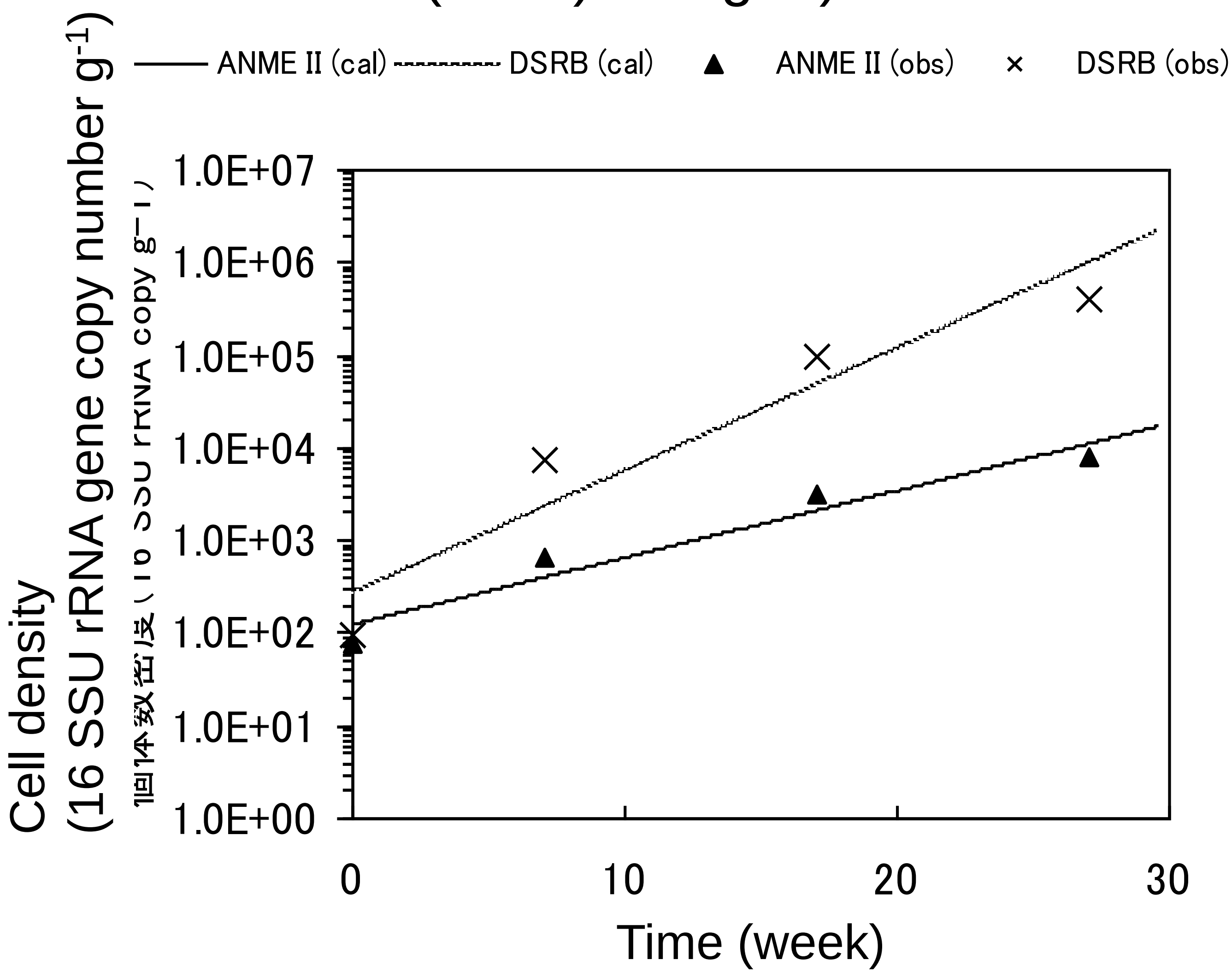
Yamazaki, T. et al. (2008). Non-steady Growth Modeling of Anaerobic Consortium of Microorganisms around Methane Seepage, *Proc. 18th Int. Offshore and Polar Eng. Conf.*, Vancouver, pp. 521-526.

Table 6 Parameters assumed in growth model

	assumed value	unit
cell increase factor for ANME-2	6.95×10^{4}	μmol^{-1}
cell increase factor for *D*SRB	1.25×10^{5}	μmol^{-1}
kinetic constant for AOM	8.7×10^{-8}	$cm^{3}\ yr^{-1}$
kinetic constant of natural death rate	1.0×10^{-9}	yr^{-1}
Monod constant for CH_4	1.0	$mmol\ L^{-1}$
acceleration factor defining natural death at low methane concentration	5.5	-

Yamazaki, T. et al. (2008). Non-steady Growth Modeling of Anaerobic Consortium of Microorganisms around Methane Seepage, *Proc. 18th Int. Offshore and Polar Eng. Conf.*, Vancouver, pp. 521-526.

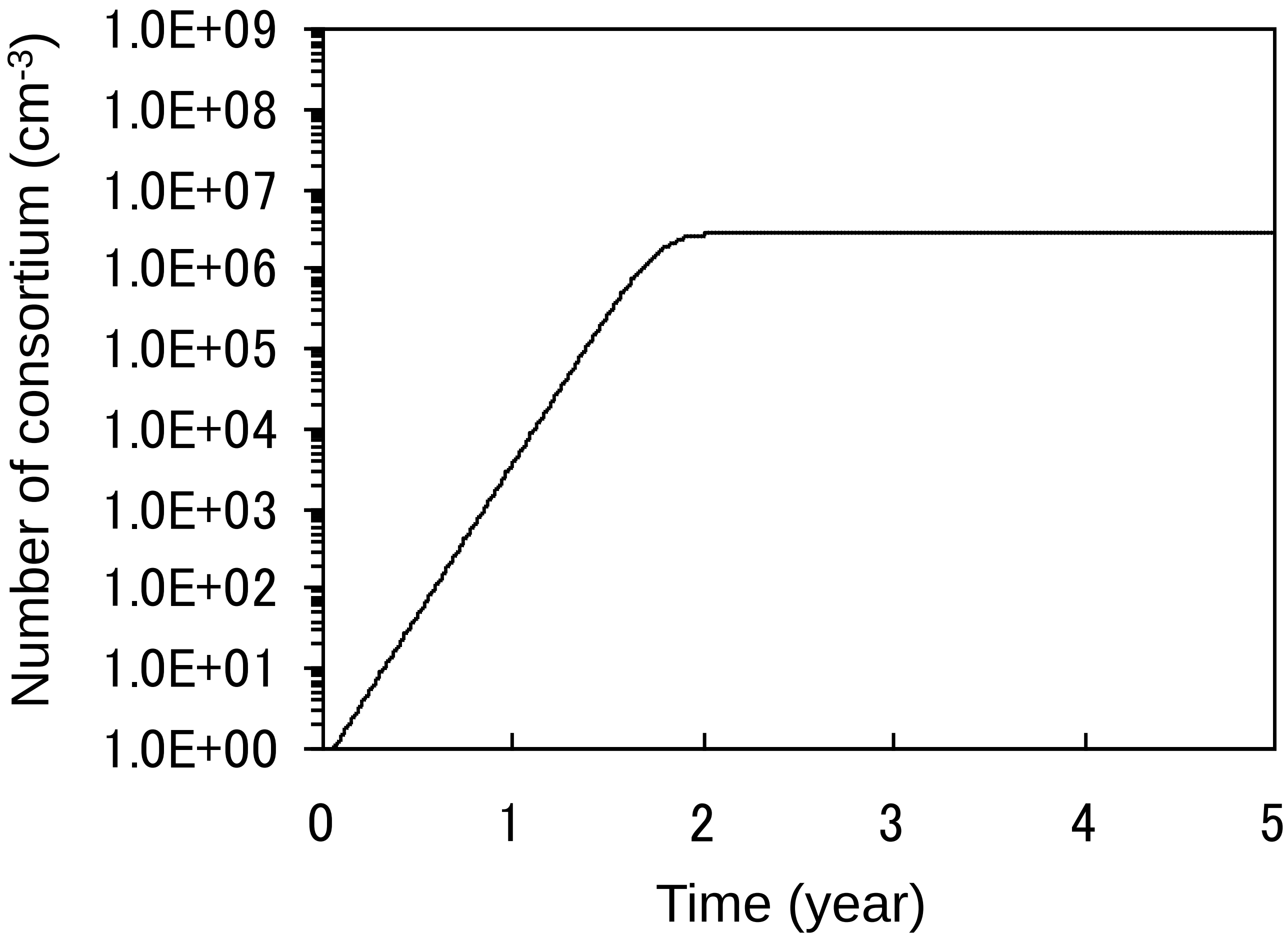
Fig. 4 Comparison between test calculation and experiments of growth of ANME-2 and DSRB in non-seep sediments (Data plotted are from Girugus et al. (2005) and lines calculated are from Yamazaki et al. (2008) in Fig. 4).



Parameters are selected to re-create experimental results by Girgus et al. (2005)

Fig. 5 Calculated population of consortia of microorganisms

In the calculated results, the population situates at 10^7 cm^{-3} level in two years. The consortia population in surface sediment layer at Hydrate Ridge introduced in Boetius et al. (2000) was 7×10^7 aggregates cm^{-3} at 1-2 cm deep in maximum. The calculated result was good at the observed data.



AOM rate measured by an incubation test

On the seafloor surface in Amagasaki Port, Osaka Bay, Japan, white mat-like microbial community called bacterial mat is formed every year from May to October under anoxic condition. It is known that hydrogen sulfide is abundant in this bacterial mat, and sulfur-oxidizing bacteria are the dominant species in this mat. Hydrogen sulfide produced by AOM from organic matters present in the surface layer of the hypoxic sediment is the main source.

In 2020, an incubation experiment was conducted by using cored sediment samples from the bacteria mat. After aeration with nitrogen gas in two vials containing the sediment core, artificial seawater and methane gas were placed in both the vials. Among the two, one was added Na_2SO_4 and the other nothing. The methane gas reduction in the vial with Na_2SO_4 was measured and compared with the other one. Assuming that the methane gas reduction was brought about by AOM, the AOM rate was determined from the methane decrease after one month. The calculated AOM rate was 81.3 μmol/g (in dry condition) per day.

Preliminary concluding remarks

A quite unique and large-scale ecosystem community is frequently created on the seafloor around MTMH. It is a chemosynthesis-base ecosystem depending on methane supply. In case of MTMH exploitation, quite severe damages on the seafloor ecosystem community are expected. In order to minimize and expect the damages and the recovery, an ecosystem model, which numerically calculates the chemical processes and the ecosystem reactions, must be created. For the completion of the model, it is necessary to monitor the extension of damages and the re-colonization of ecosystem under a small-scale exploitation experiment.

End of presentation

Thank you for your interests and attentions!

ACKNOWLEDGMENTS

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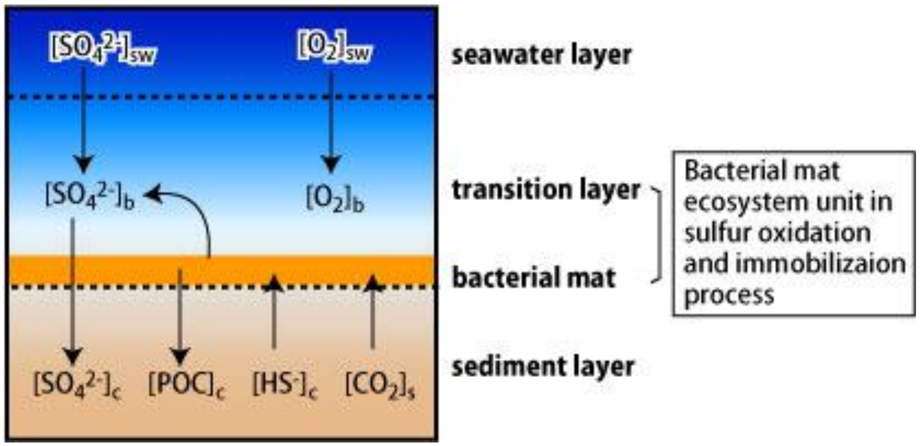

Fig. 3 Structural image of sulfur oxidizing in bacterial mat field