Anaerobic Oxidation of Methane Coupled to Metal Reduction in an Archean Ocean Analogue

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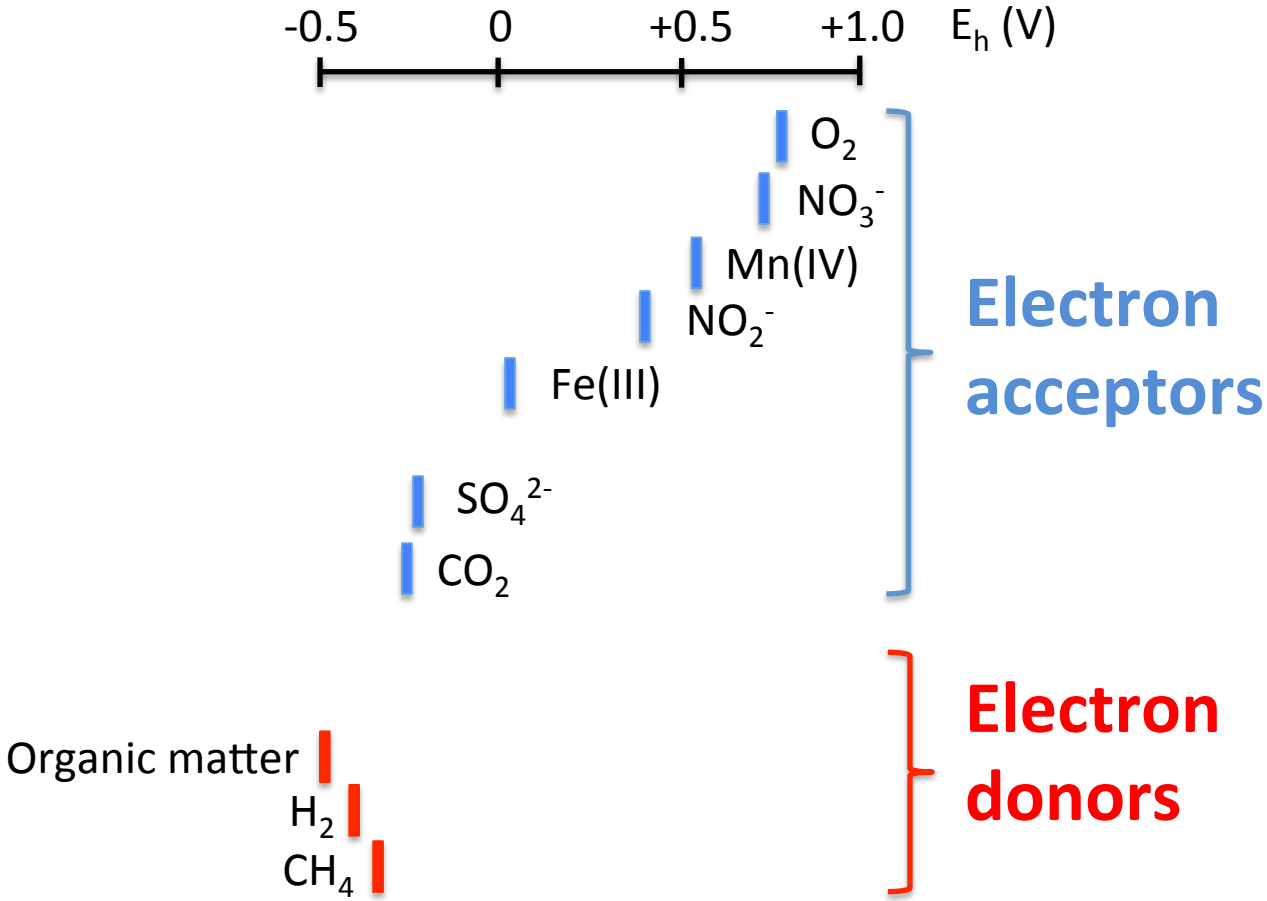
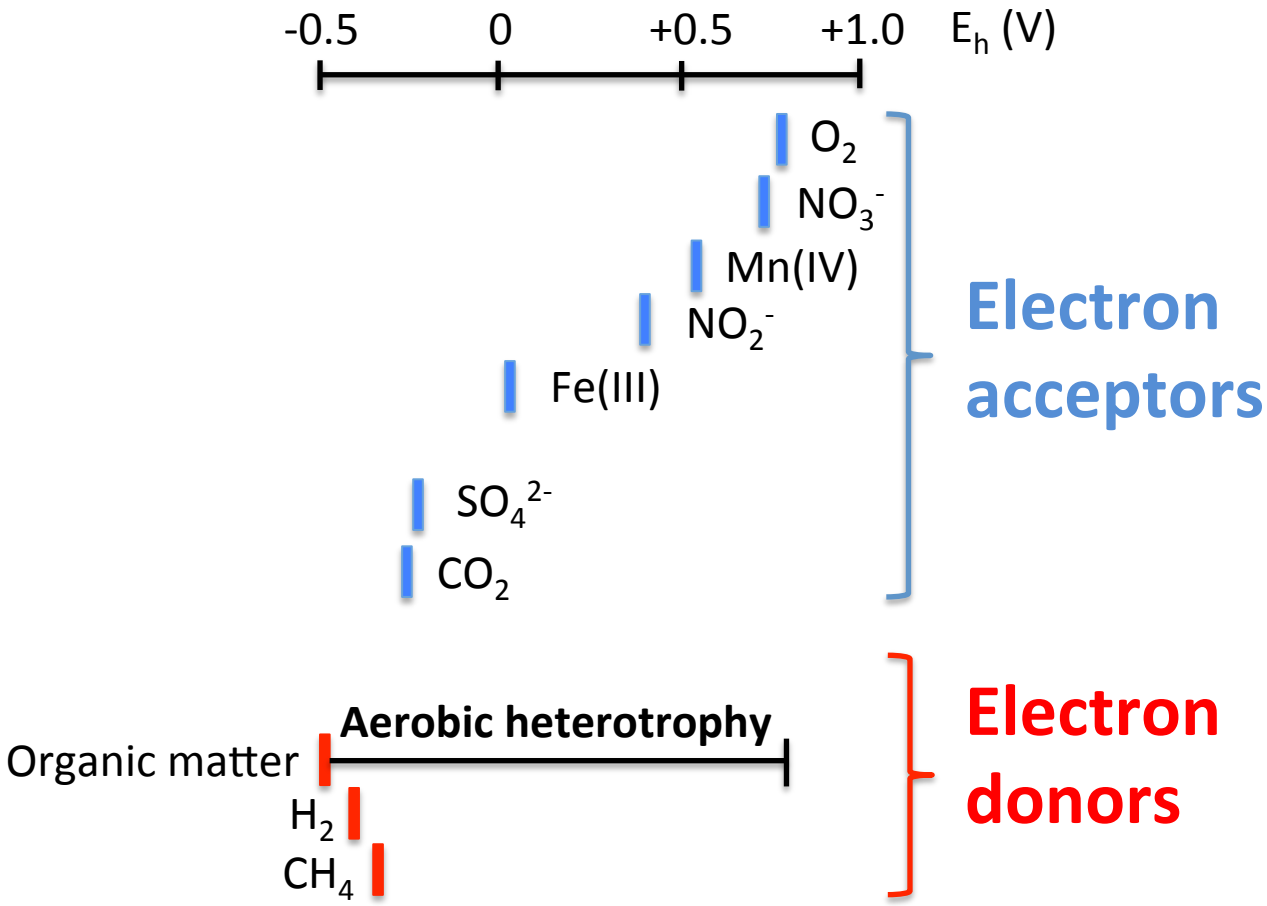
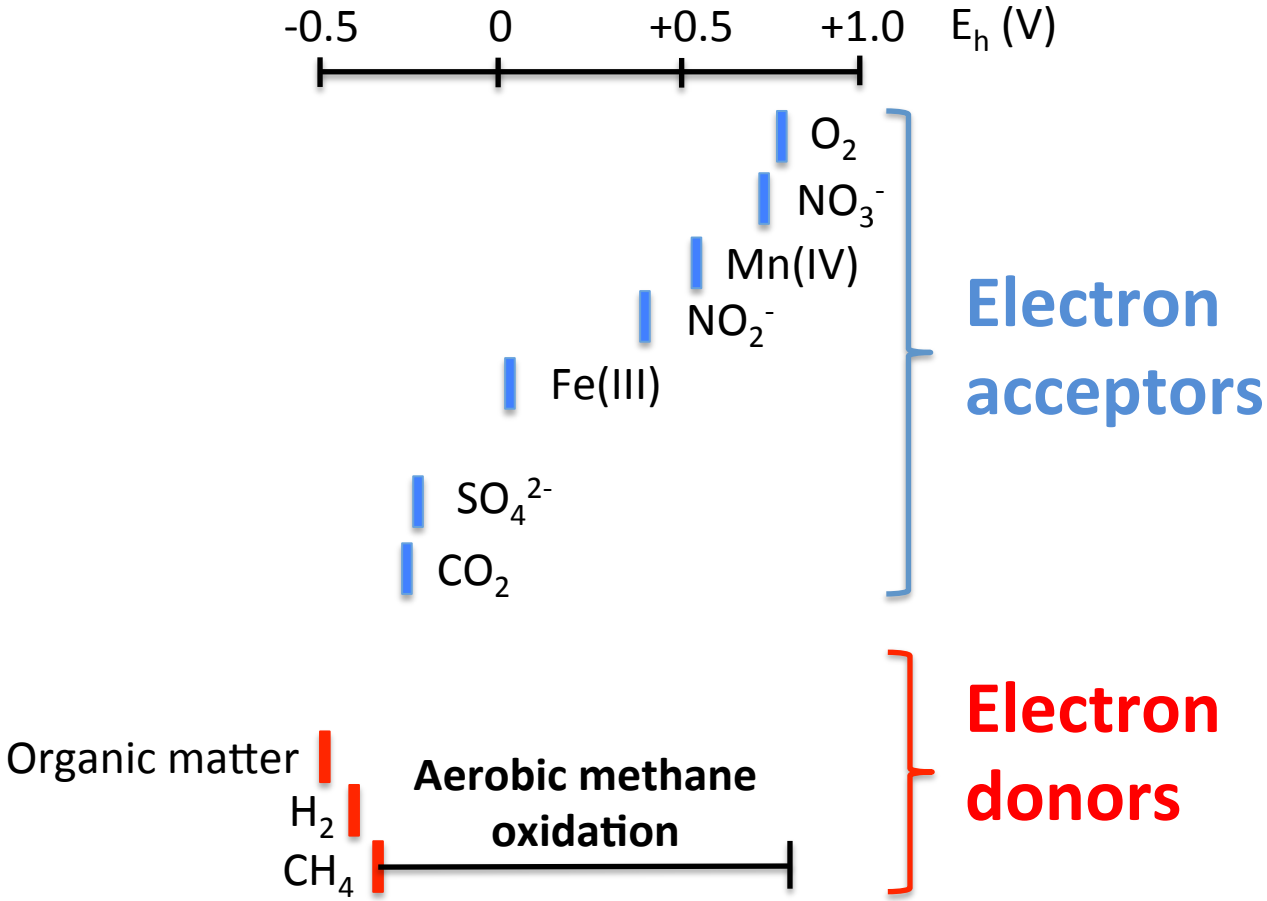
Thermodynamics of Methane Oxidation



Thermodynamics of Methane Oxidation



Thermodynamics of Methane Oxidation



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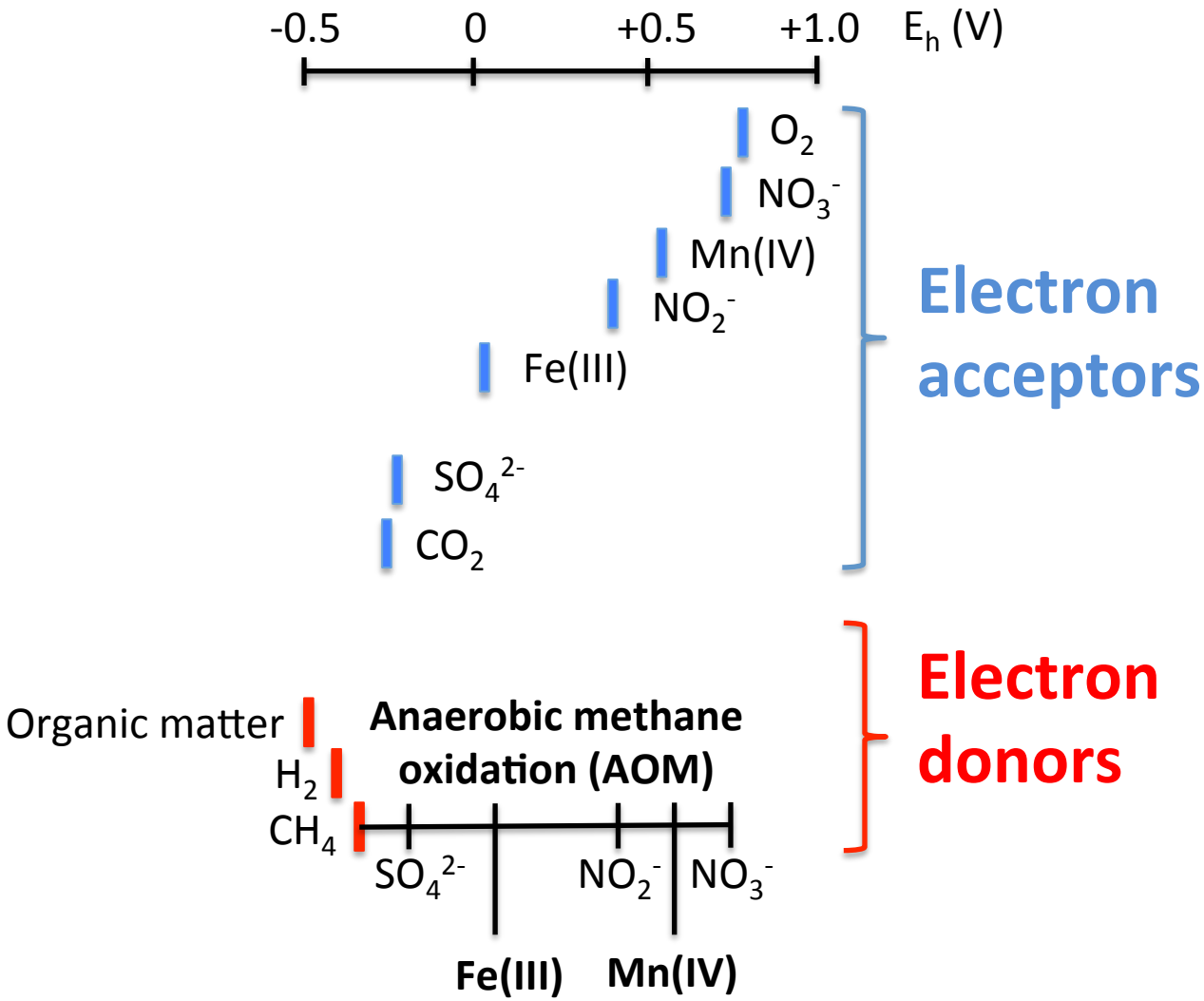
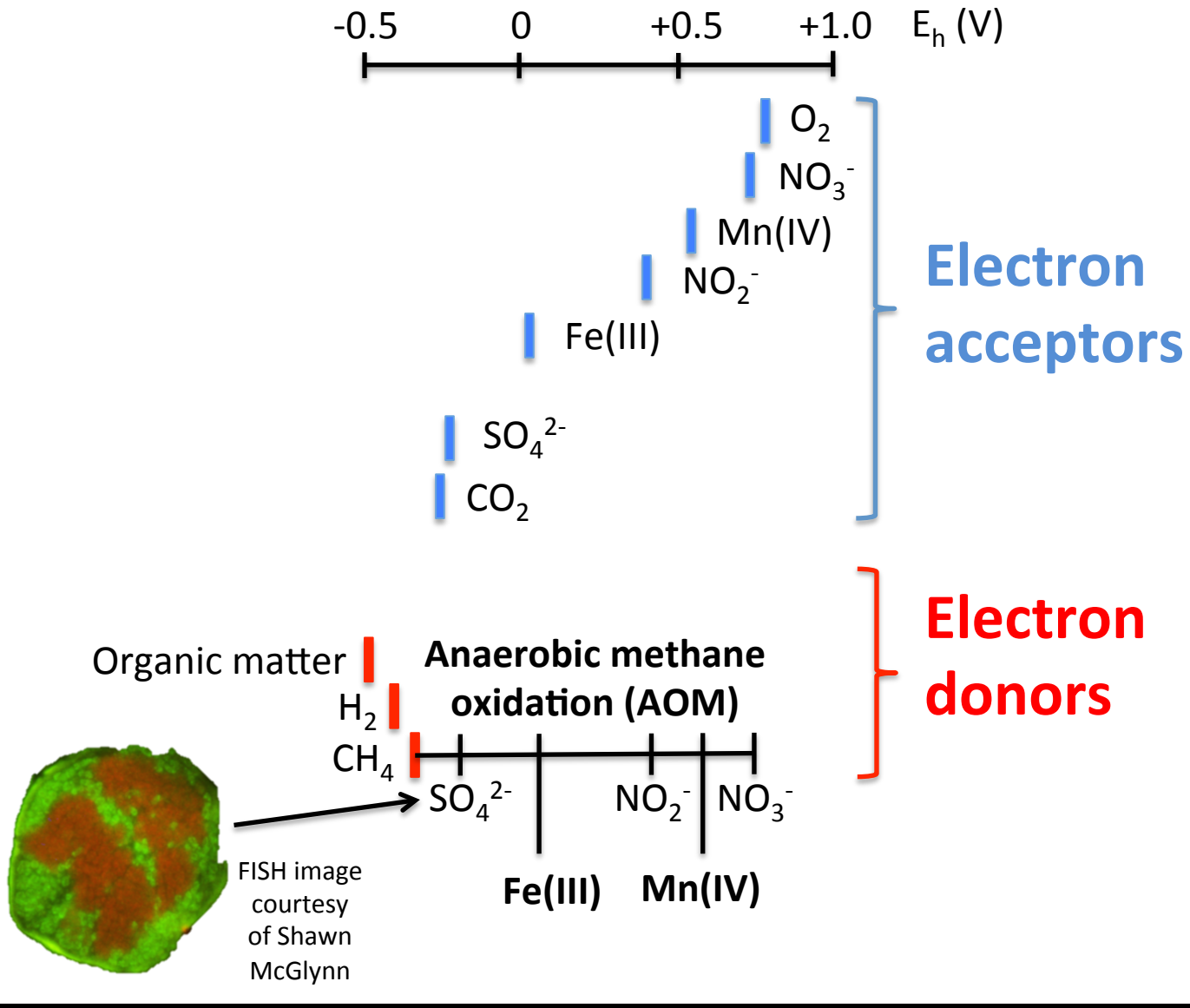


Microbiology of Anaerobic Methane Oxidation



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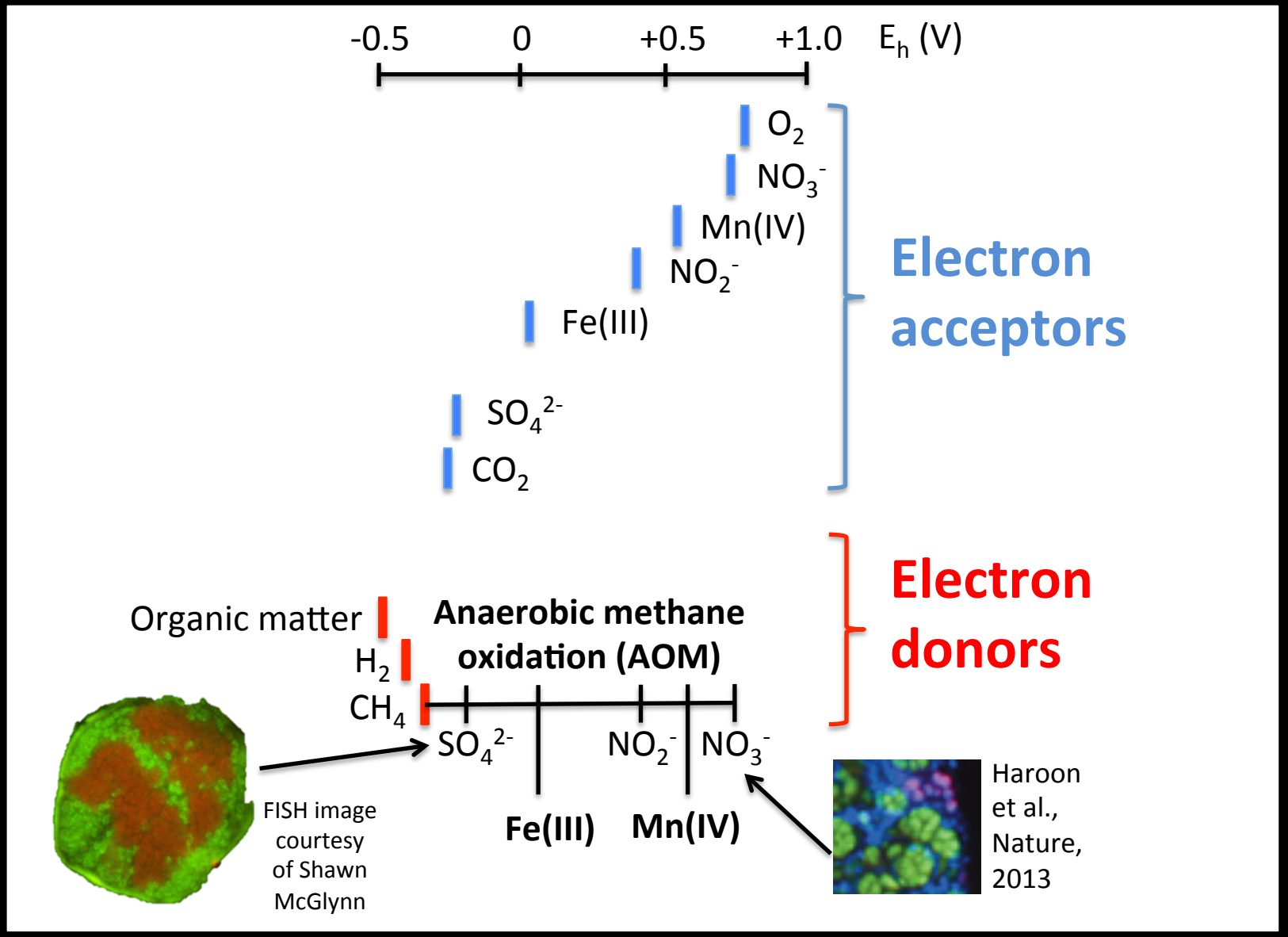
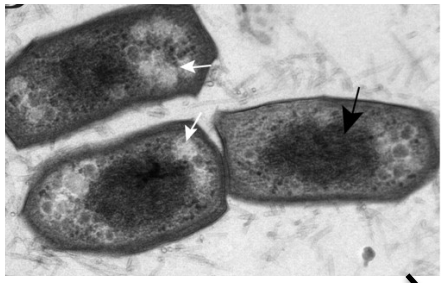


Microbiology of Anaerobic Methane Oxidation



Wu et al., 2012, J Bact

-0.5 0 +0.5 +1.0 E_h (V)

O_2

NO_3^-

Mn(IV)

NO_2^-

Fe(III)

SO_4^{2-}

CO_2

Electron acceptors

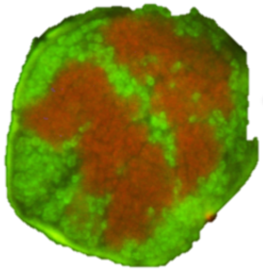
Organic matter

H_2

CH_4

Anaerobic methane oxidation (AOM)

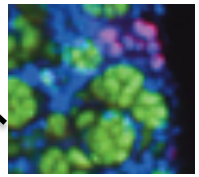
Electron donors



FISH image courtesy of Shawn McGlynn

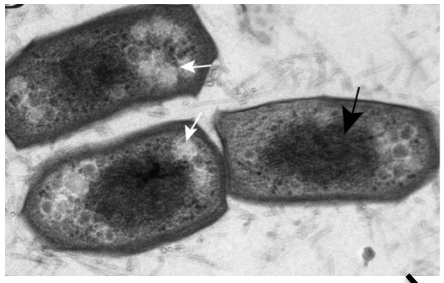
SO_4^{2-} NO_2^- NO_3^-

Fe(III) **Mn(IV)**



Haroon et al., Nature, 2013

Microbiology of Anaerobic Methane Oxidation



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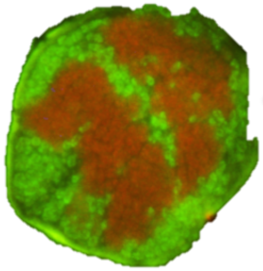

FISH image courtesy of Shawn McGlynn

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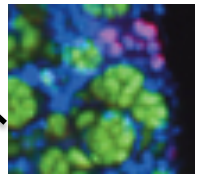
? **?**

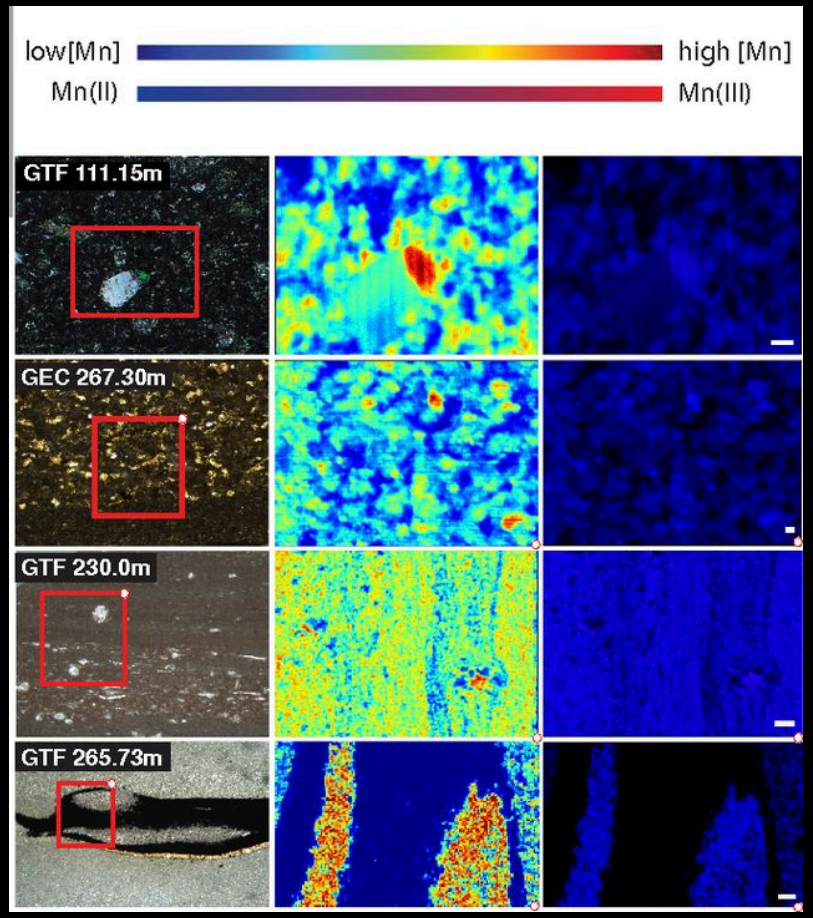


Haroon et al., Nature, 2013

Fe/Mn-AOM as an important metabolism in Archean?

Abundant substrates: Fe(III), Mn(III, IV) and CH_4

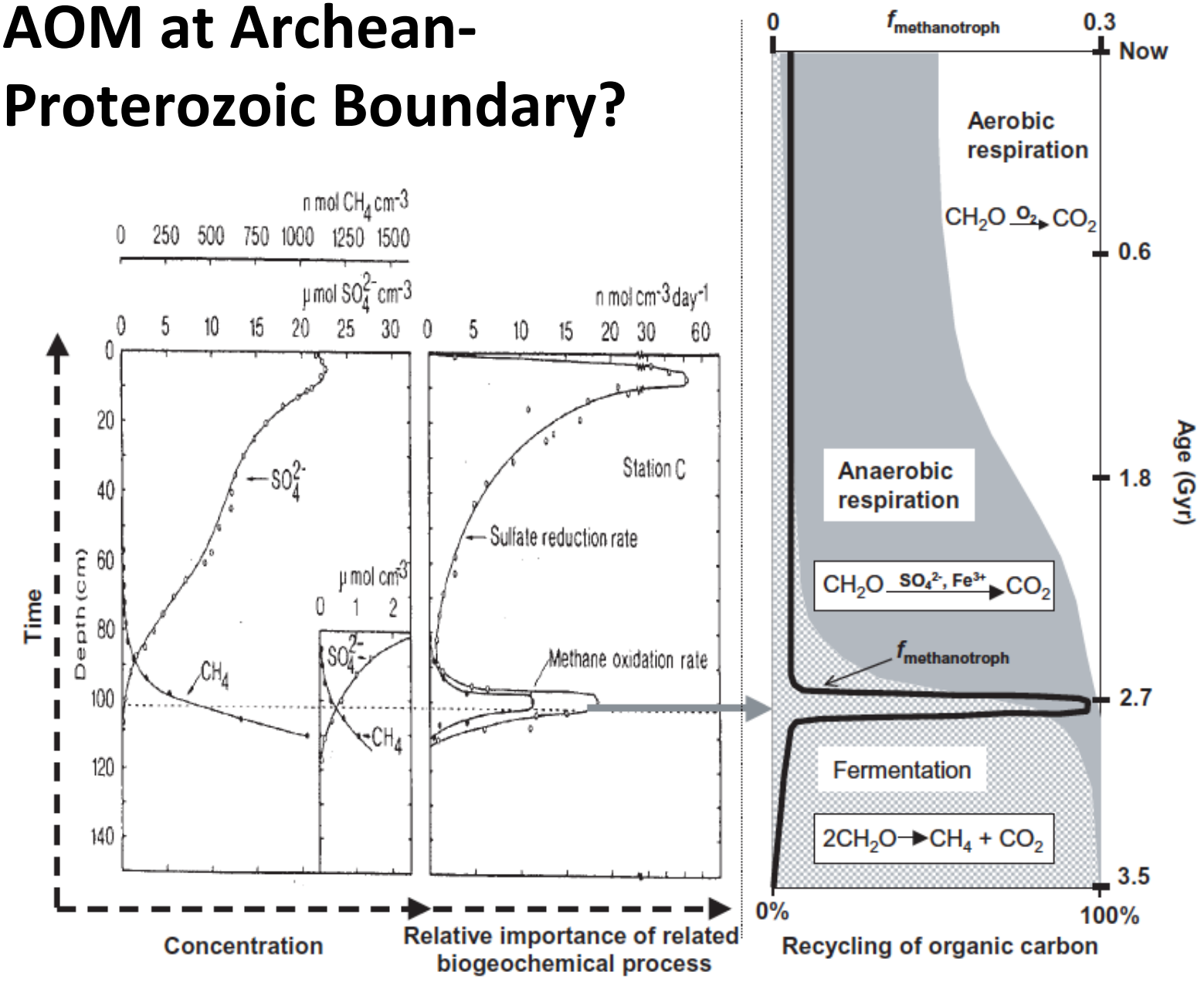
Banded Iron Formations, W. Australia



Mn

Johnson et al., PNAS, 2013

AOM at Archean-Proterozoic Boundary?



Hinrichs et al., 2002, Geochemistry, Geophysics, Geosystems

Fe/Mn-AOM in marine sediments

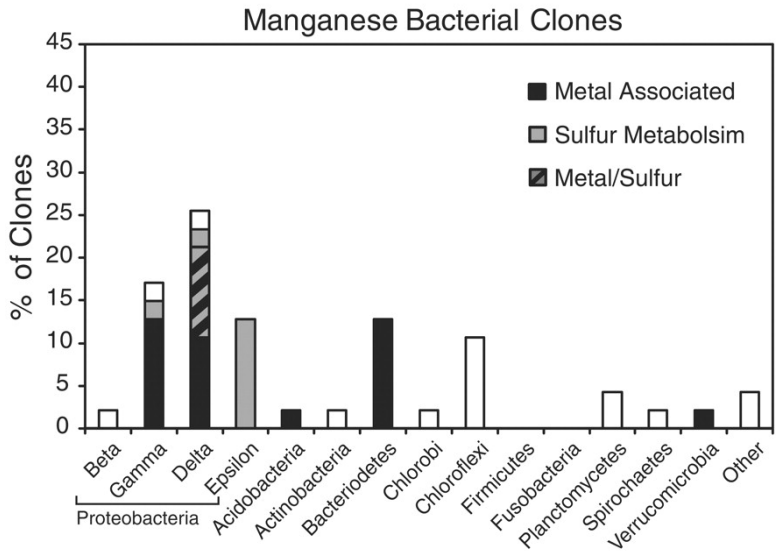
Manganese- and Iron-Dependent Marine Methane Oxidation

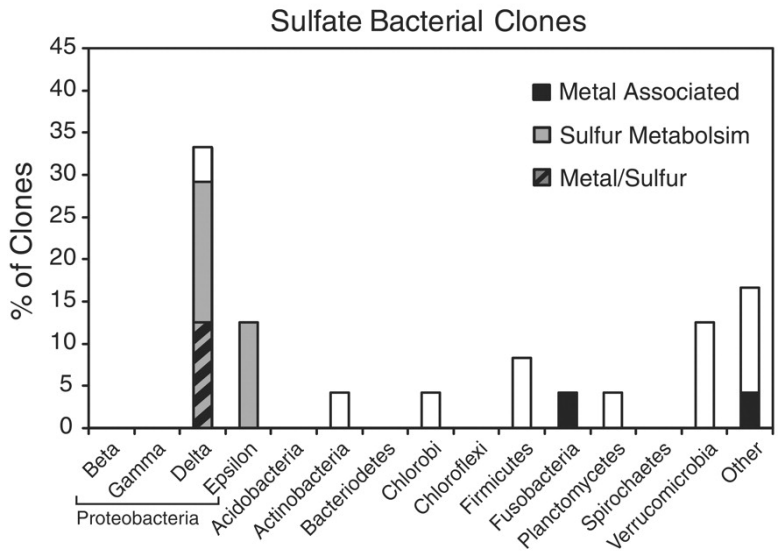
Science 2009

Emily J. Beal,[1*] Christopher H. House,[1*] Victoria J. Orphan[2]

Table 1. Rates and potential energy gain from AOM with different electron acceptors.

Reaction	Rate (μmole/year/cm$^3_{sed}$)	Potential energy gain (J/year/cm$^3_{sed}$)
$SO_4^{2-} + CH_4 \rightarrow HCO_3^- + HS^- + H_2O$	52	0.7
$CH_4 + 4MnO_2 + 7H^+ \rightarrow HCO_3^- + 4Mn^{2+} + 5H_2O$	14	7.8
$CH_4 + 8\ Fe(OH)_3 + 15H^+ \rightarrow HCO_3^- + 8Fe^{2+} + 21H_2O$	6	1.6





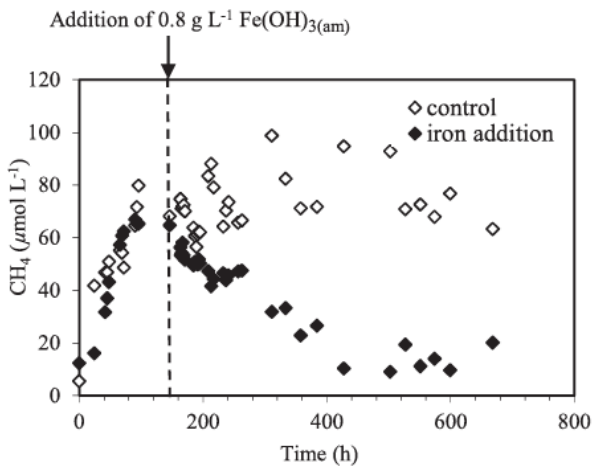
Fe-AOM in lake sediments

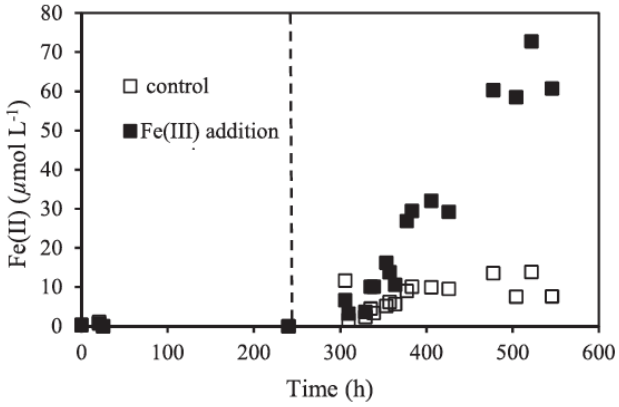
Limnol. Oceanogr., 56(4), 2011, 1536–1544

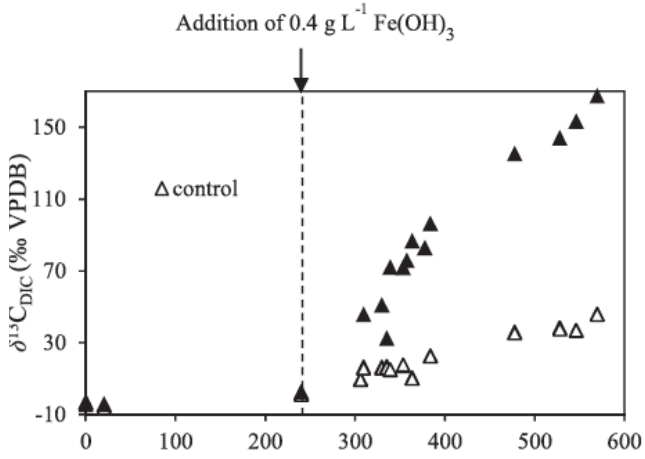
doi:10.4319/lo.2011.56.4.1536

Geochemical evidence for iron-mediated anaerobic oxidation of methane

Orit Sivan,[a,*] Michal Adler,[a] Ann Pearson,[b] Faina Gelman,[c] Itay Bar-Or,[a] Seth G. John,[d] and Werner Eckert[e]







Fe-AOM in oil-contaminated aquifer and subsurface marine sediments

Geobiology (2012), **10**, 506–517 DOI: 10.1111/j.1472-4669.2012.00341

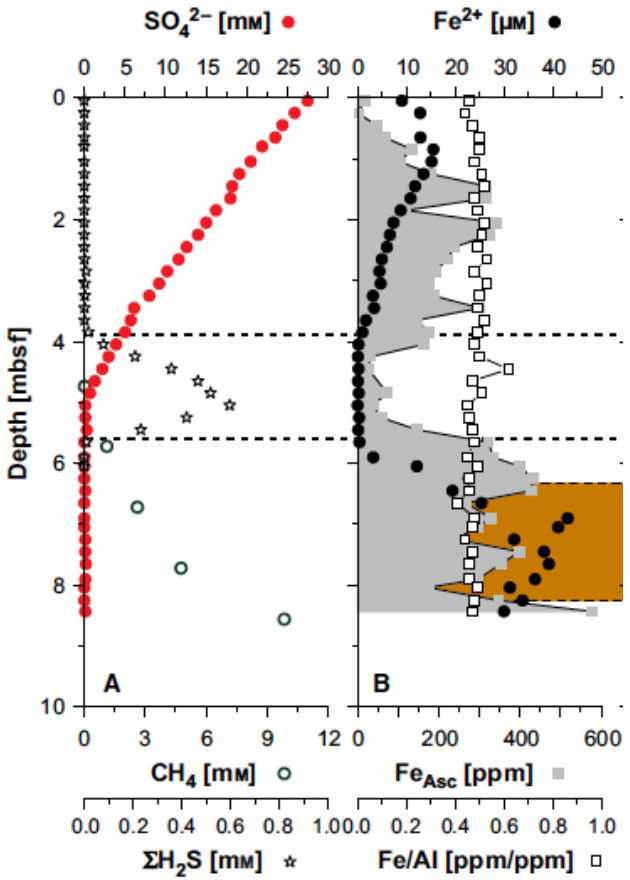
Evidence for iron-mediated anaerobic methane oxidation in a crude oil-contaminated aquifer

R. T. AMOS,[1] B. A. BEKINS,[2] I. M. COZZARELLI,[3] M. A. VOYTEK,[4] J. D. KIRSHTEIN,[4] E. J. P. JONES[4] AND D. W. BLOWES[1]

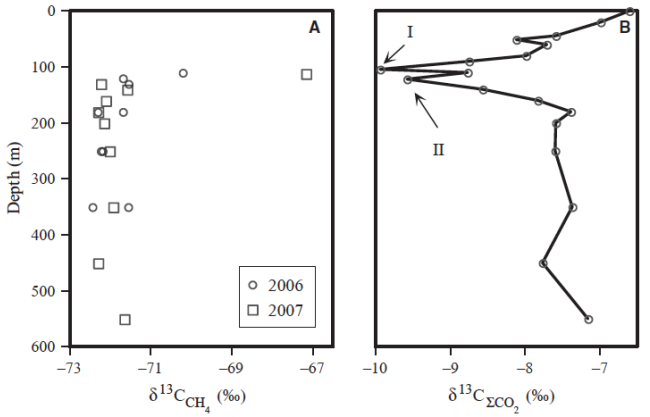
Geobiology (2014), **12**, 172–181 DOI: 10.1111/gbi.12077

An inorganic geochemical argument for coupled anaerobic oxidation of methane and iron reduction in marine sediments

N. RIEDINGER,[1] M. J. FORMOLO,[2] T. W. LYONS,[1] S. HENKEL,[3,*] A. BECK[4] AND S. KASTEN[3,5]



Archean Ocean Analogue: Lake Matano, Indonesia



Crowe et al., 2011, Geobiology

Crowe et al., 2008, PNAS

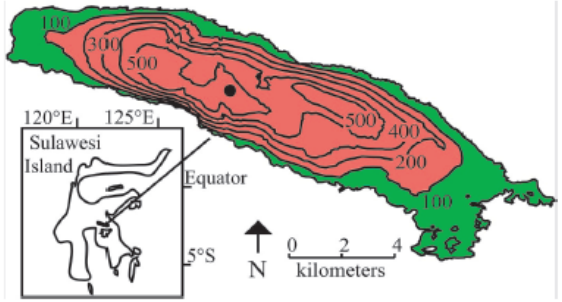


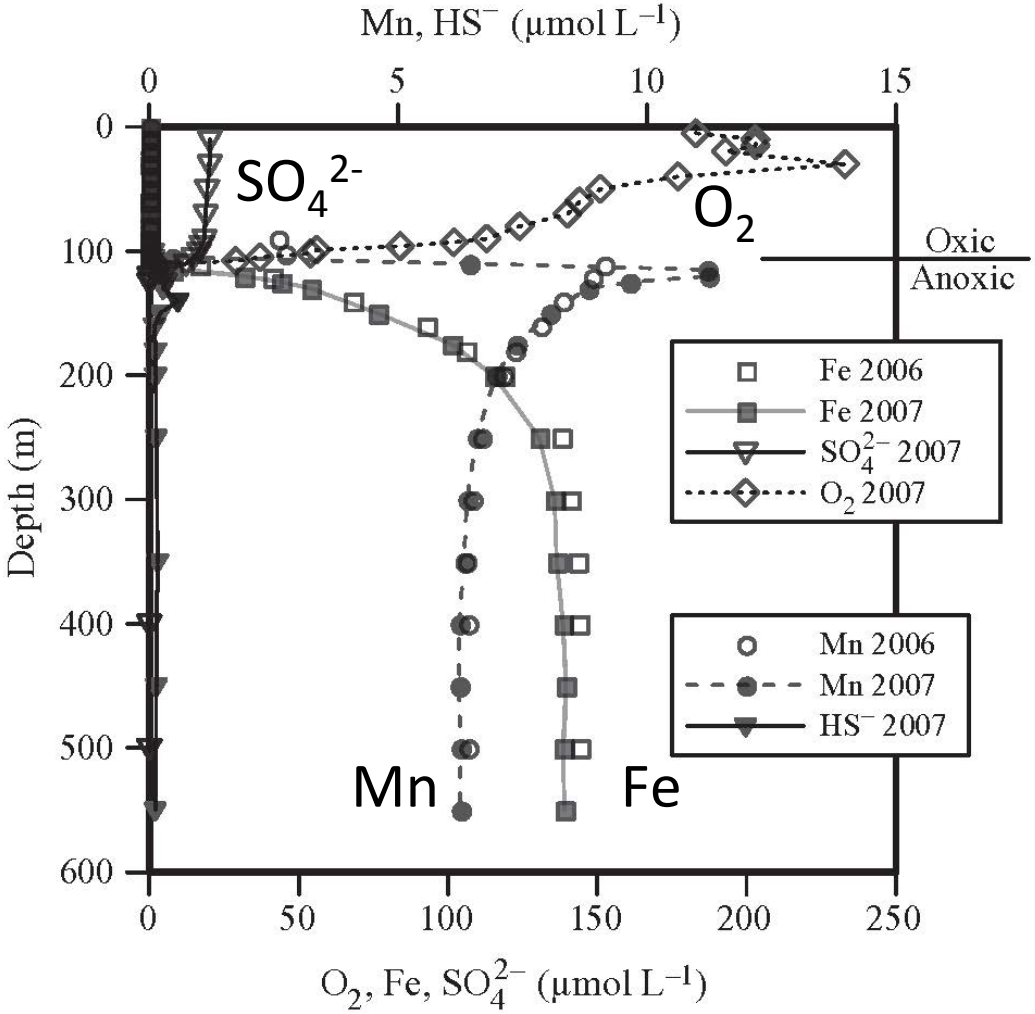
Fig. 1. Map showing the location of Lake Matano on Sulawesi Island, Indonesia (*Inset*), and bathymetric map of Lake Matano. The circle marks a central deep water master station, and the area shaded in red is underlain by anoxic water.

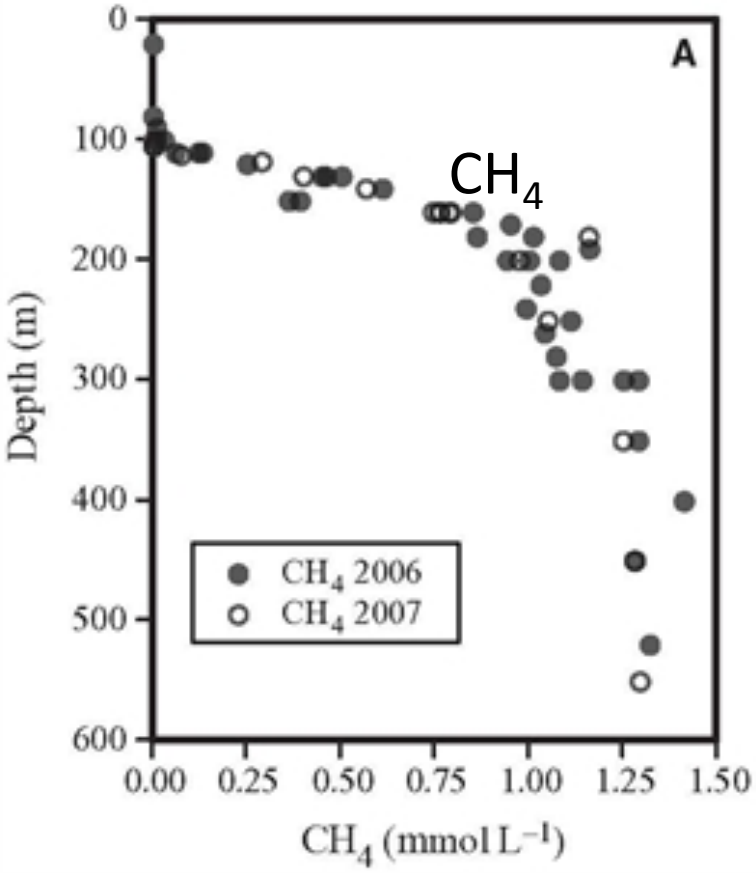
Table 1. Comparing Lake Matano with the Archean Ocean

	Lake Matano		Archean Ocean
Surface mixed layer	100 m		>200 m (13)
	Mixed layer	Anoxic layer	
Fe(II)		140 μmol·liter^{-1}	40–120 μmol·liter^{-1} (1)
O_2	Saturated	<1 μmol·liter^{-1}	<0.08% PAL* (1)
SO_4^{2-}	<20 μmol·liter^{-1}	<0.1 μmol·liter^{-1}	<200 μmol·liter^{-1} (32)
PO_4^{3-}	<0.025 μmol·liter^{-1} (25)	9 μmol·liter^{-1}(25)	0.03–0.29 μmol·liter^{-1} (28)
$SiO_{2(aq)}$	300 μmol·liter^{-1} (25)	420 μmol·liter^{-1} (25)	670–2200 μmol·liter^{-1} (7)
pH	8.6 (25)	7.00 (25)	>6.5 (28, 50)
Euphotic zone	<130 m		<150 m (13)
Ionic strength	300 mmol·liter^{-1} (25)	4.6 mmol·liter^{-1} (25)	?
T	25–28°C (25)		≈40°C (7)

*PAL, present atmospheric levels.

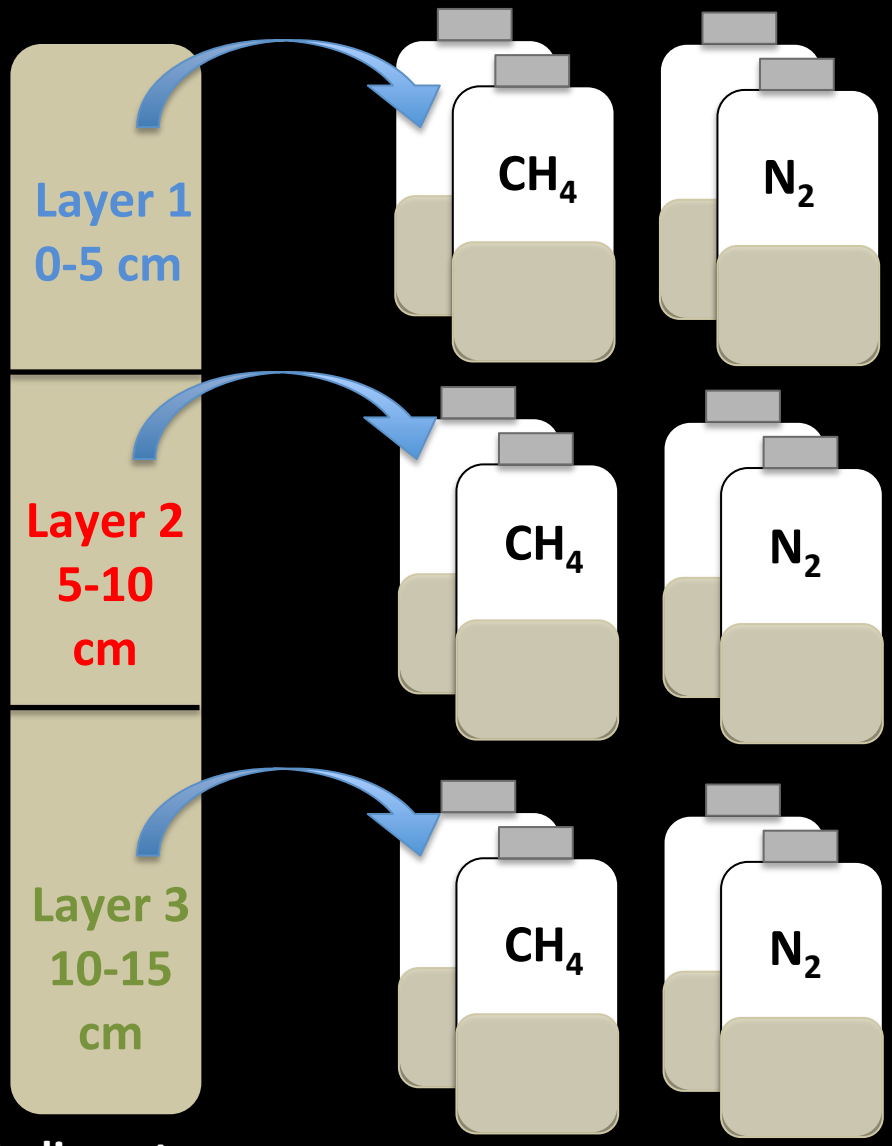
Lake Matano water column depth profiles





Crowe et al., 2011, Geobiology

Enrichments from Lake Matano sediments



Artificial freshwater medium

Lacking nitrate/sulfate

Metal substrate

Fe(III): goethite (10 mM)

Mn(IV): birnessite (10 mM)

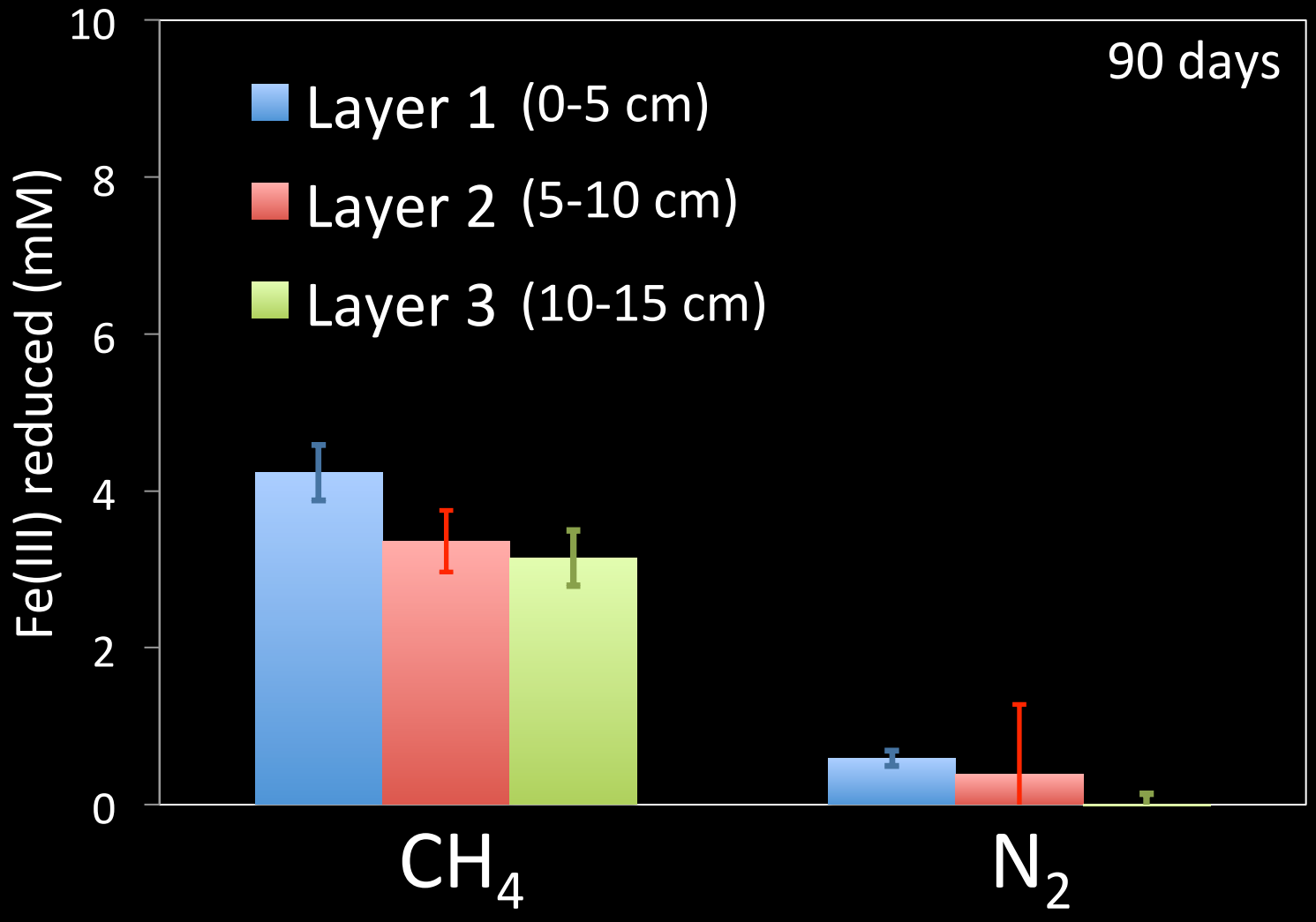
Measured

Ferrozine for Fe(II)

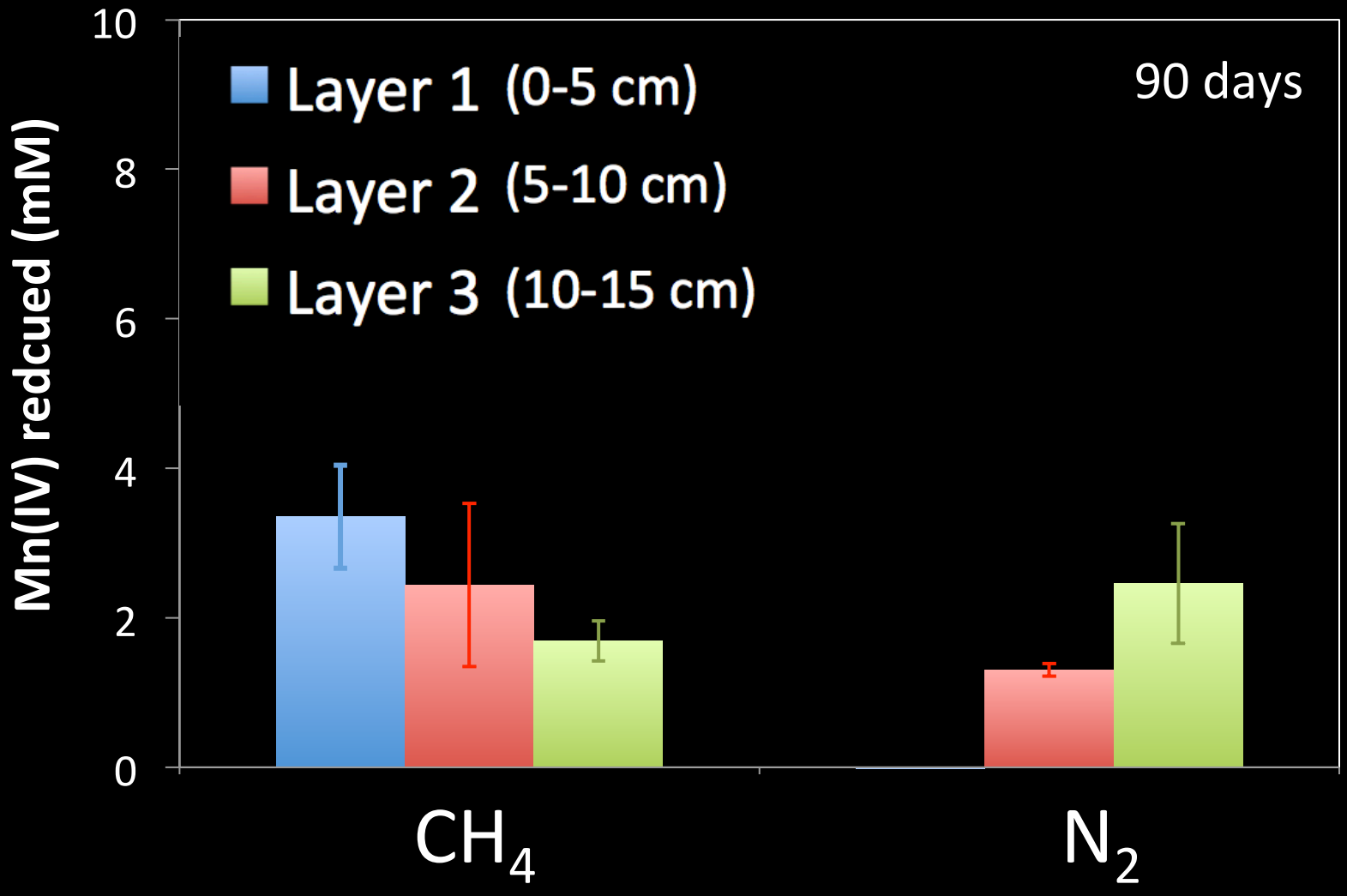
DNA for 16S amplicon

MiSeq sequencing

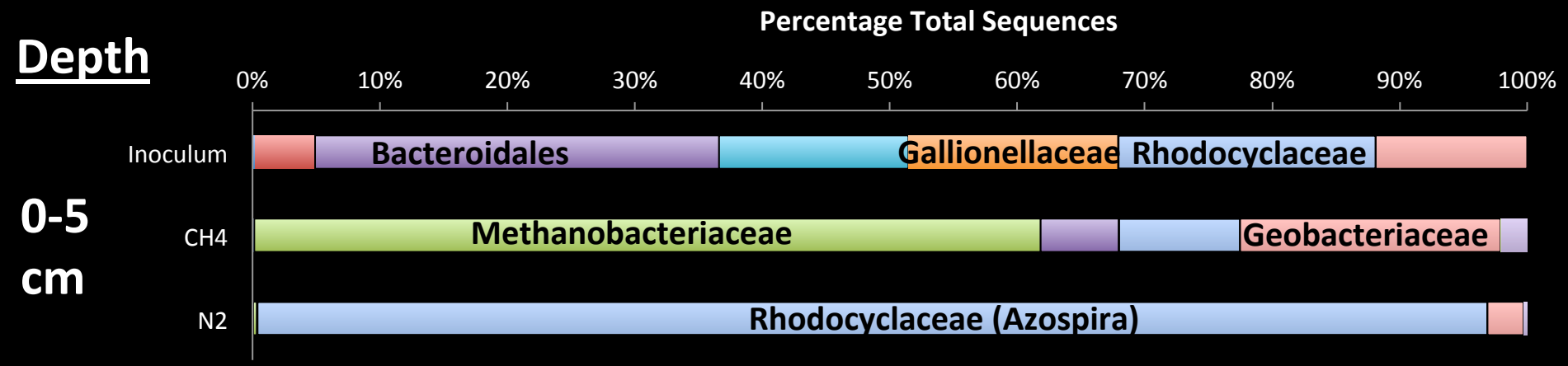
Methane stimulated Fe(III) reduction in all layers



Methane stimulated Mn(IV) reduction in surface layers



Microbial taxonomy in Fe(III) enrichments



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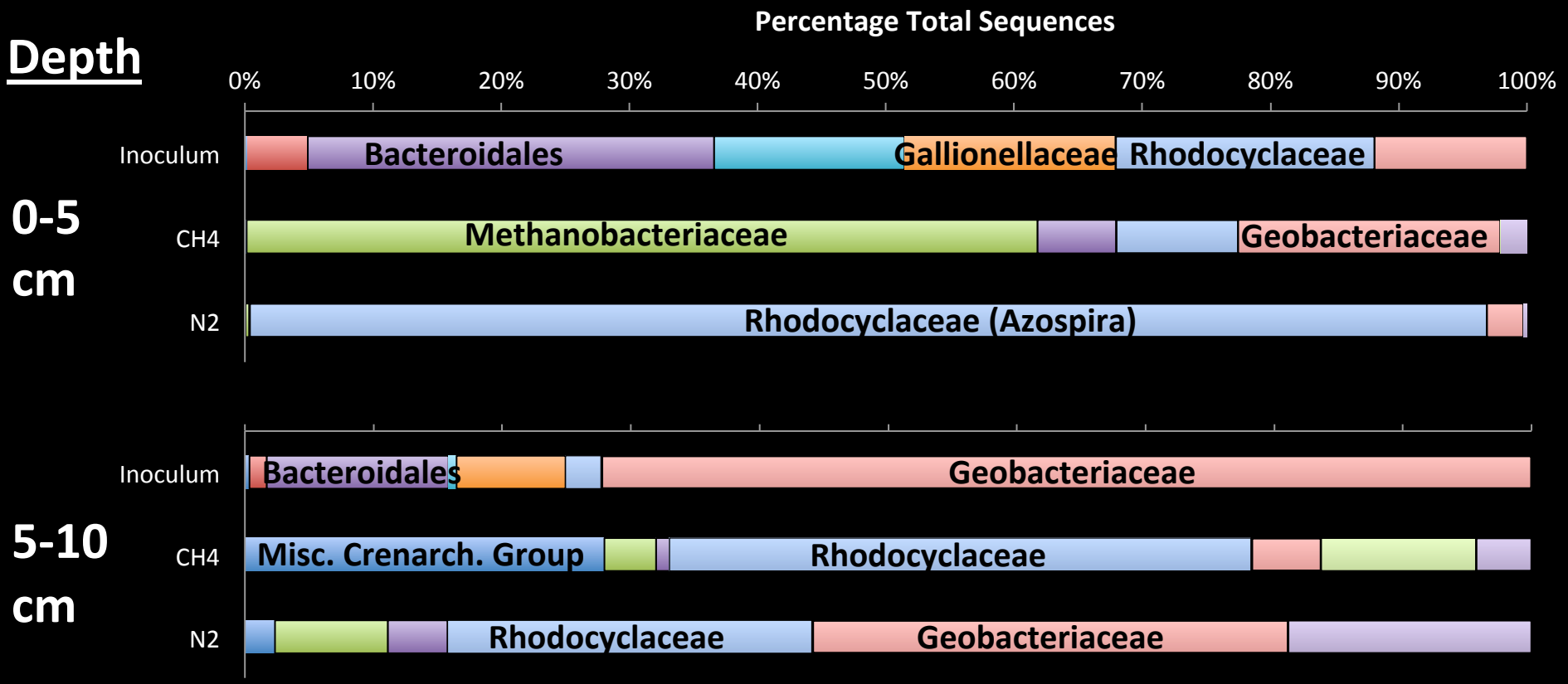

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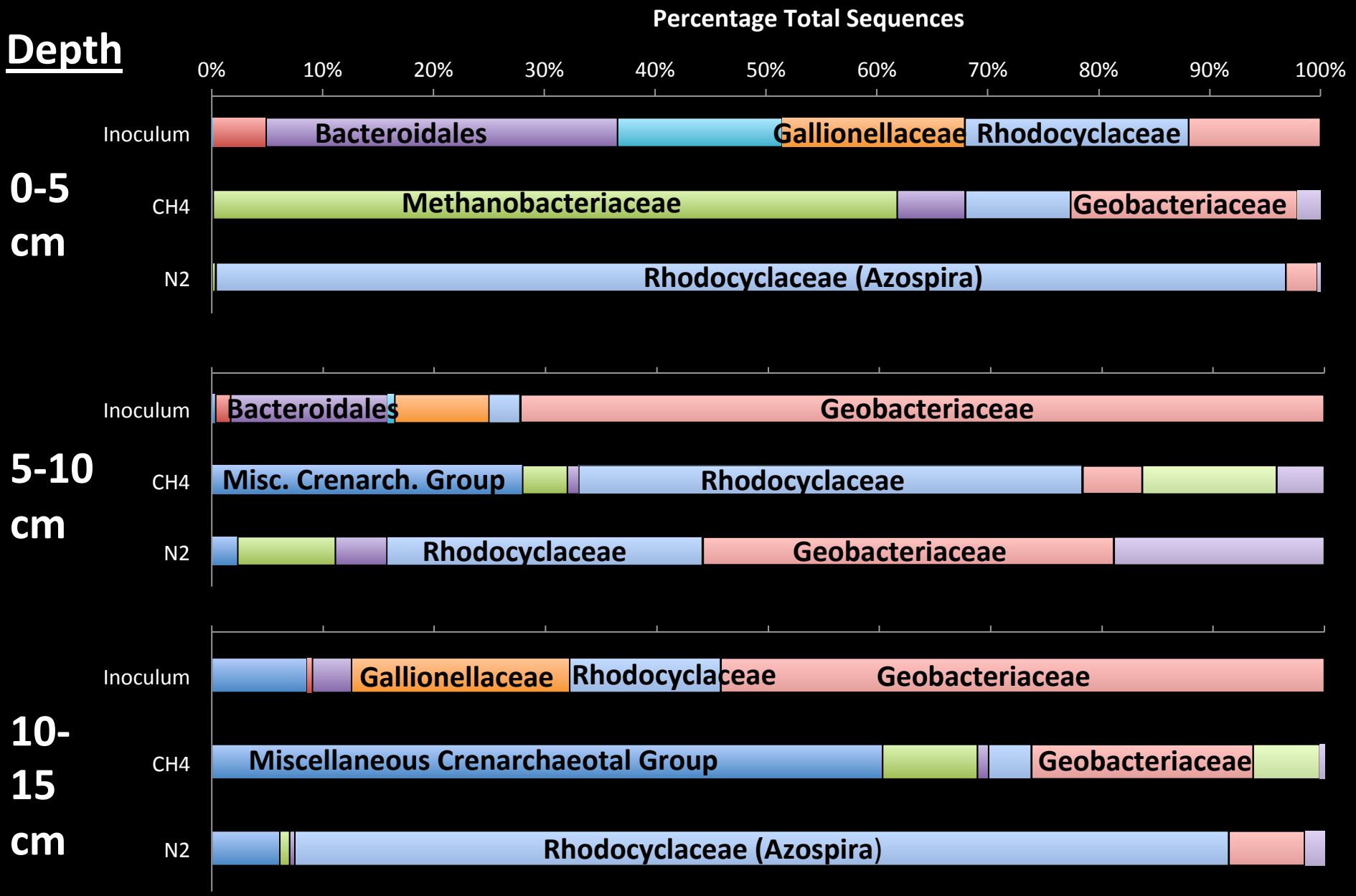
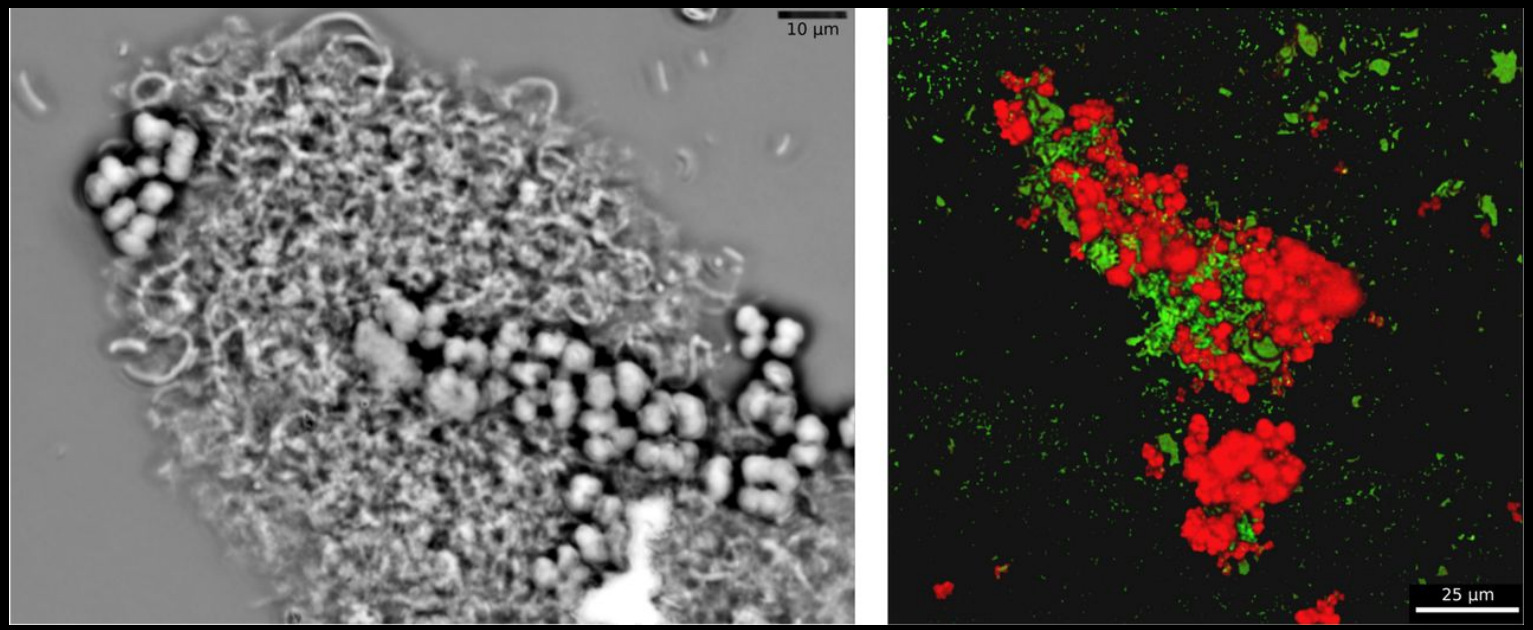


Possible players in methane-metal interactions

- Diverse methanogens reduce Fe(III) (Bond & Lovley, 2002)
- *Geobacter*-methanogen interaction?

Geobacter metallireducens
Methanosarcina barkeri

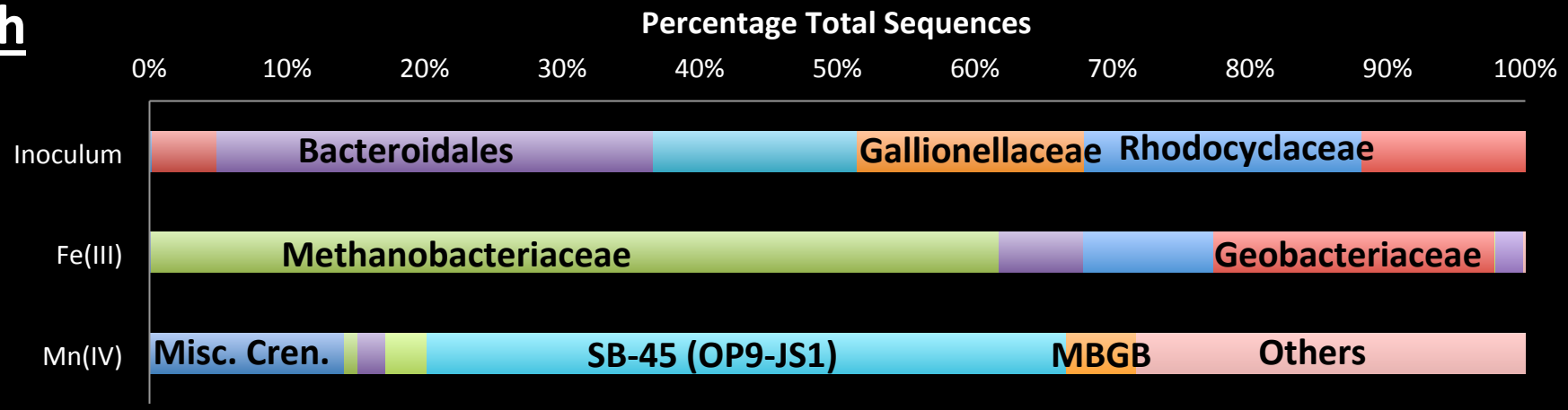


Rotaru et al., 2014, AEM

Comparison between Fe(III) and Mn(IV) enrichments

Depth

0-5 cm +CH_4



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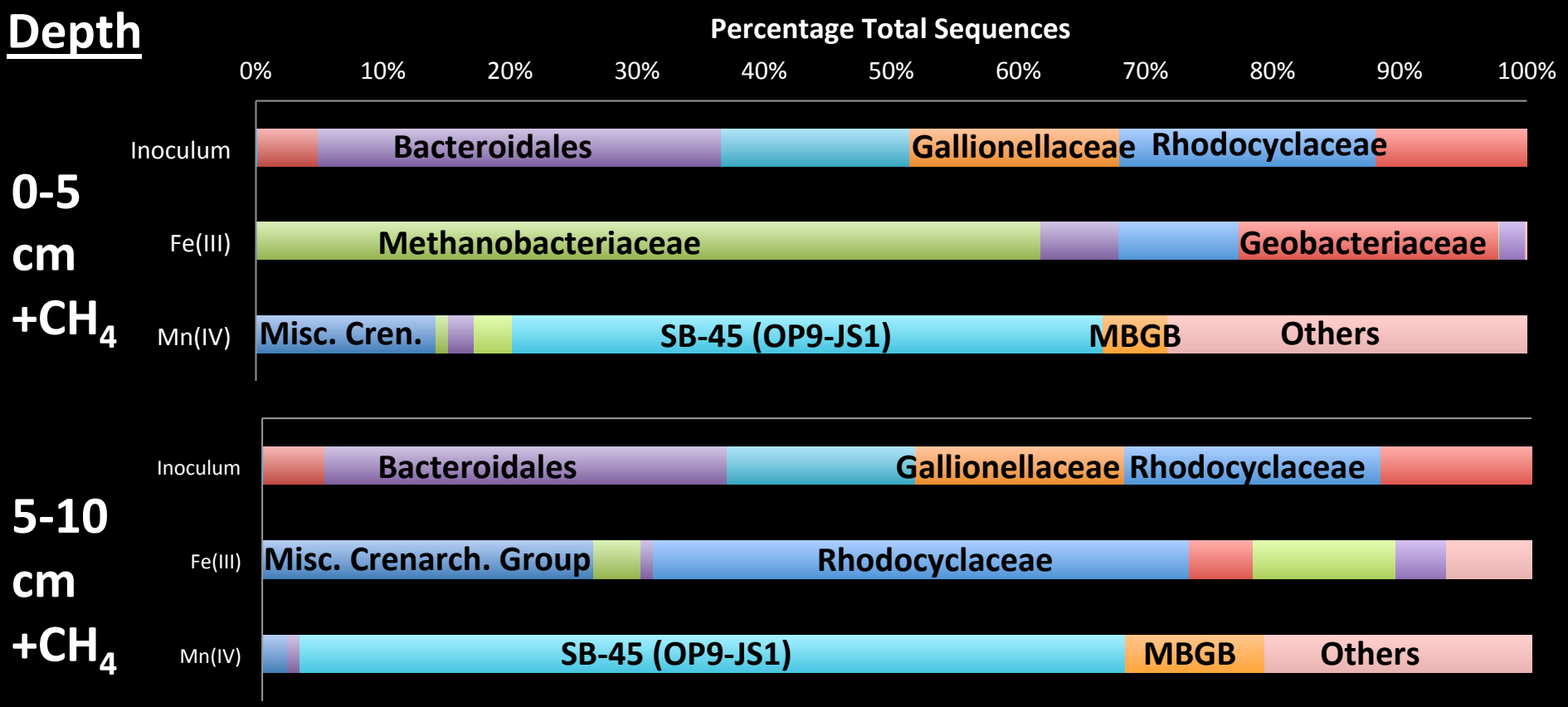

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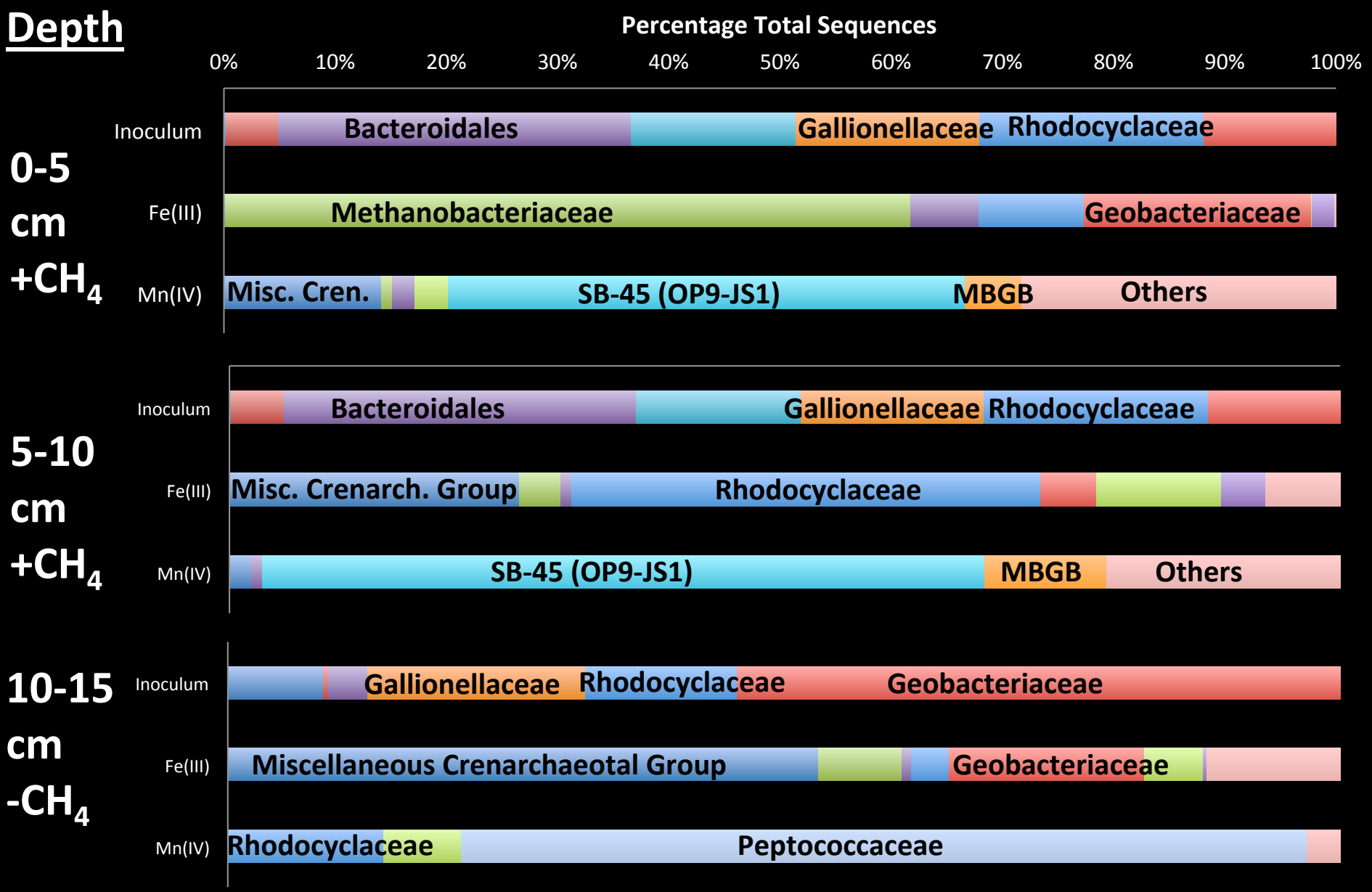

Initial Findings

- Methane stimulated Fe(III) reduction in all sediment layers of Lake Matano sediment

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- Methane stimulated Mn(VI) reduction in surface layers of Lake Matano sediment

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- Miscellaneous Crenarchaeotal Group, Methanobactericeae, Geobacteriaceae and Rhodocyclaceae enriched in Fe(III) + CH_4 incubations
vs. primarily Rhodocyclaceae in Fe(III) - CH_4 incubations

Initial Findings

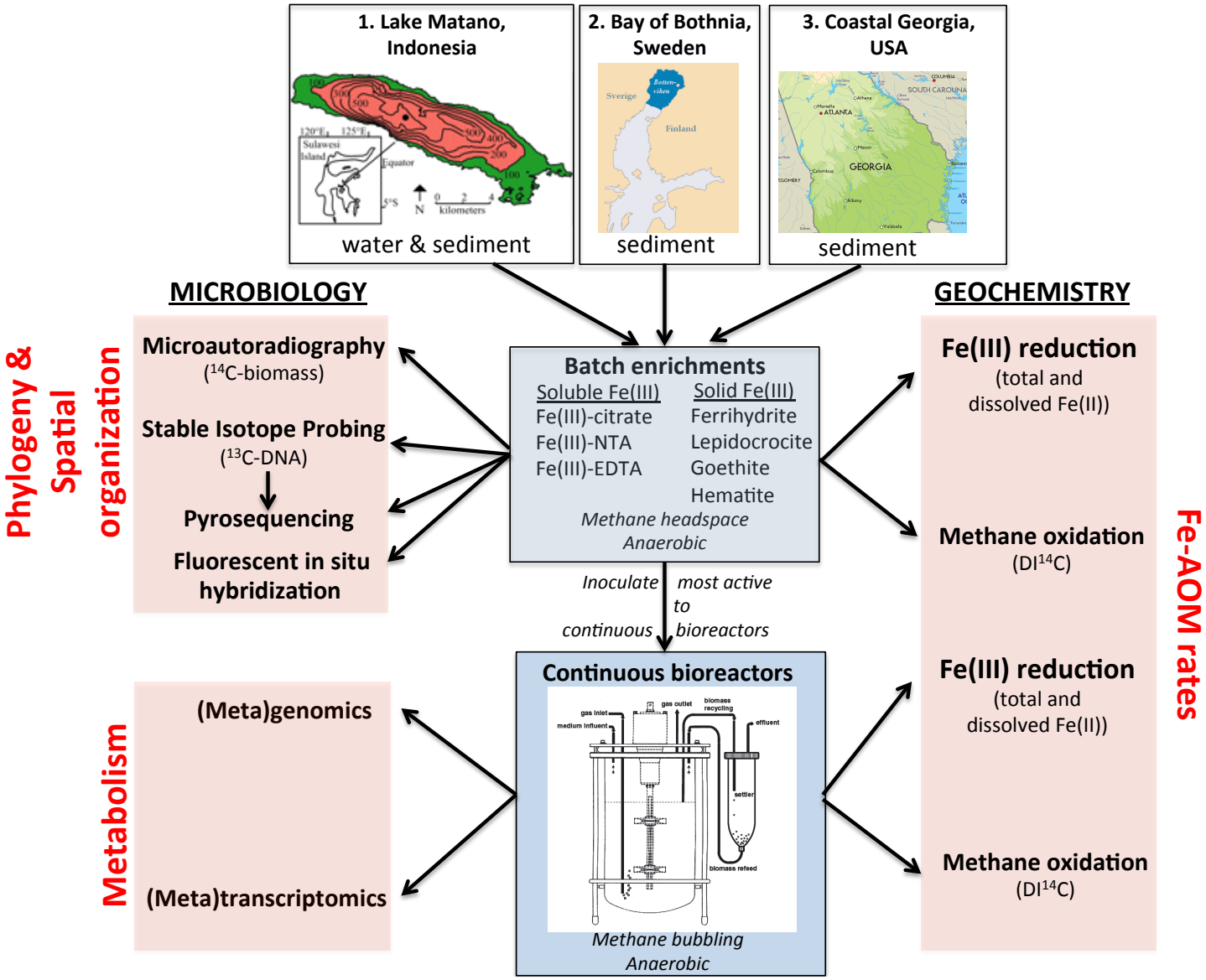
- Methane stimulated Fe(III) reduction in all layers of Lake Matano sediment

- Methane stimulated Mn(VI) reduction in surface layers of Lake Matano sediment

- Miscellaneous Crenarchaeotal Group, Methanobactericeae, Geobacteriaceae and Rhodocyclaceae enriched in Fe(III) + CH_4 incubations
vs. primarily Rhodocyclaceae in Fe(III) - CH_4 incubations

- OP9 subclade SB-45 enriched in Mn(IV) + CH_4 incubations
vs. Peptococcaceae in Mn(IV) - CH_4 incubations

Next Steps


1. Lake Matano, Indonesia
water & sediment
2. Bay of Bothnia, Sweden
sediment
3. Coastal Georgia, USA
sediment
MICROBIOLOGY
GEOCHEMISTRY
Phylogeny & Spatial organization
Microautoradiography
(14C-biomass)
Stable Isotope Probing
(13C-DNA)
Pyrosequencing
Fluorescent in situ hybridization
Batch enrichments
Soluble Fe(III)
Fe(III)-citrate
Fe(III)-NTA
Fe(III)-EDTA
Solid Fe(III)
Ferrihydrite
Lepidocrocite
Goethite
Hematite
Methane headspace
Anaerobic
Fe(III) reduction
(total and dissolved Fe(II))
Methane oxidation
(DI14C)
Inoculate
most active
to
continuous
bioreactors
Continuous bioreactors
gas inlet
medium influent
gas outlet
biomass recycling
effluent
settler
biomass refeed
Methane bubbling
Anaerobic
Fe(III) reduction
(total and dissolved Fe(II))
Methane oxidation
(DI14C)
Metabolism
(Meta)genomics
(Meta)transcriptomics
Fe-AOM rates

A big thanks to….

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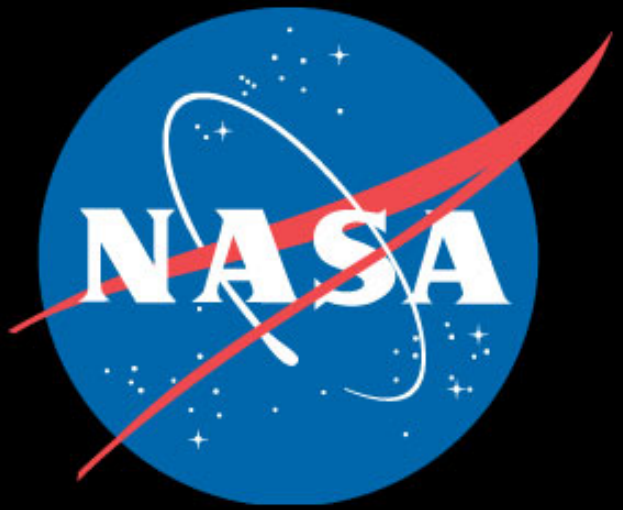
Marcus Bray
Cecilia Kretz

DiChristina Lab
Tom DiChristina
Ben Reed

Stewart Lab
Frank Stewart
Neha Sarode

University of Kansas
David Fowle

U British Columbia
Sean Crowe
CarriAyne Jones
Steven Hallam



Exobiology Grant
NNX14AJ87G

…and you all for listening today!!