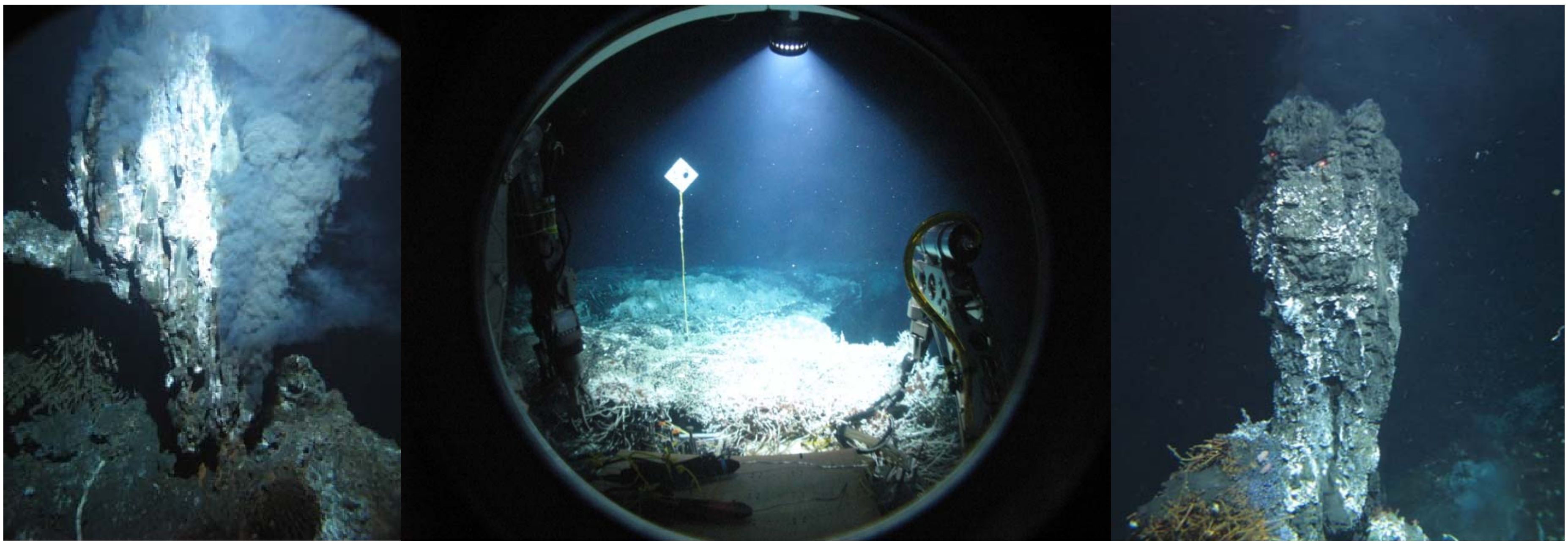
Life on the edge: Modeling thermophile habitability in deep-sea hydrothermal vents



James F. Holden
Department of Microbiology
University of Massachusetts Amherst

Acknowledgments

Holden Lab:

Helene Ver Eecke
Lucy Stewart
Jennifer Lin
Samantha Zelin
Dima Tokar
Sabrina Parise
Jacqueline Knutson
Molly Williams

Collaborators:

David Butterfield (Univ. of Washington/NOAA)
Marvin Lilley (Univ. of Washington)
Julie Huber (Marine Biological Laboratory)
Darby Dyar (Mount Holyoke College)
John Jamieson (Univ. of Ottawa)
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Pilots and crew of DSV *Alvin* and R/V *Atlantis*

Biological Oceanography
RIDGE 2000 Program

Pacific Marine Environmental Laboratory
NOAA Vents Program

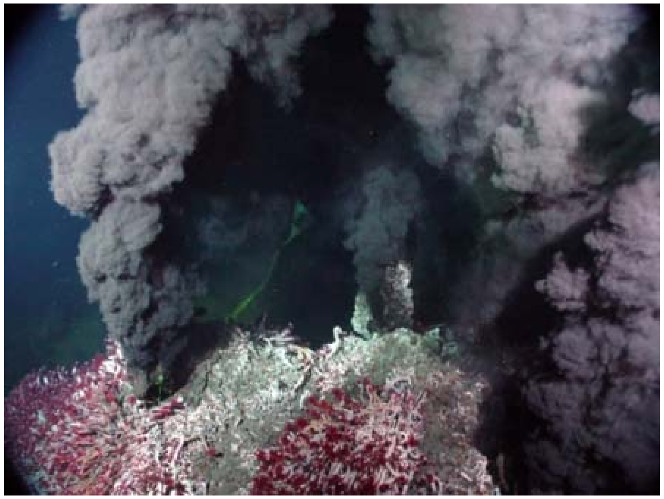
NASA Earth and Space Science
Graduate Fellowship (NESSF)

Strategy for assessing habitability and biogeochemical impact

Astrobiology mantra:

1. Follow the water
2. Follow the energy
3. Follow the nutrients

**Also true for understanding past and present life in terrestrial environments



How is this actually done?

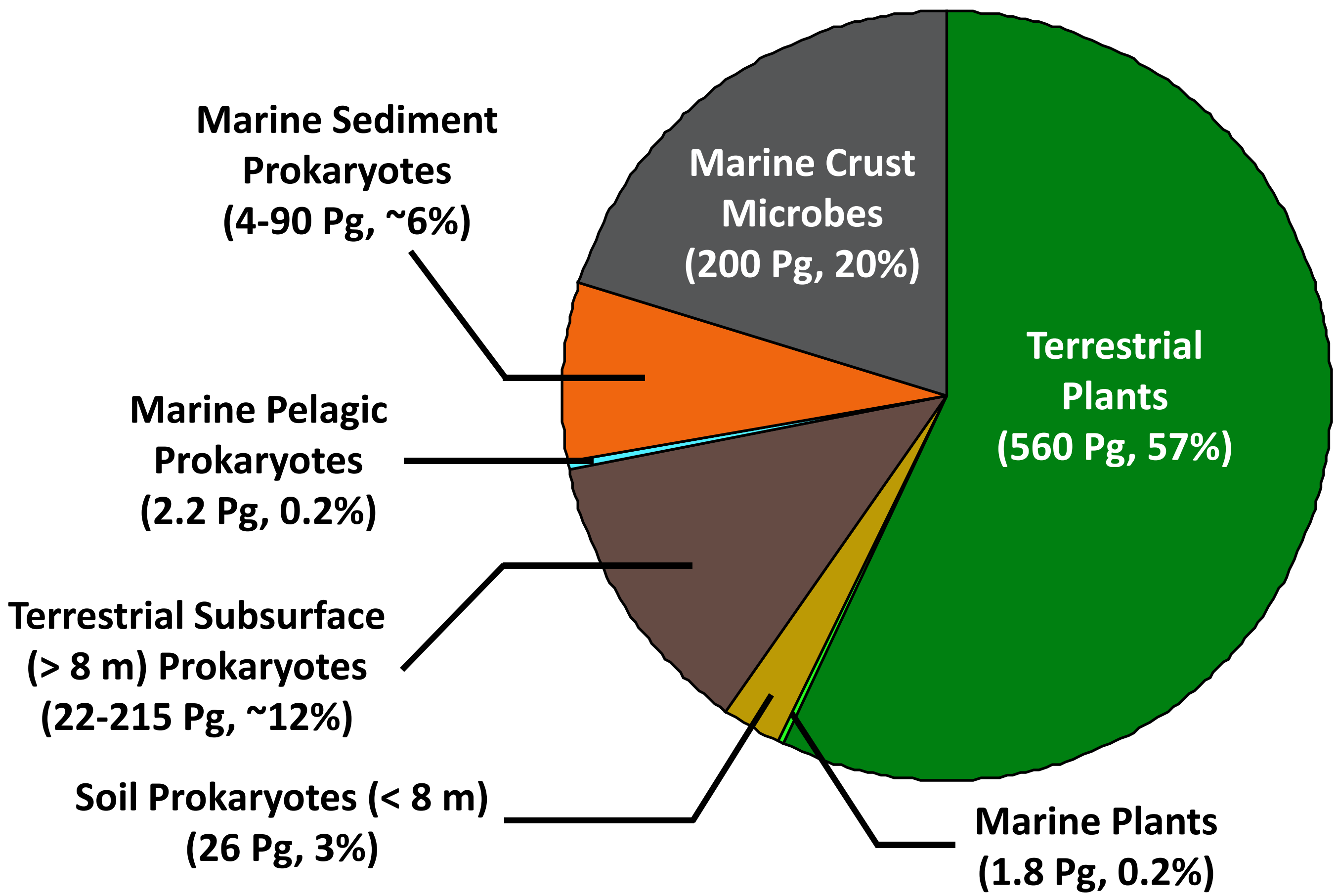
Environmental Conditions → Microbial Phenomena → Biomarker

- physical and chemical constraints on life
- rates of biogeochemical transformations
- microbial bioenergetics
- microbe-mineral interactions
- population structure and dynamics
- functional diversity

- mineral, organic and isotopic biosignatures
- differentiate biotic and abiotic markers
- depositional characteristics of markers
- effect of material properties on mineral bioalteration

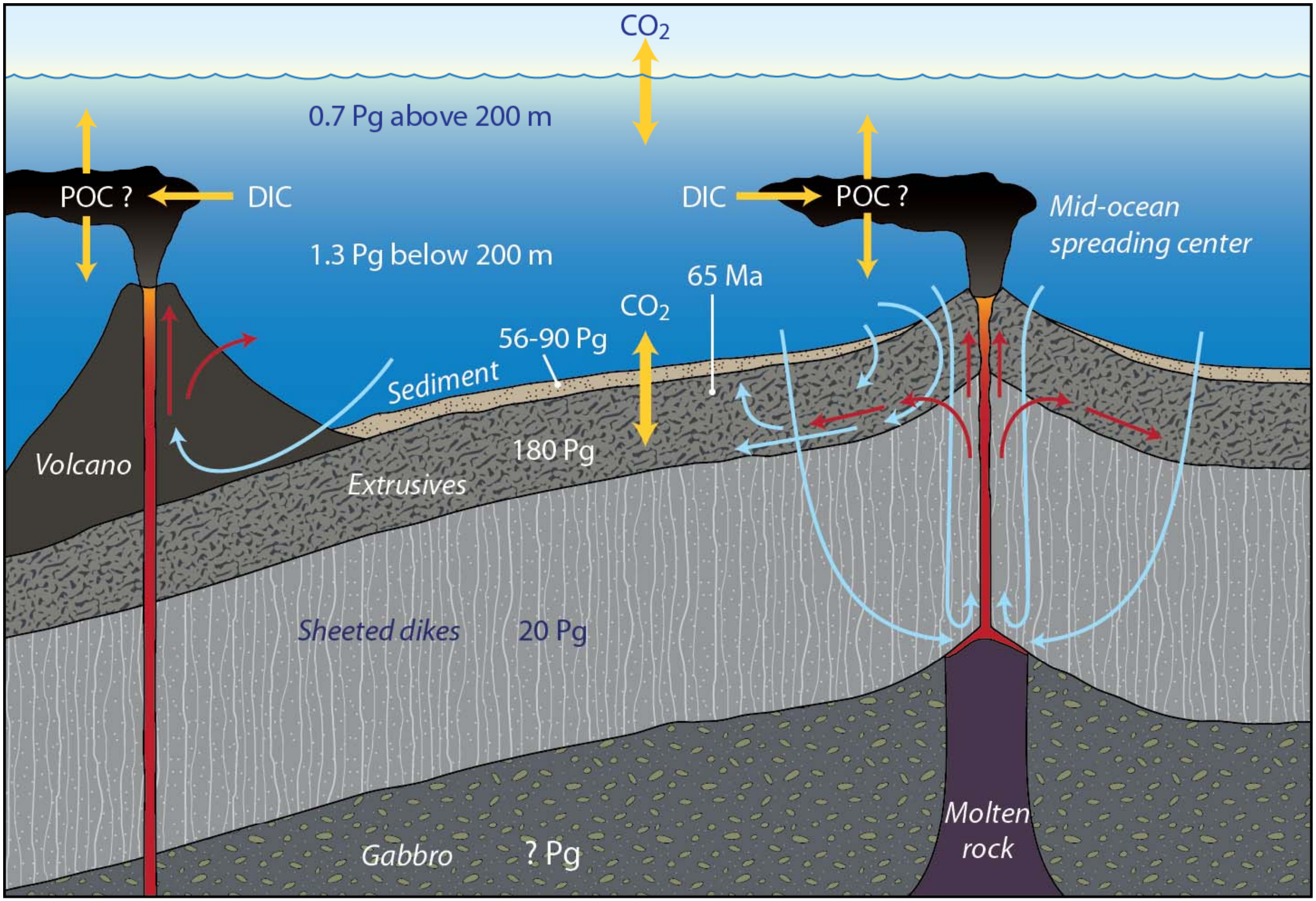
Global plant and prokaryotic biomass

Total global carbon is estimated to be 965 Pg (or 965 × 10^{15} g)



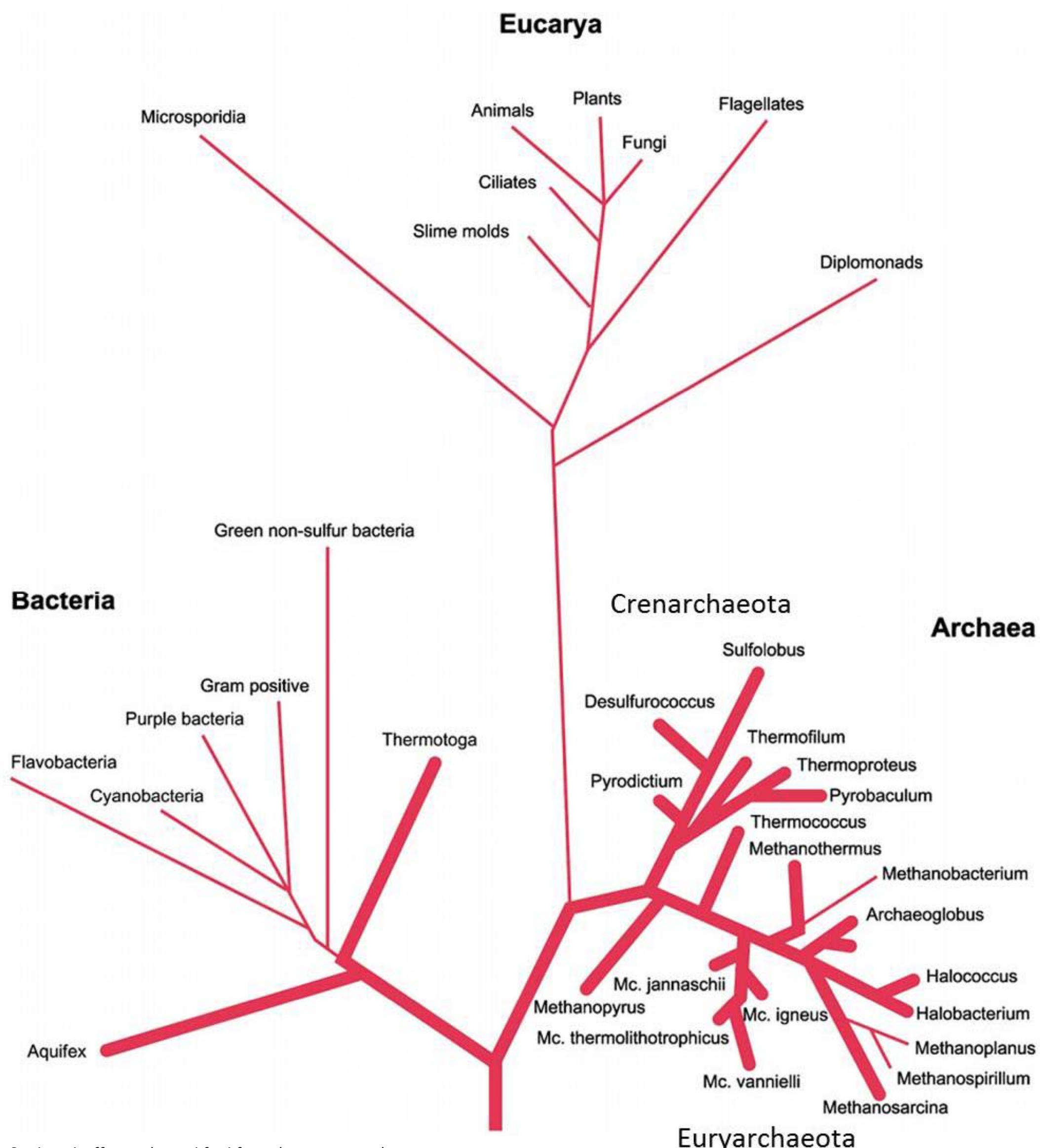
From Whitman et al. (1998), Parkes et al. (1994), Lipp et al. (2008), Heberling et al. (2010), Kallmeyer et al. (2012)

Life in the ocean crust

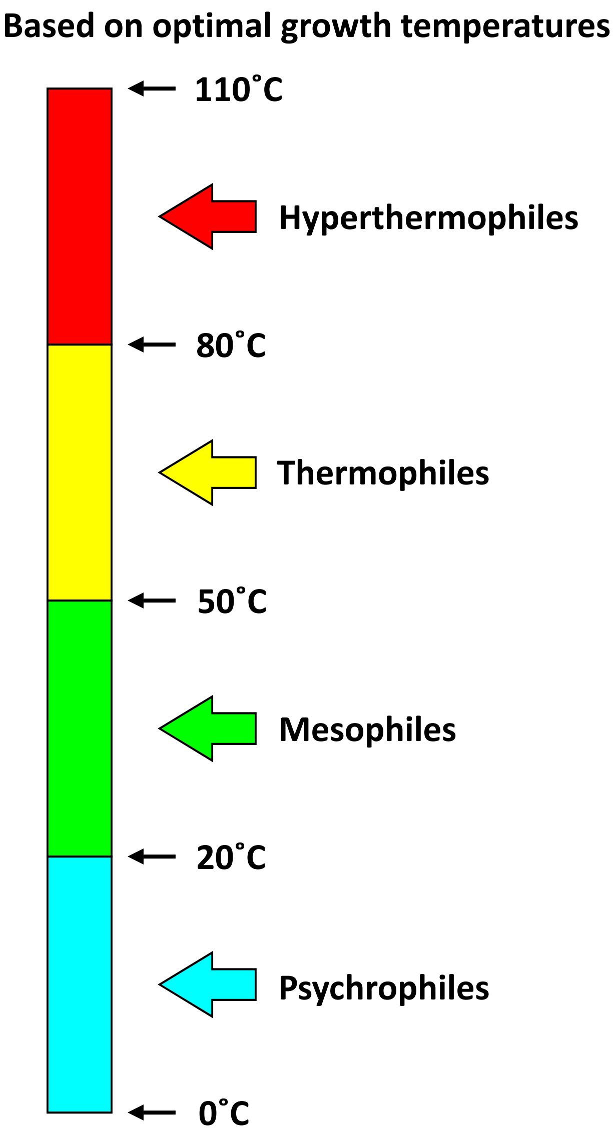


Holden et al. (2012)

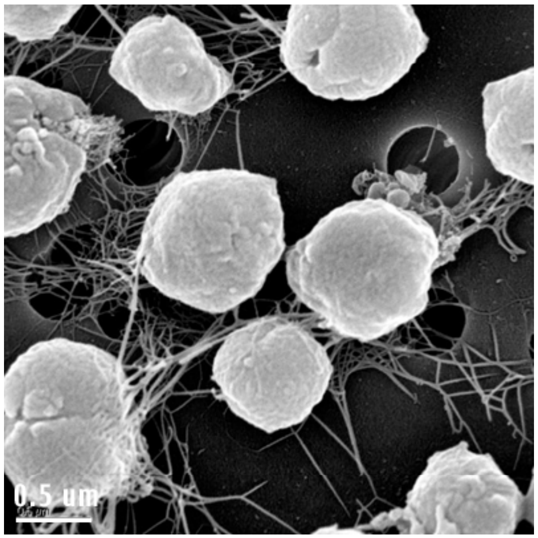
Hyperthermophile background



(Xu & Glansdorff, 2002), modified from (Stetter, 1996)



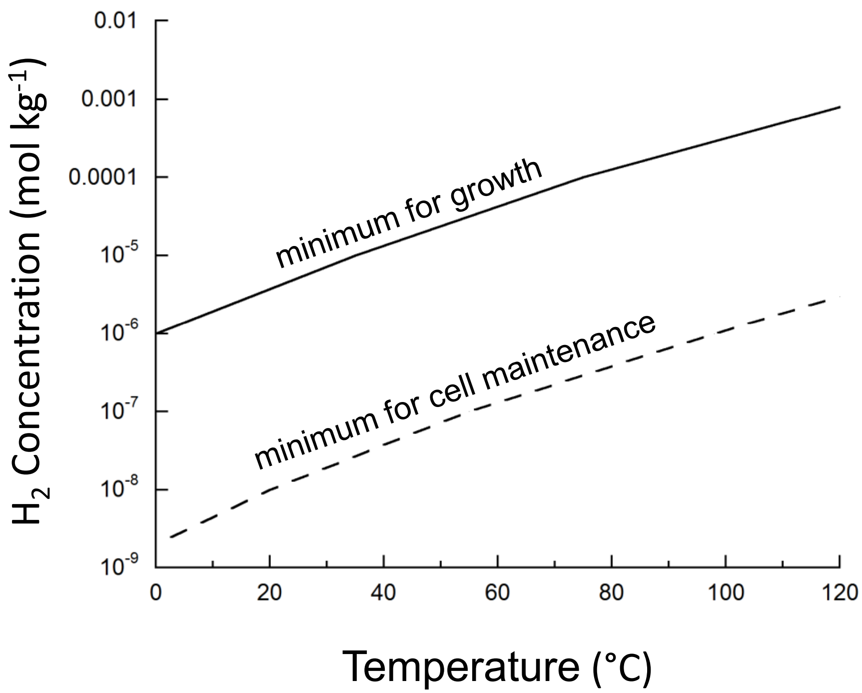
Hydrogenotrophic methanogens



- $4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$
- Found in all thermal classes of organisms
- They are common in deep-sea hydrothermal vents
- They are *not* found in all vents
  - present in high H_2 vent systems (e.g., serpentinization, recent eruptions)
  - generally absent in low H_2 vent systems

“Energy balance concept” for modeling methanogenesis

$$\{H_2\}_{BEQ} = \left(\frac{\{CH_4\}}{\{CO_2\}} \cdot \exp\left(\frac{\Delta G^{\circ}_{(T,P)} - \Delta G_{BEQ}}{RT} \right) \right)^{1/4}$$



Hoehler (2004)

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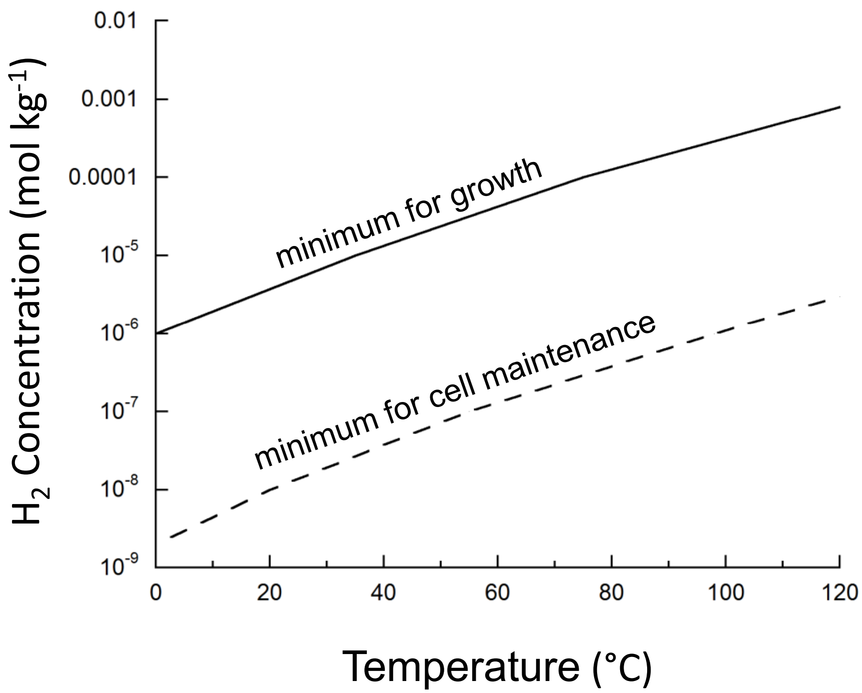
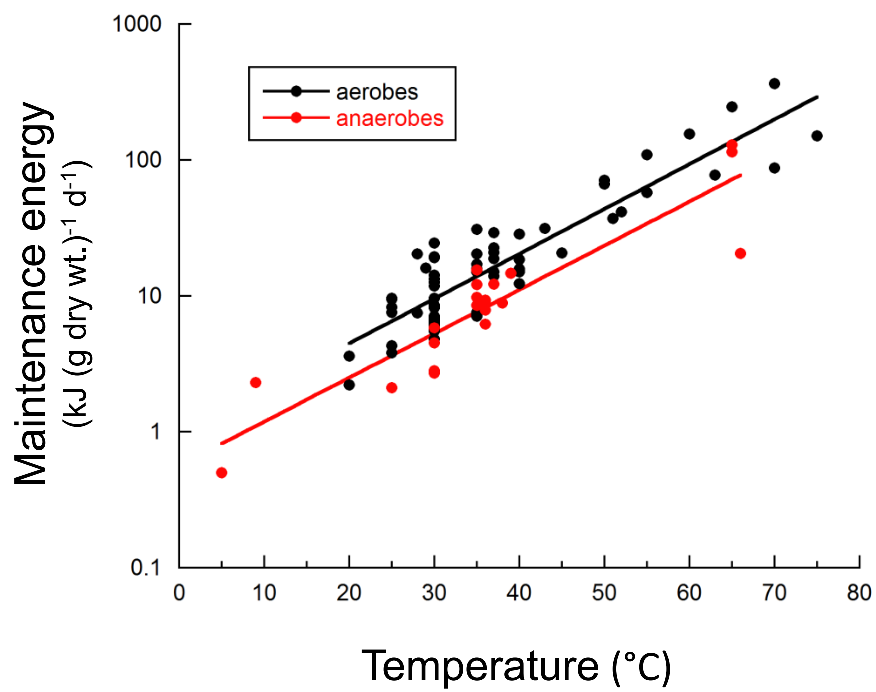


Hoehler (2004)



Tijhuis et al. (1993)

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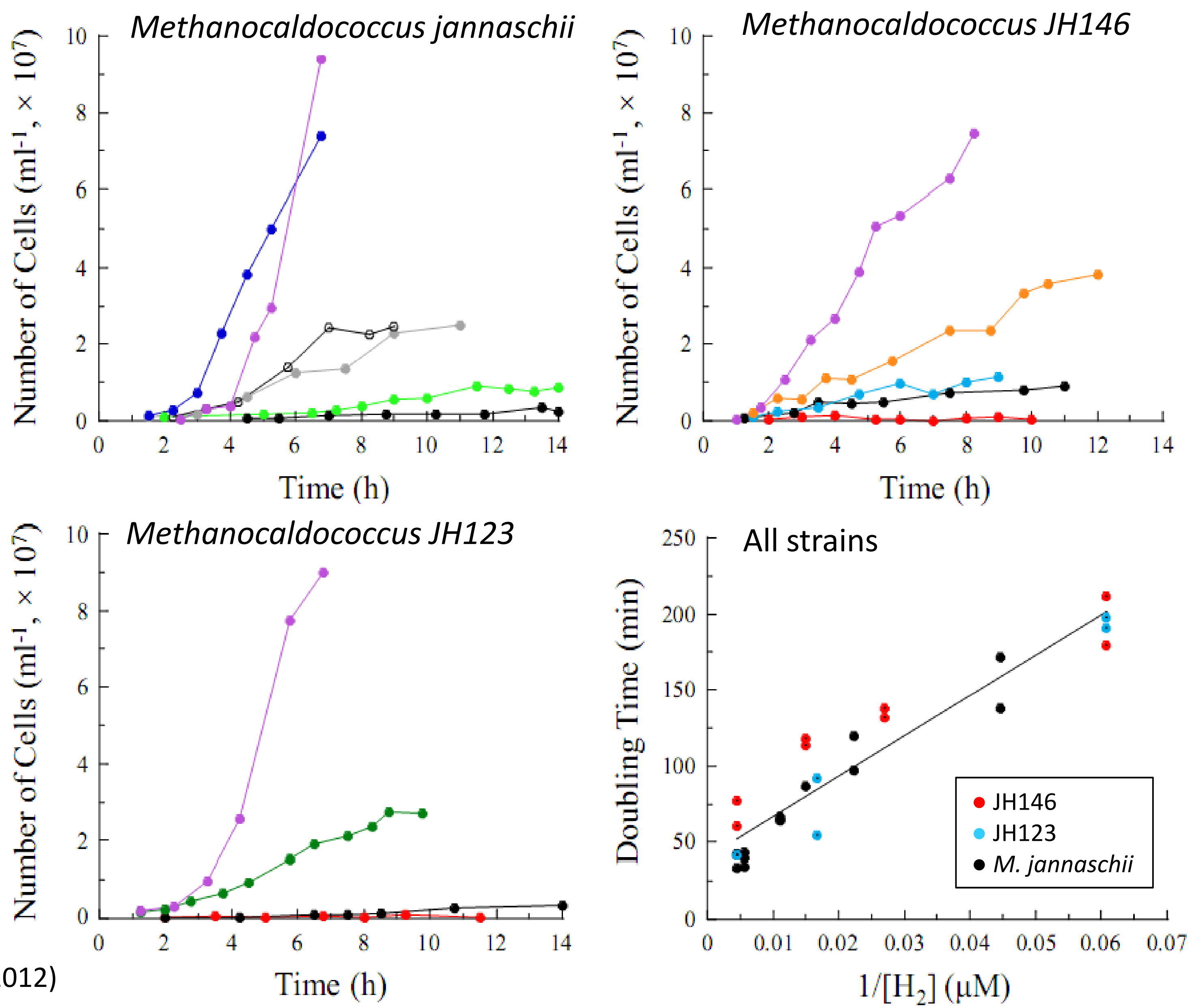
Methanocaldococcus growth under varying [H_2]

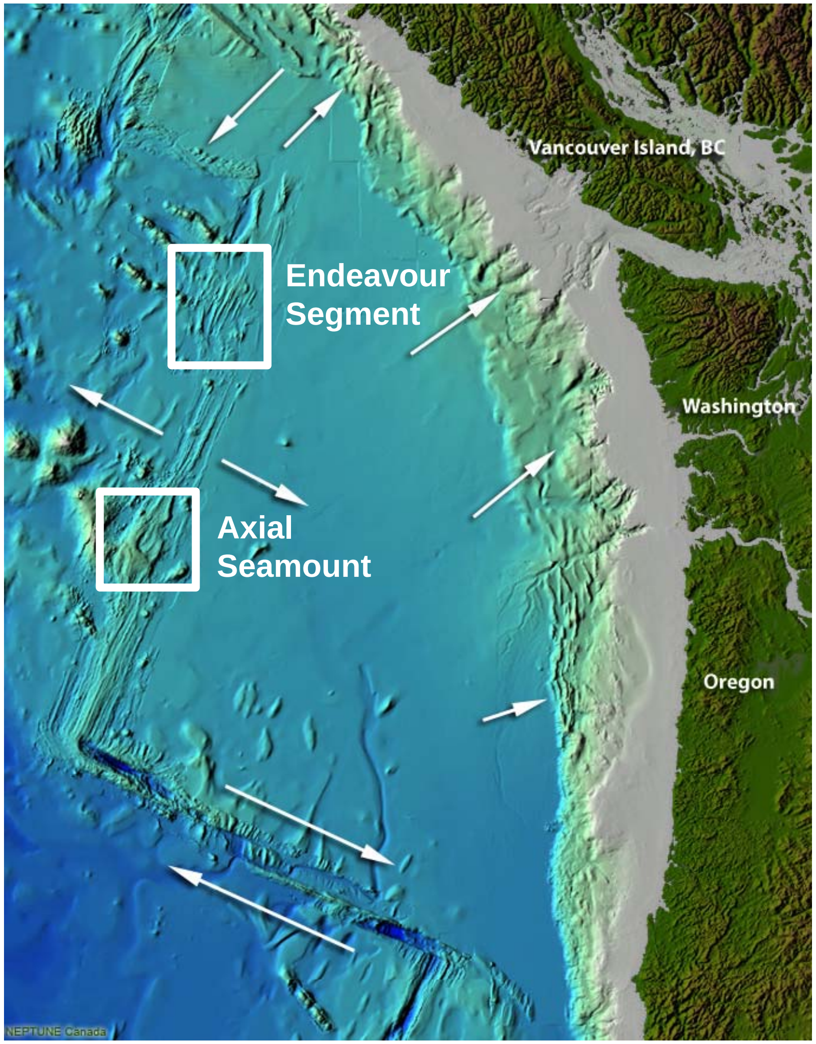
[H_2]

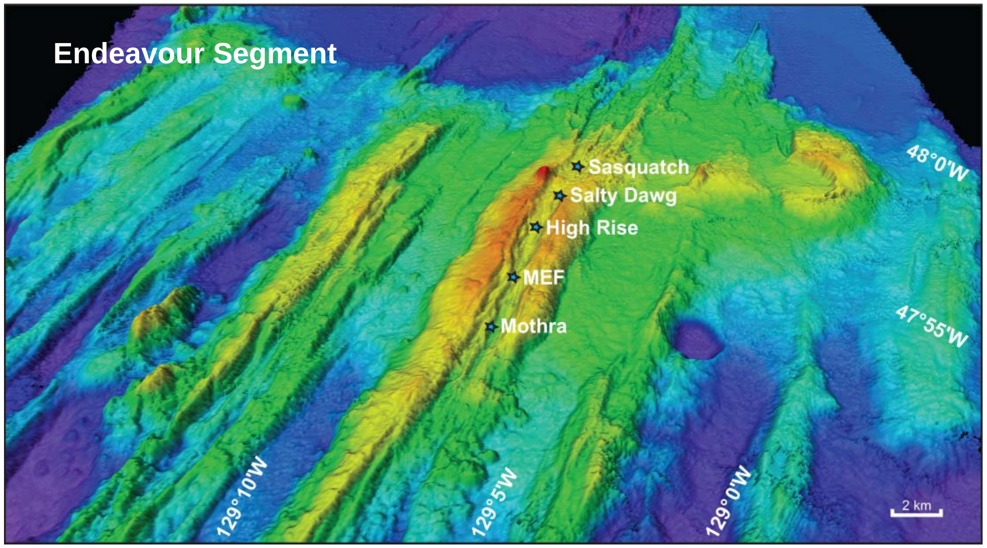
- 10 µM
- 16.5 µM
- 22.5 µM
- 37 µM
- 45 µM
- 60 µM
- 67 µM
- 90 µM
- 180 µM
- 225 µM

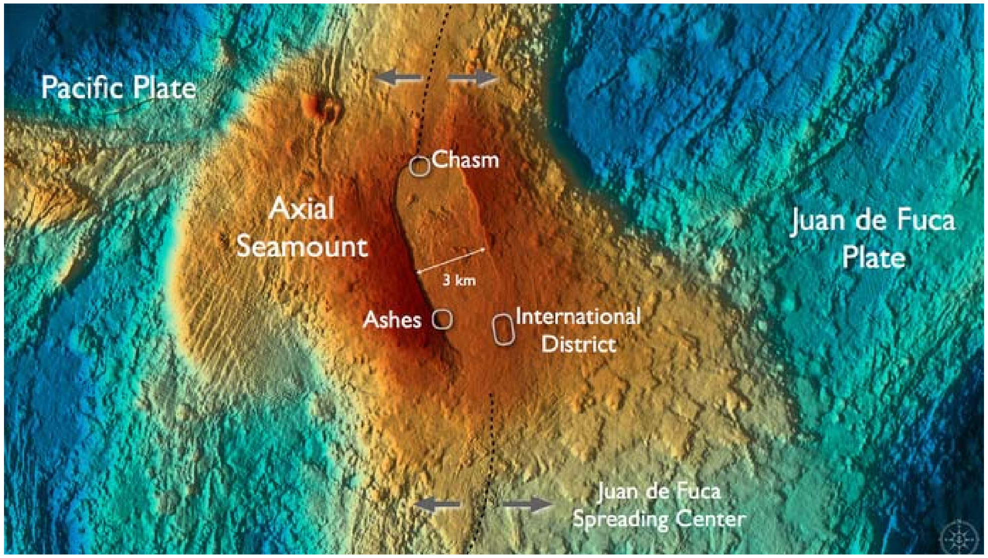


Ver Eecke et al. (2012)

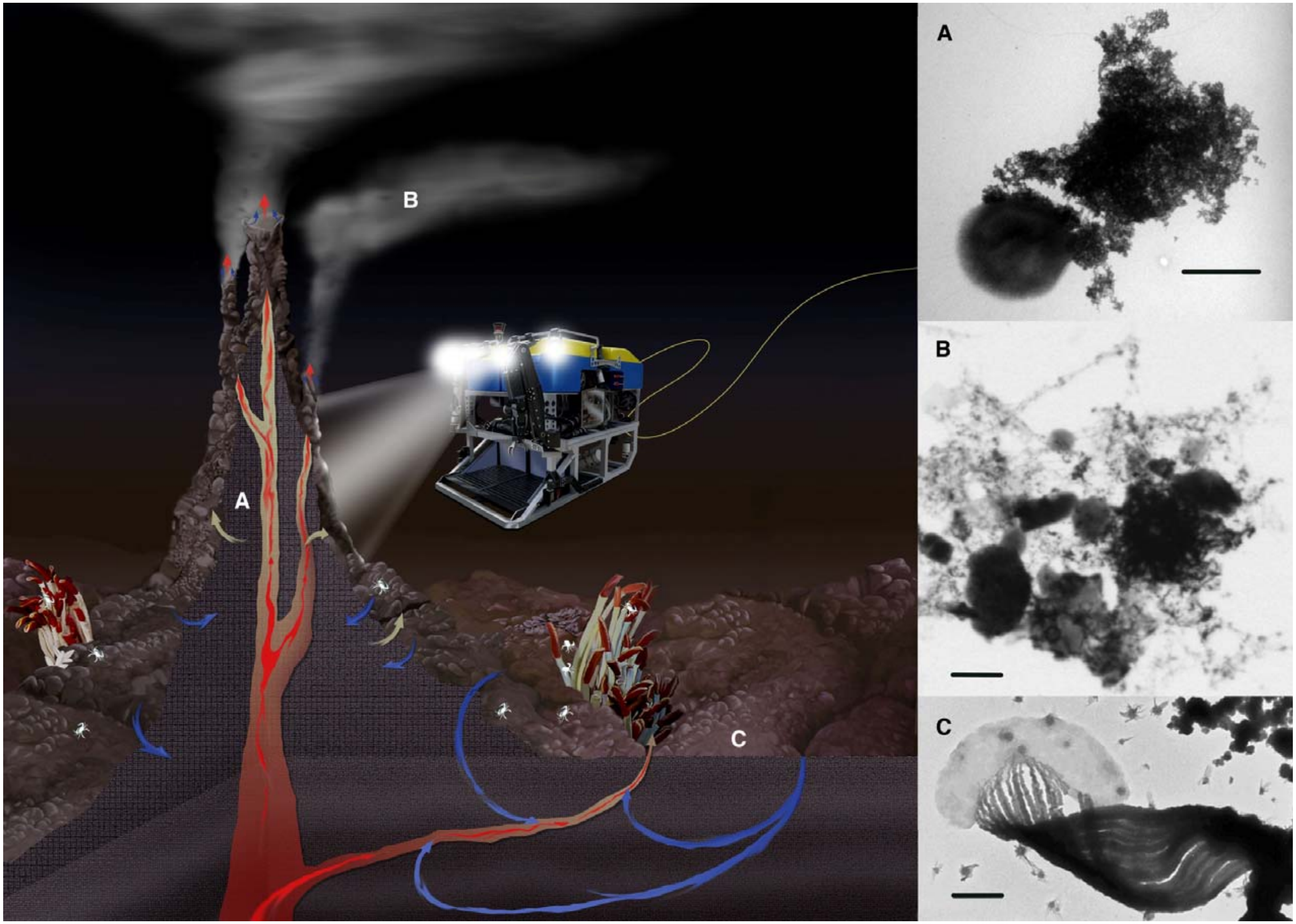
Hydrothermal vents on the Juan de Fuca Ridge





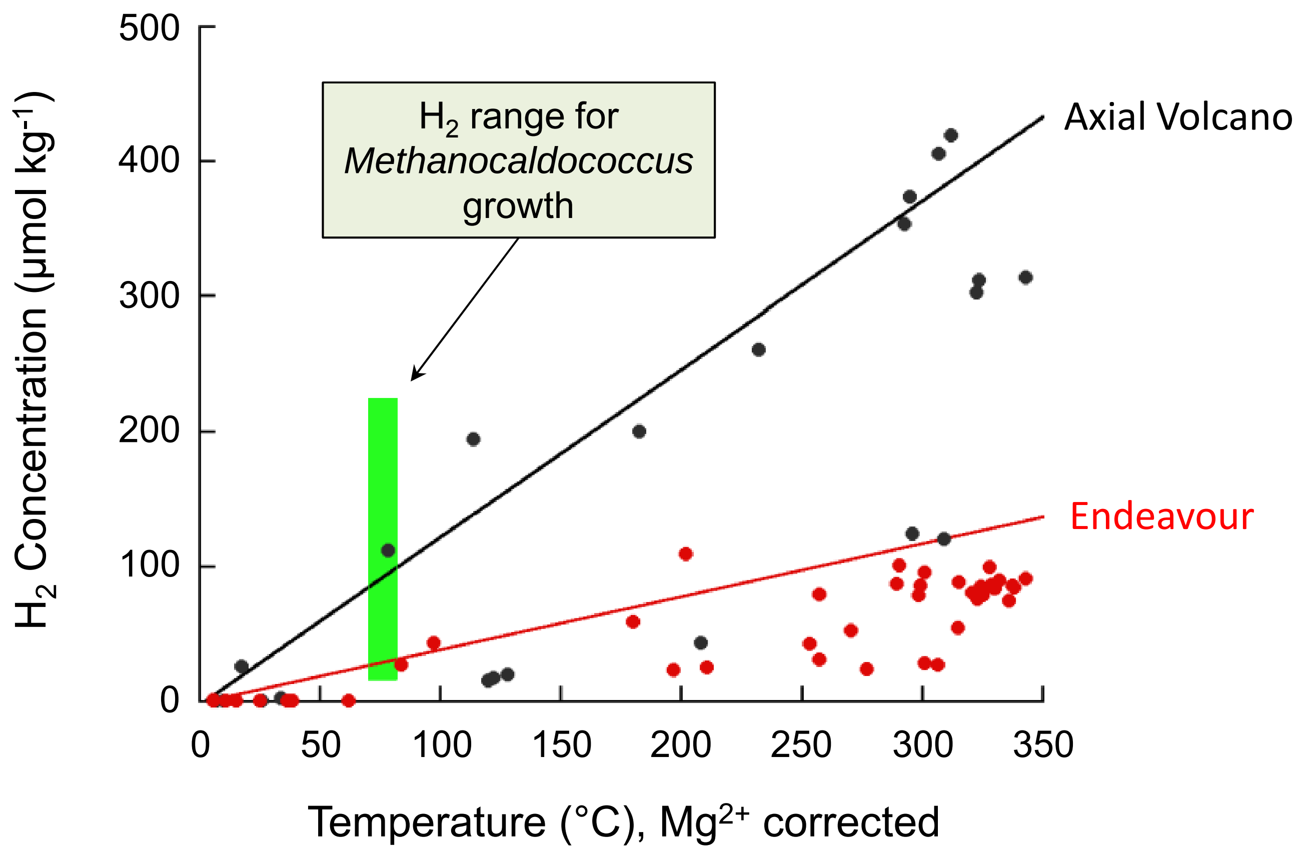


Sampling at deep-sea hydrothermal vents



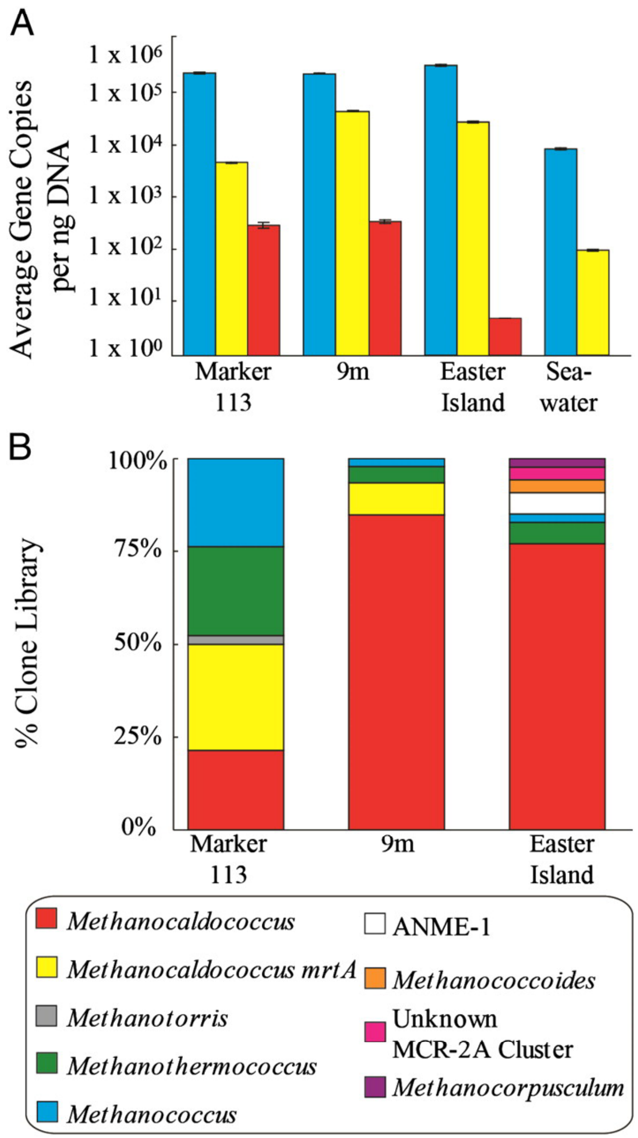
Holden et al. (2012)

Vent field H_2 fluid chemistry



Ver Eecke et al. (2012)

Molecular analyses for methanogens in diffuse fluids



Axial Seamount:
- 6 fluids tested
- 2 showed evidence of methanogens
- one site was Marker 113 vent

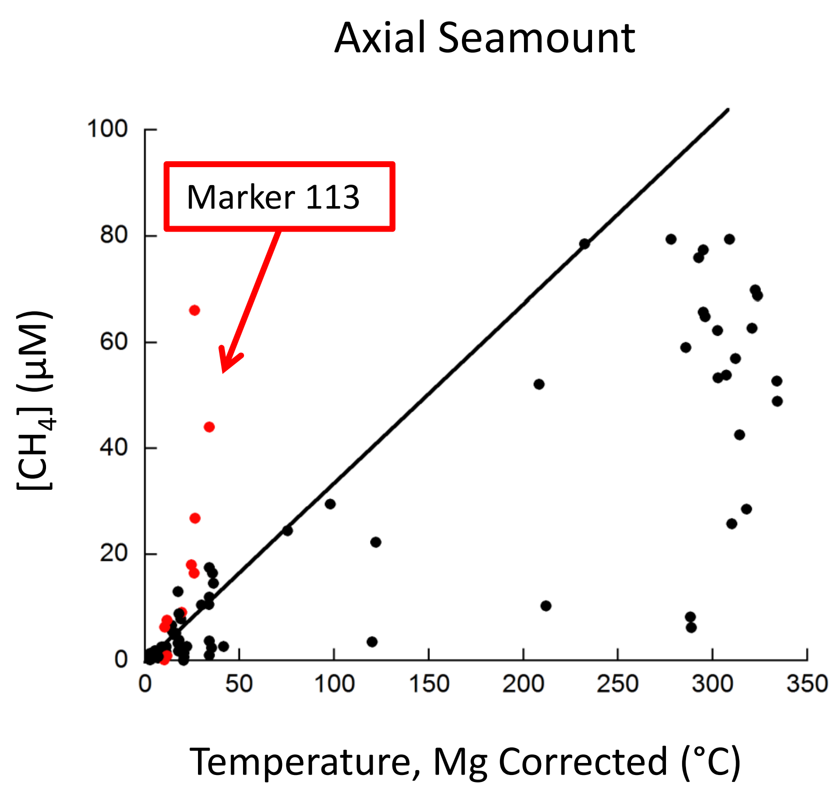
Endeavour Segment:
- 11 fluids tested
- 1 showed evidence of methanogens

Ver Eecke et al. (2012)

Fluid chemistry and culture-dependent survey for hyperthermophilic methanogens

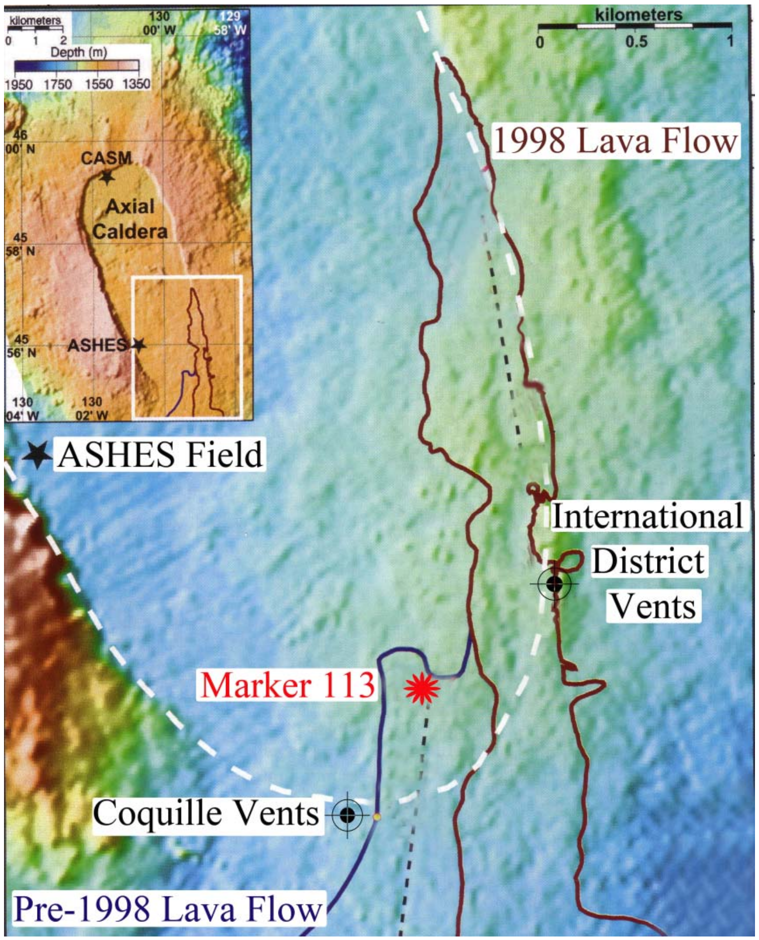
Axial Seamount MPNs
- 2 of 10 fluid samples had methanogens
- both were from Marker 113
- 1 of 2 sulfide chimney samples had methanogens

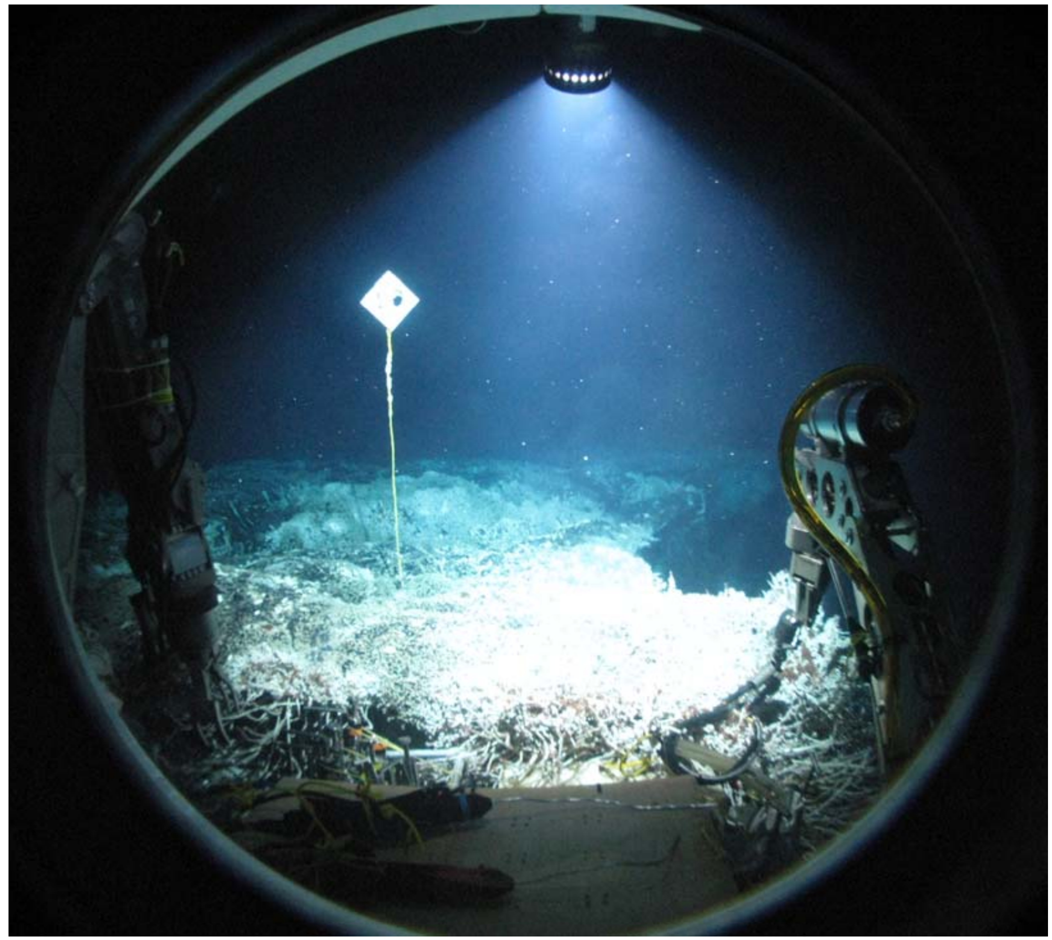
Endeavour Segment MPNs
- 2 of 18 fluid samples had methanogens
- both came from high H_2 vents
- 3 of 6 sulfide chimney samples had methanogens
- evidence of H_2 syntrophy



Ver Eecke et al. (2012)

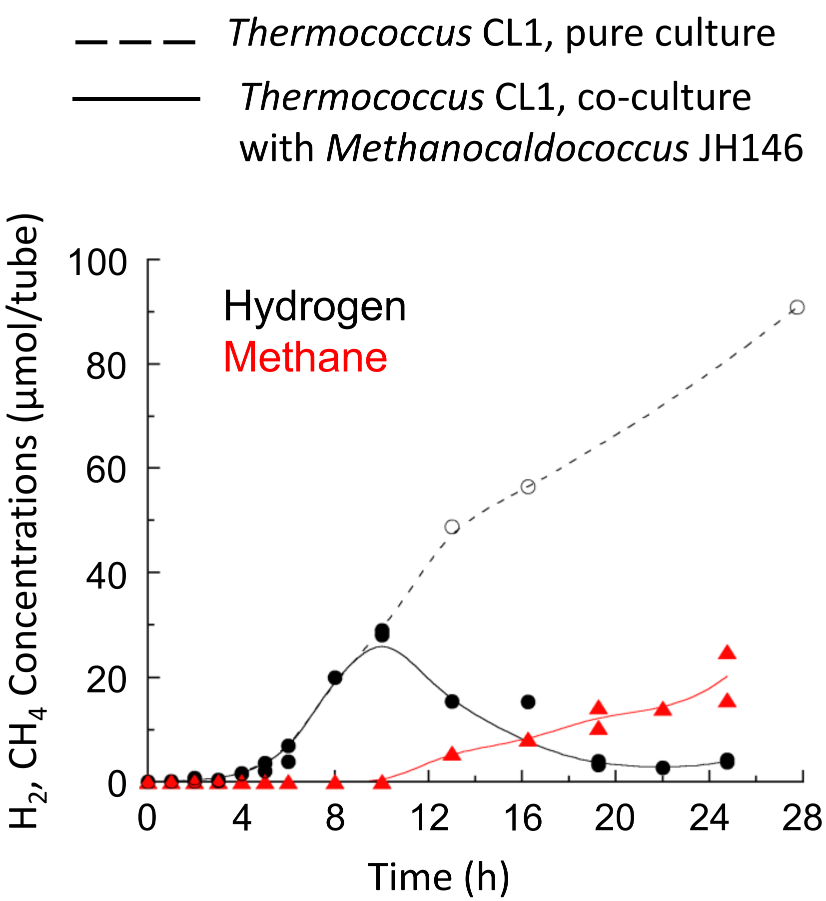
Marker 113 at Axial: Methanogen hot spot





Heterotrophs a syntrophic source of H_2

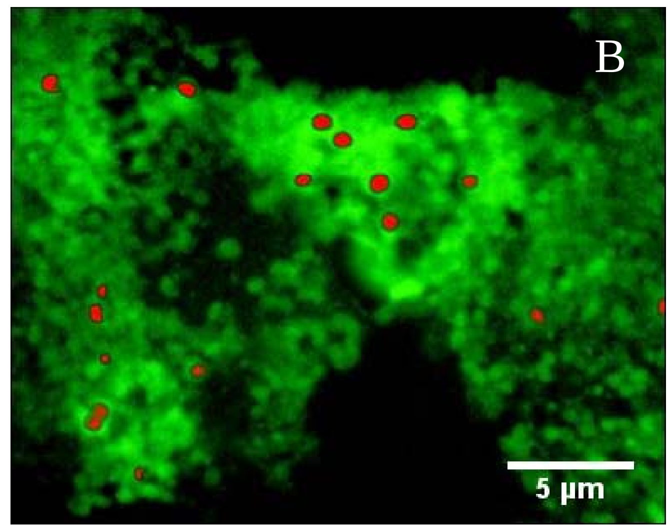
Hyperthermophilic heterotrophs were found in 27 of 28 diffuse vent fluids and in all sulfide chimney samples, and were >100x higher in concentration than methanogens



Fluorescent *in situ* hybridization (FISH)

Thermococcus

Methanocaldococcus



Ver Eecke et al. (2012)

17-23 μM H_2: Global threshold for methanogens

	Axial Volcano	Endeavour Segment	Mariner Field	TOTO Caldera	Brothers Volcano	Iheya North Field	Kairei Field
H_2 concentration, μM (82ºC)	17-162	0-31	13	5	5	~50	550
Hyperthermophilic methanogens (max.)	1,290 L^{-1} 4 g^{-1}	690 L^{-1} 34 g^{-1}	not detected	not detected	not detected	650 g^{-1}	2,500 g^{-1}
Hyperthermophilic heterotrophs (max.)	>33,000 L^{-1} >45,200 g^{-1}	>72,000 L^{-1} 7,200 g^{-1}	10^7 g^{-1}	10^7 g^{-1}	10^7 g^{-1}	3.5×10^7 g^{-1}	6×10^6 g^{-1}

Ver Eecke et al. (2012)

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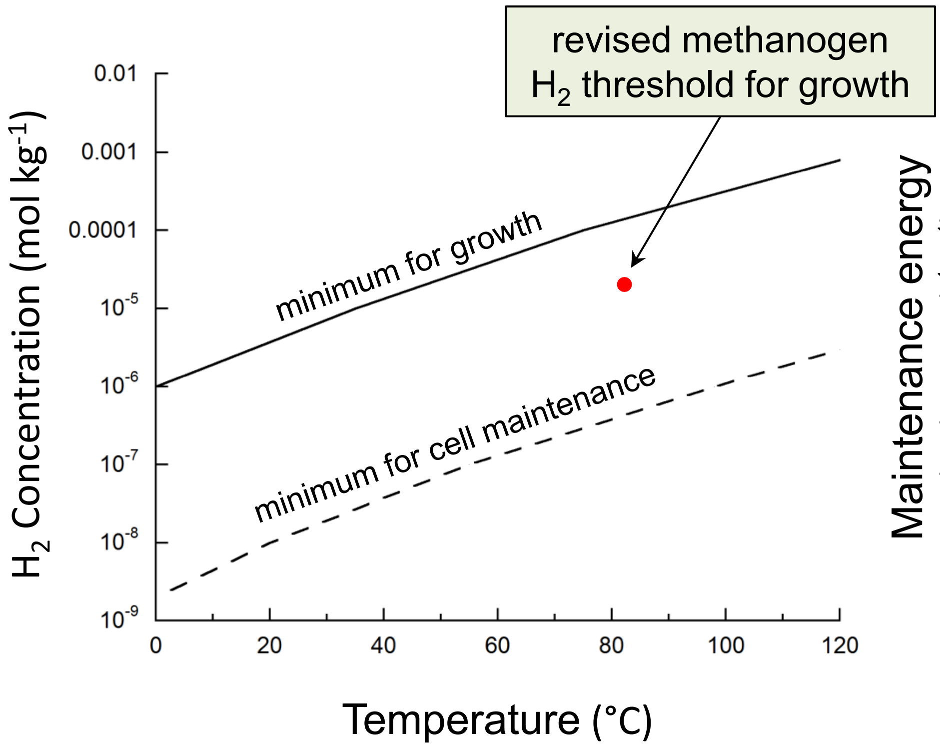
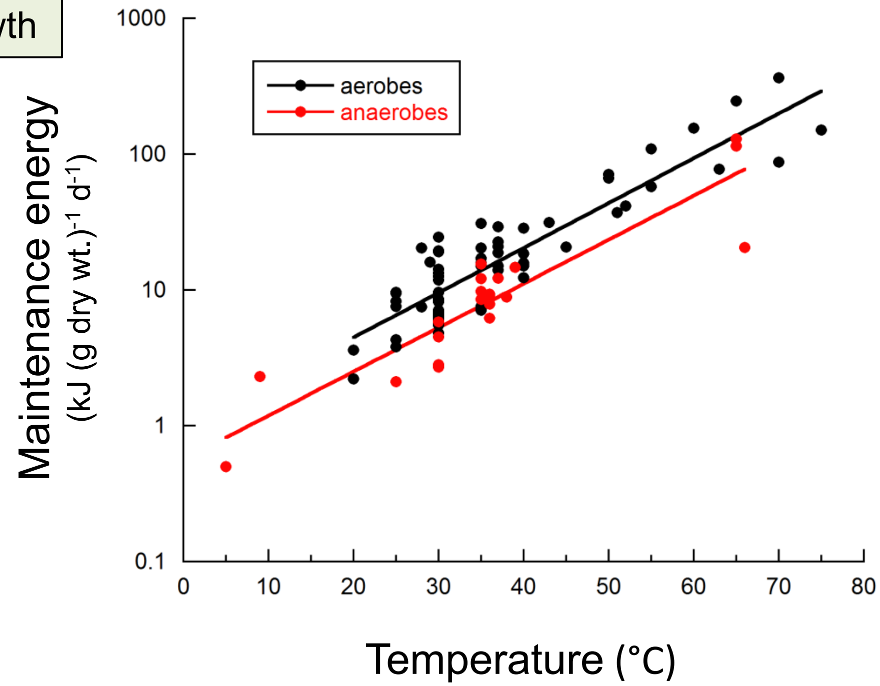


Hoehler (2004)



Tijhuis et al. (1993)

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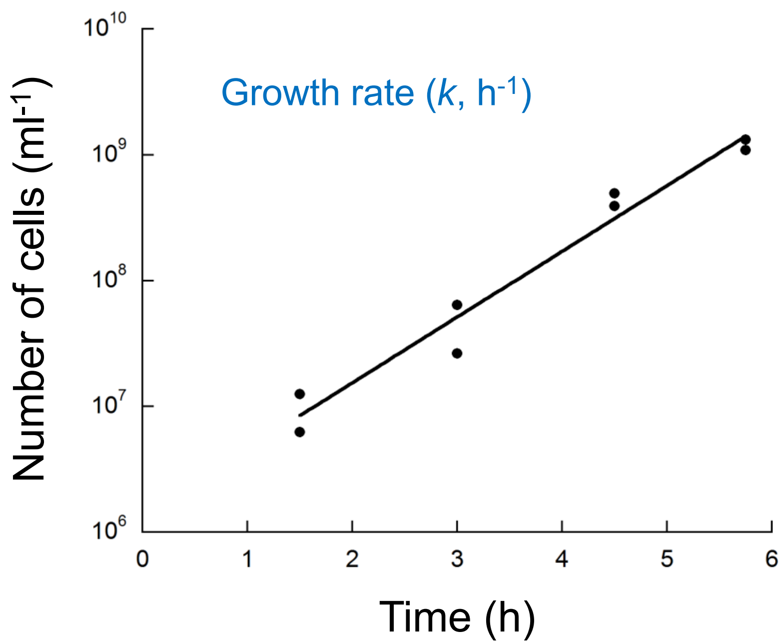
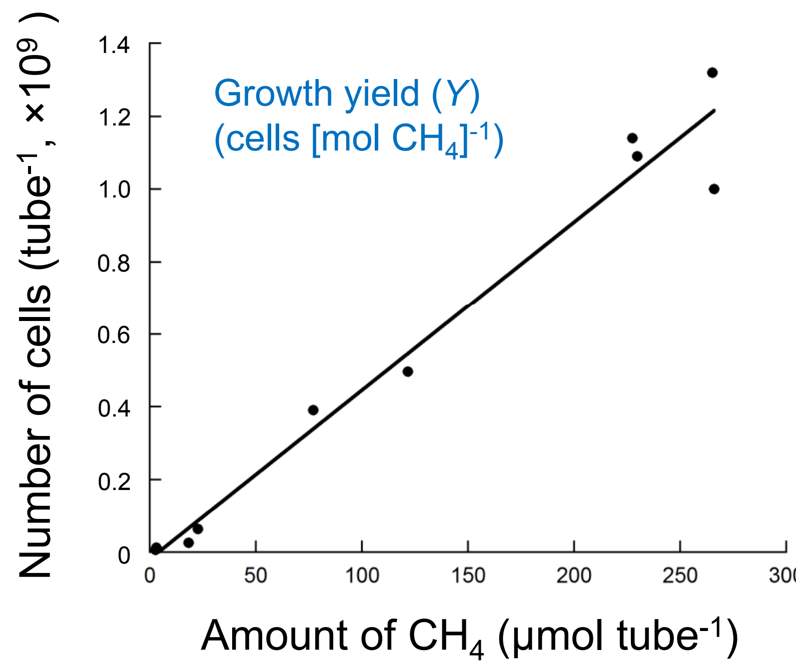
3c. Do these organisms leave behind a mineral biosignature?

Growth energy calculations for methanogens

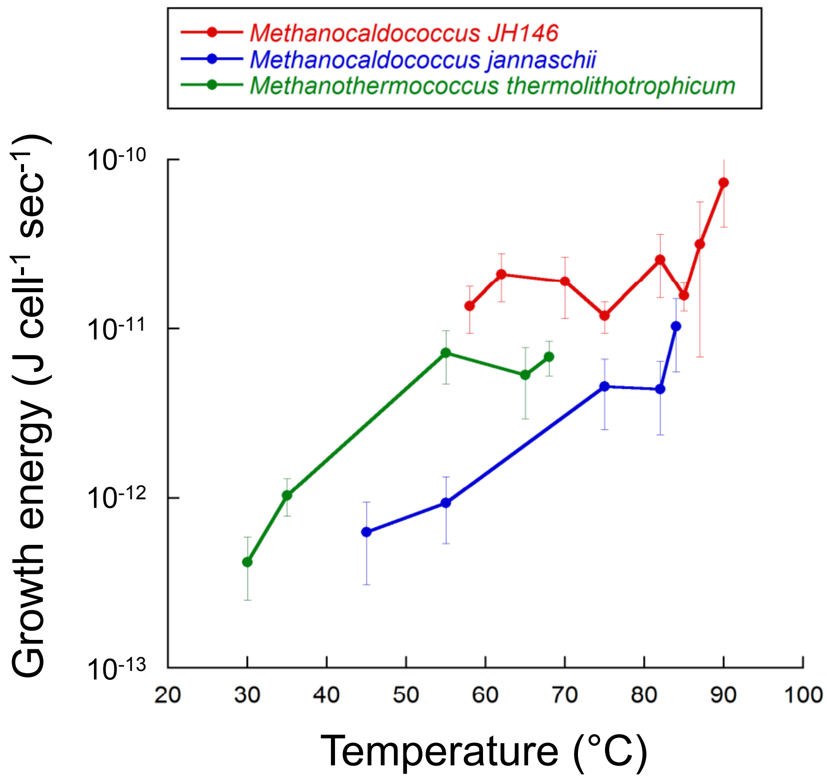
$$\text{Growth energy} = \Delta G_r \times \frac{k}{Y \times 0.693}$$





Ver Eecke et al. (in prep.)

Effect of temperature on growth energy



Ver Eecke et al. (in prep.), Stewart & Holden (unpubl.)

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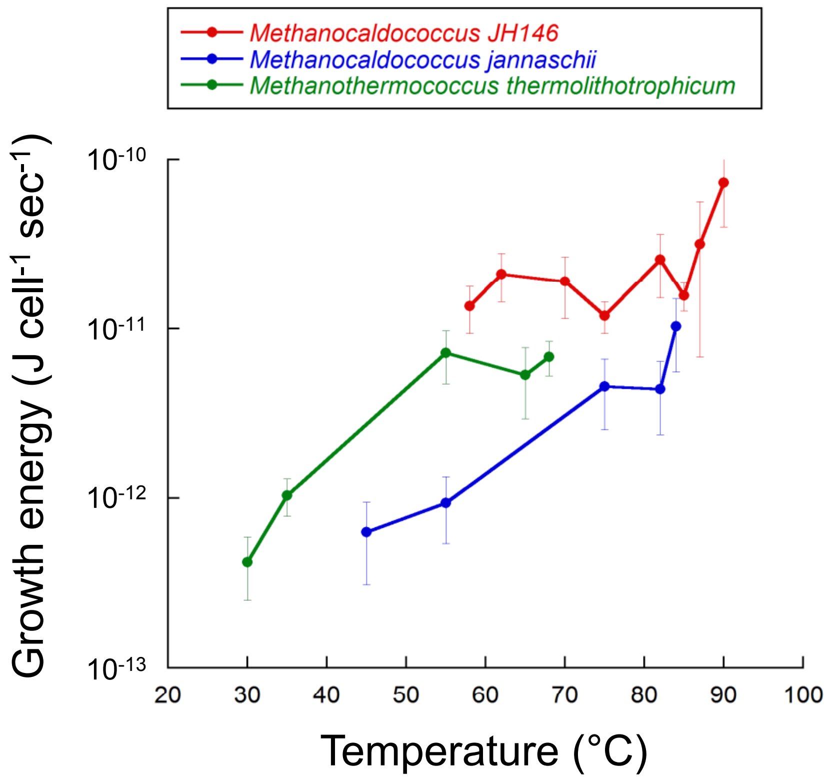
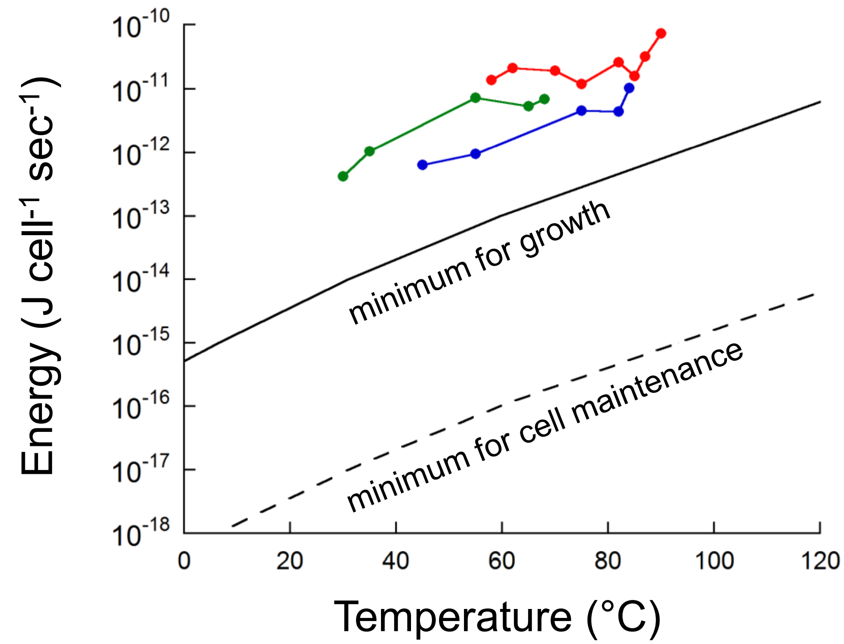


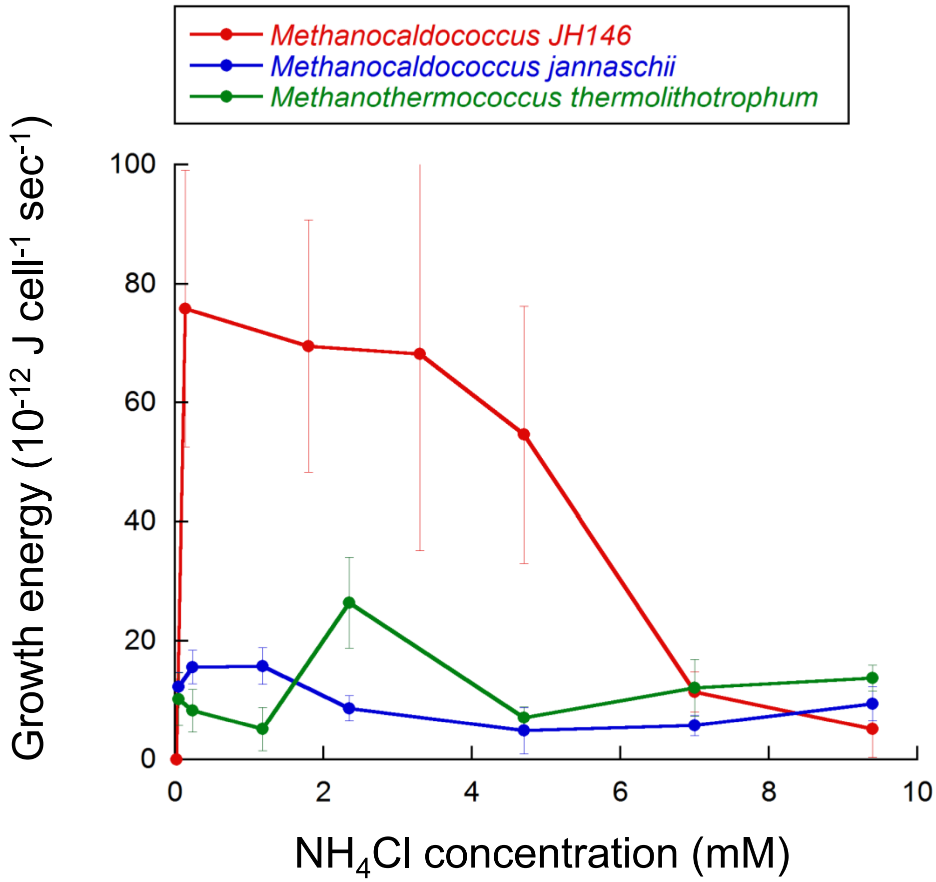
Future studies: chemostat experiments to refine 'energy balance' model



Ver Eecke et al. (in prep.), Stewart & Holden (unpubl.)

Hoehler (2004)

Effect of N availability on growth energy



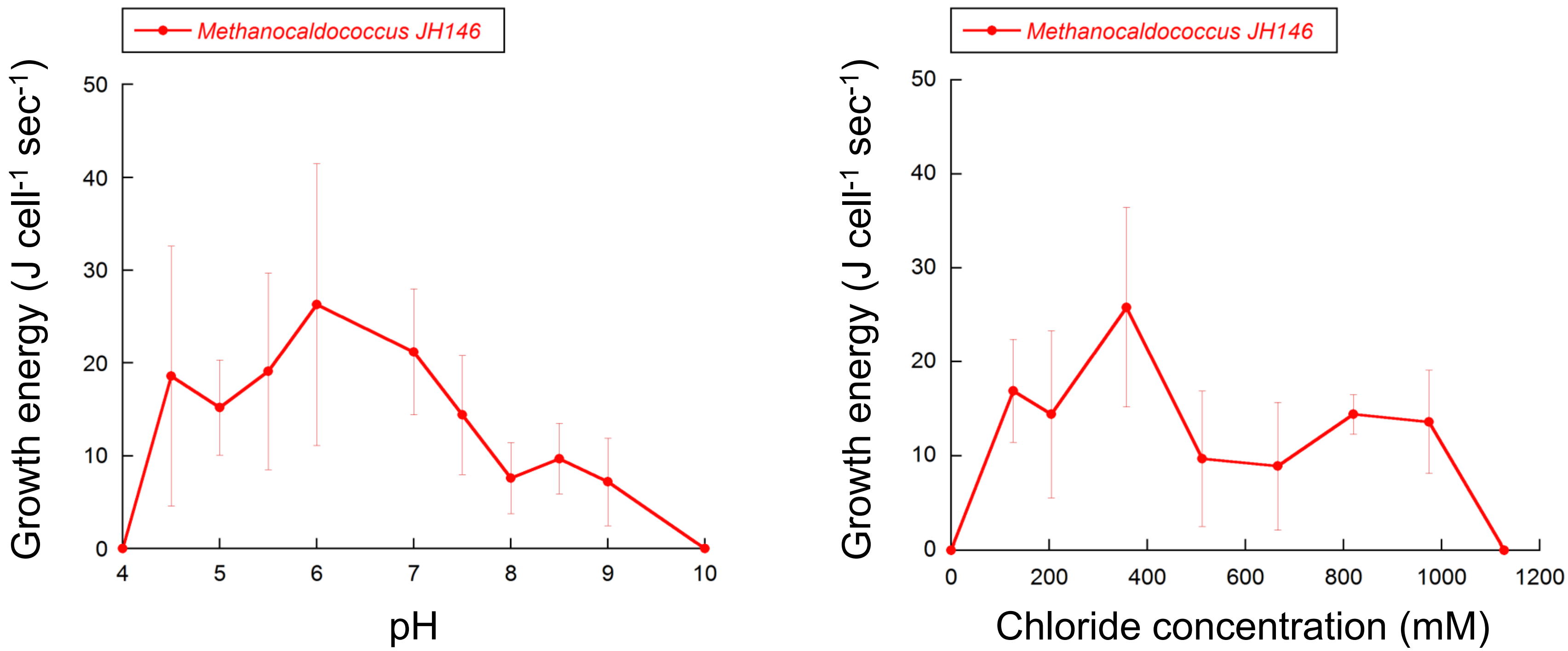
Hydrothermal fluid-seawater mix
NH_4^+ concentration ~ 15 μM

Standard growth medium
NH_4^+ concentration = 4.7 mM

Ver Eecke et al. (in prep.), Stewart & Holden (unpubl.)

Effects of pH and chlorinity on growth energy

No effect at environmentally relevant pH and Cl^- concentrations



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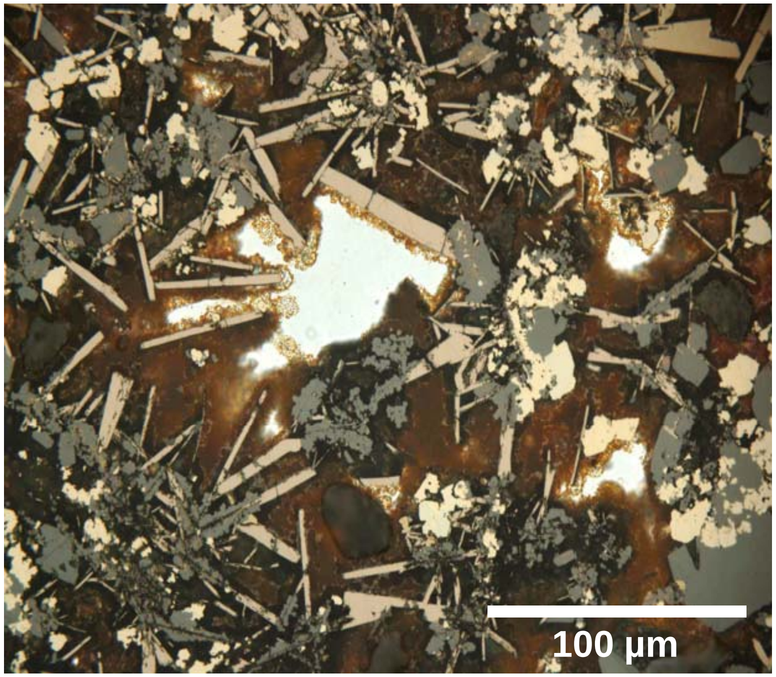
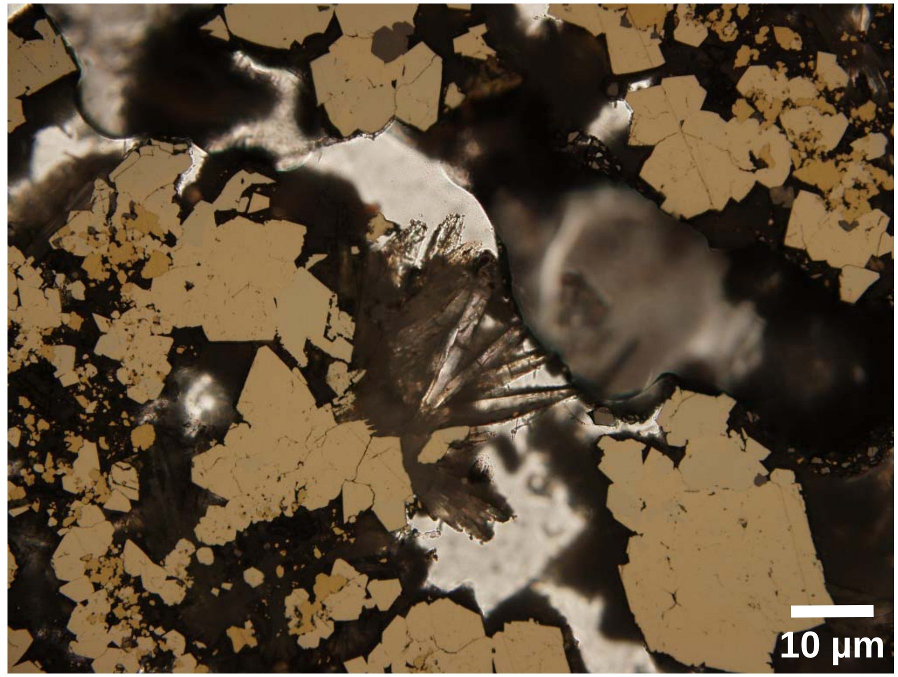
Petrography and mineralogy of active hydrothermal sulfide deposits





Lin et al. (in prep.)

August 2012 MPN results for Axial Seamount diffuse vents

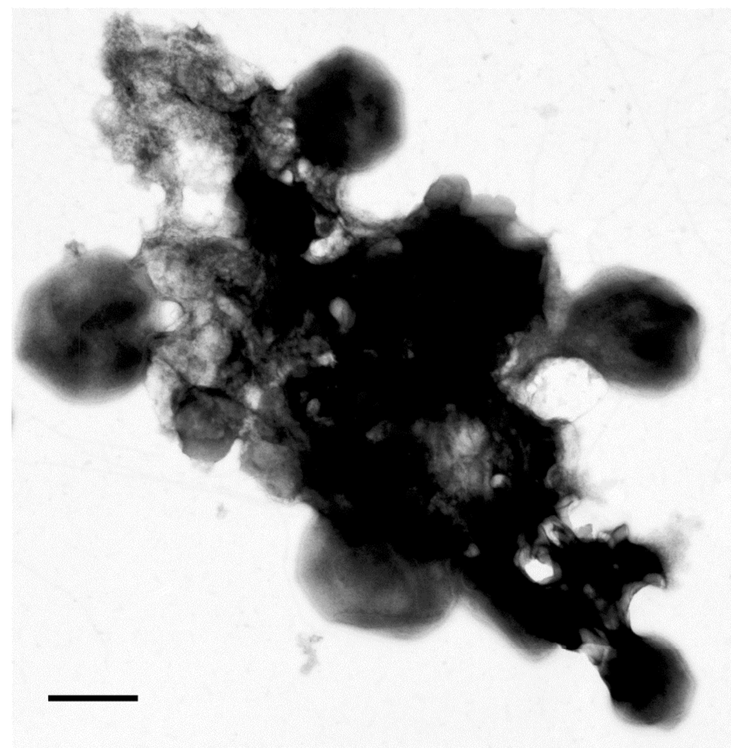
Location (Temp.)	Methanogens (L^{-1})		Sulfur reducers (L^{-1})		Iron reducers (L^{-1})		Heterotrophs (L^{-1})		Total cells (L^{-1})
	55°C	80°C	55°C	80°C	55°C	80°C	55°C	80°C	
Anemone (33°C)	n.d.	n.d.	n.d.	n.d.	n.d.	90	690	7,200	7.9×10^{7}
Fuzzy Tubeworm Bush (28°C)	n.d.	n.d.	270	n.d.	90	n.d.	270	2,790	4.7×10^{7}
Boca (10°C)	120	n.d.	90	n.d.	450	n.d.	270	690	2.3×10^{8}
Marker 113 (28°C)	n.d.	120	n.d.	n.d.	n.d.	13,800	n.d.	2,790	3.4×10^{8}
Off-summit, 1,300 m (~2°C)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.5×10^{7}

n.d., not detected

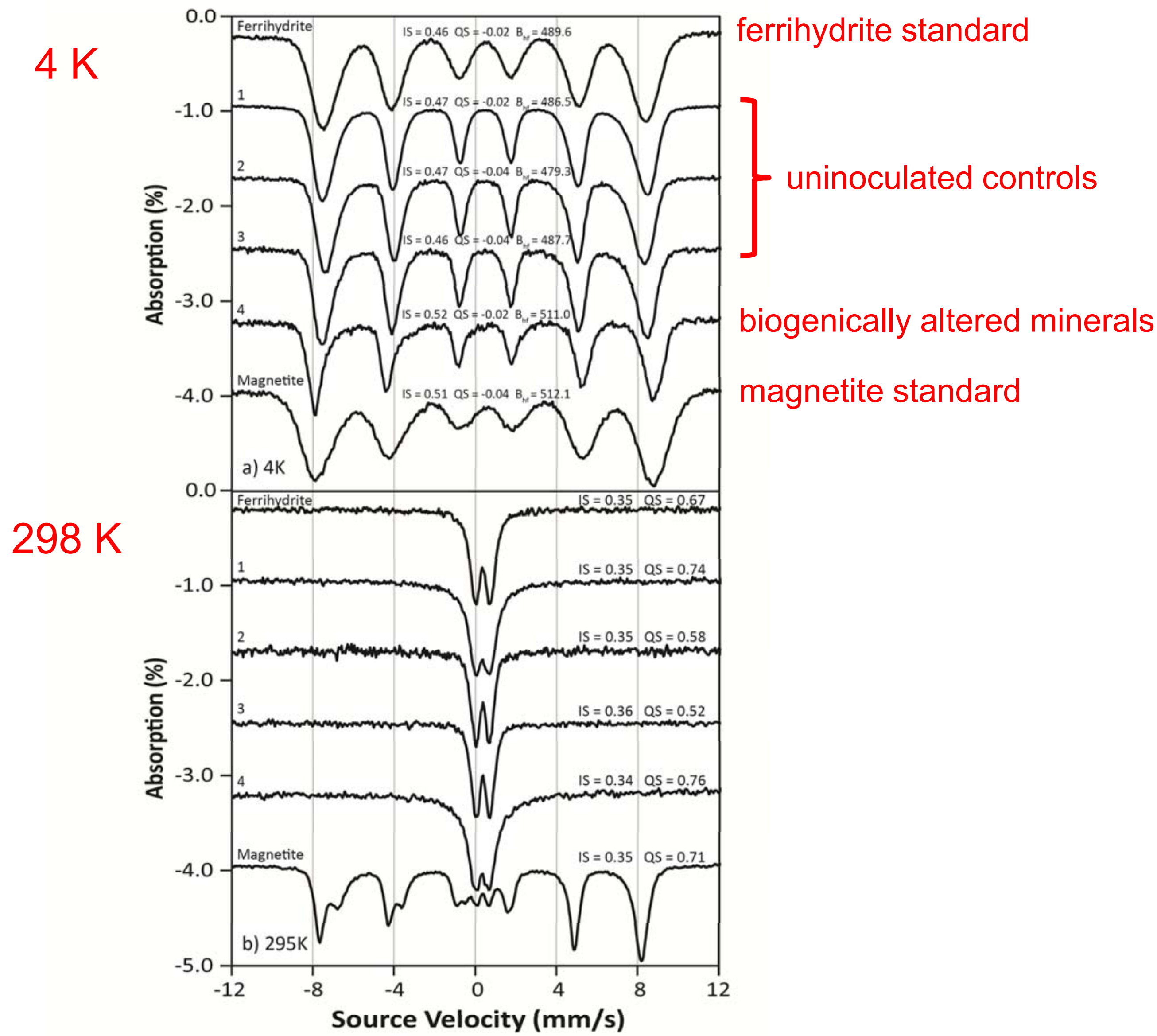
J.F. Holden (unpublished data)

Alternative to methanogens in low H_2 hydrothermal systems

Growth Reaction	ΔG_r° $_{100°C}$
$H_{2(aq)} + 6\ Fe(OH)_3 \leftrightarrow 2\ Fe_3O_4$(magnetite) $+ 10\ H_2O$	-303 kJ/mol
$H_{2(aq)} + 0.25\ CO_{2(aq)} \leftrightarrow 0.25CH_{4(aq)} + 0.5\ H_2O$	-45 kJ/mol



Biogenic mineral transformations as determined by Mössbauer spectroscopy



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3a. Are usable minerals available in vents? Yes, in mixing zones

3b. Can hyperthermophiles use minerals as a growth substrate? Yes

3c. Do these organisms leave behind a mineral biosignature? Yes

How is this actually done?

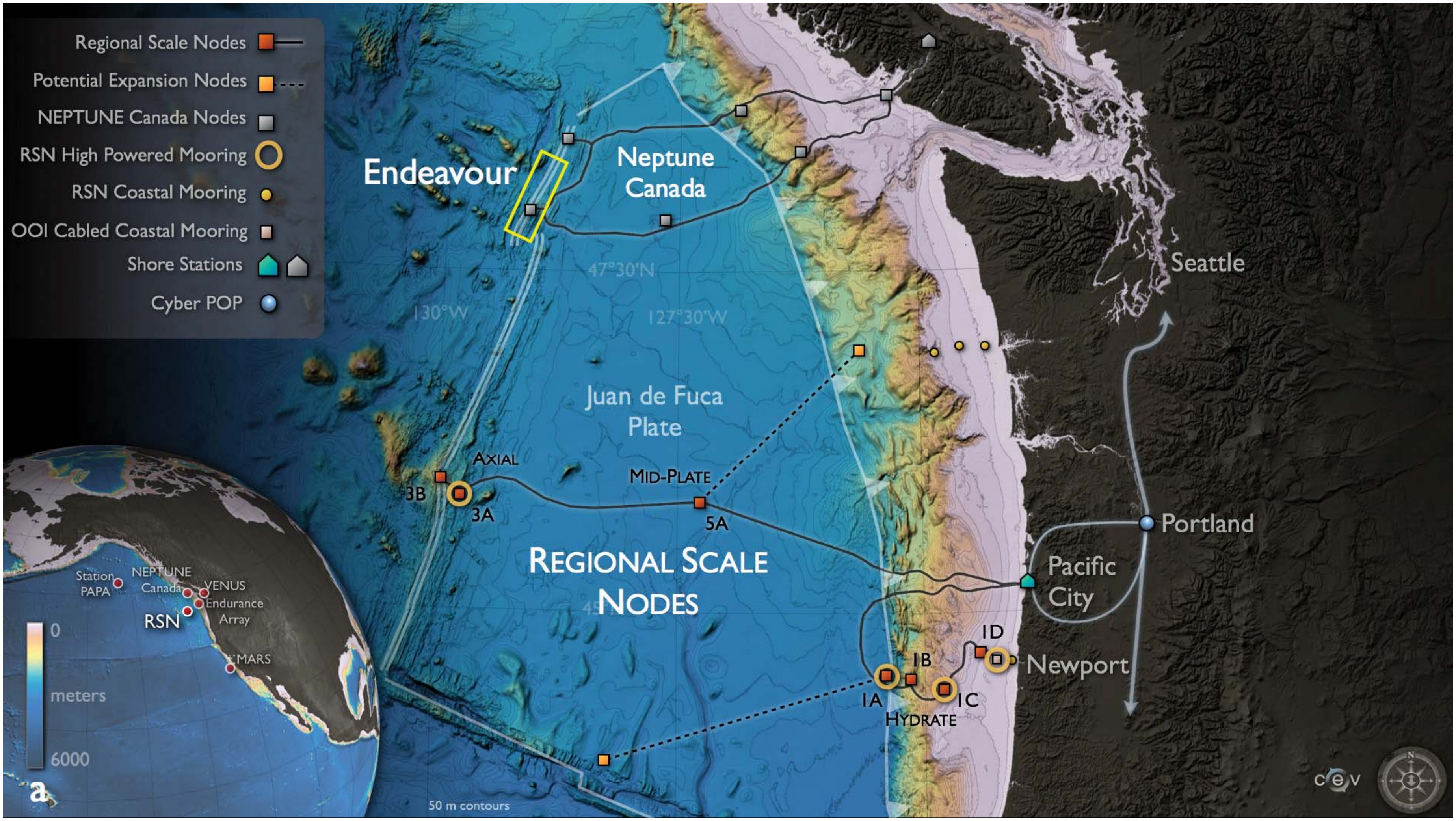
Environmental Conditions → Microbial Phenomena → Biomarker

- physical and chemical constraints on life
- rates of biogeochemical transformations
- microbial bioenergetics
- microbe-mineral interactions
- population structure and dynamics
- functional diversity

- mineral, organic and isotopic biosignatures
- differentiate biotic and abiotic markers
- depositional characteristics of markers
- effect of material properties on mineral bioalteration

and …

Cabled observatories in the northeastern Pacific Ocean



Kelley et al. (2012)

Biologically relevant chemistry of end-member hydrothermal fluids from various sites and host-rock environments

LOCATION	RANGE OF CONCENTRATIONS				
	pH	H_2 (mM)	CH_4 (mM)	H_2S (mM)	Fe (mM)
MAFIC ROCK					
Main Endeavour Field	4.2-4.5	0.16-1.5	1.8-4.5	2-29	0.53-1.36
ASHES, Axial Volcano	3.5-4.4	0.07-0.27	0.07-0.28	7.1	0.01-1.07
9°50'N East Pacific Rise	ND	0.33-8.91	0.05-0.75	6.2-23.2	0.2-6.64
Kilo Moana, Lau Basin	2.9-4.0	ND	ND	5.4-6.3	2.5-3.8
Lucky Strike, Mid-Atlantic Ridge	3.5-4.9	0.02-0.73	0.30-0.85	1.4-4.6	0.03-0.86
ULTRAMAFIC ROCK					
Rainbow, Mid-Atlantic Ridge	2.8	16	2.5	1.2	24.1
Logatchev, Mid-Atlantic Ridge	3.3-3.9	12-19	2.1-3.5	0.8-2.5	2.4-2.5
Kairei, Central Indian Ridge	3.4-3.5	7.9-8.2	0.08-0.20	3.9-4.1	3.5-6.0
DACITIC/ANDESITIC ROCK					
Mariner Field, Lau Basin	2.4-2.7	0.04-0.10	0.01	6.9-9.0	10.5-13.0
DESMOS Caldera, Manus Basin	2.1-2.7	ND	ND	5.3-9.7	0.01-4.4
Brothers Volcano, Kermadec Arc	2.8-3.0	0.01-0.02	< 0.01	2.3-7.9	4.2-7.3
Seawater	7.8	0.0004	0.00001	0	0.000061

ND = not determined.

Holden et al. (2012)