EXTREMOPHILES

Concepts: environmental stresses and adaptation mechanisms,

life in cold, dry, hot, acidic, basic, radioactive, sulfidic places, names for different extremophiles, animals in extreme environments

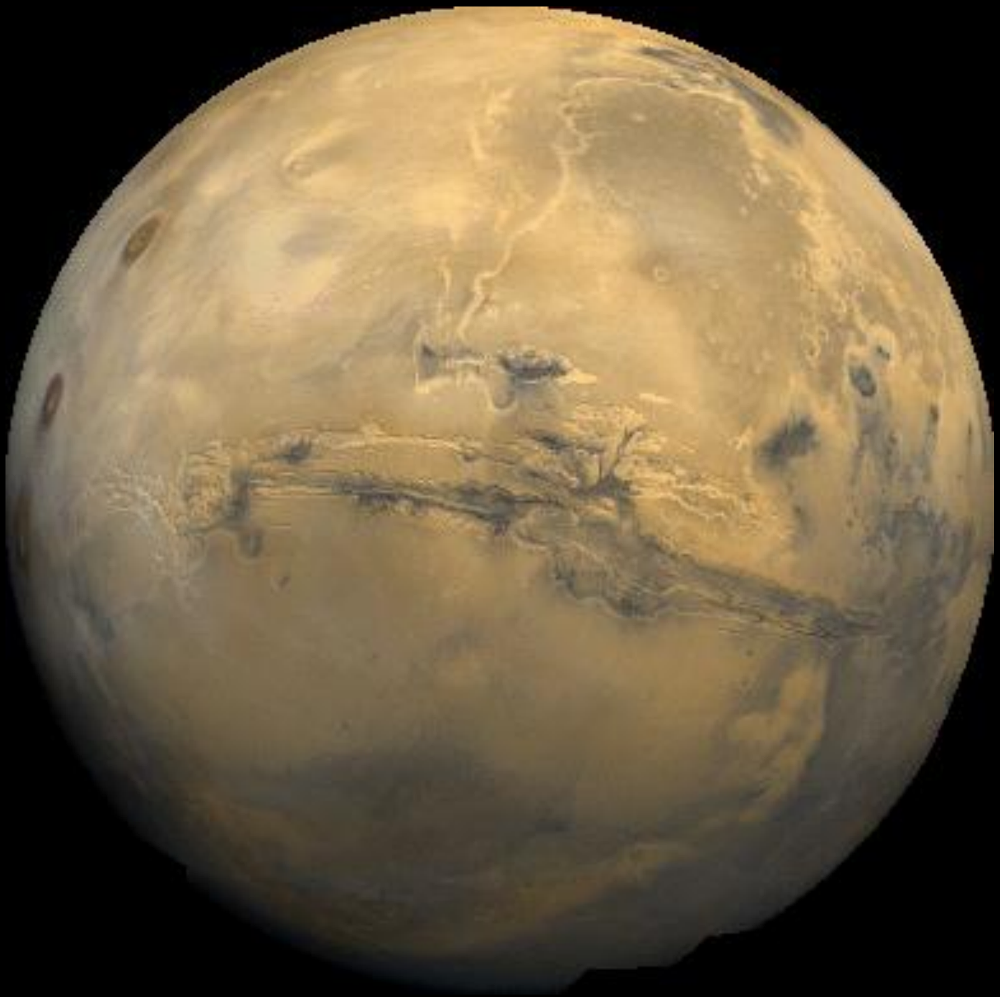
Reading: Rothschild and Mancinelli, Nature, 409, p 1092, 2001

What you should know

- Examples of ‘extreme’ environments
- Some concepts of what is ‘extreme’ and why
- A strategy for quantifying ‘habitability
- Strategies that allow organisms to survive ‘extreme’ environments
- Examples of pertinent research and its application to understanding limits of life in the solar system

Historical Perspective

- Most early attention given to hydrothermal systems
- 1881, first thermophile cultured
- 1903, Setchell notices “algae” in Yellowstone hot spings
- Very little attention given to “extreme” habitats prior to mid 20th C
- 1977, deep-sea hydrothermal vents first discovered
- 1977, the Archaea are “discovered” (Woese and Fox)
- 1980-1990, the Archaea are slowly recognized as a legitimate group; the 3 domain system is proposed
- 1985, PCR-based molecular methods first applied to hydrothermal systems
- 1998-present, Astrobiology “boom”; search for Earth analog systems fuels rapid increase in studies of “extreme” environments



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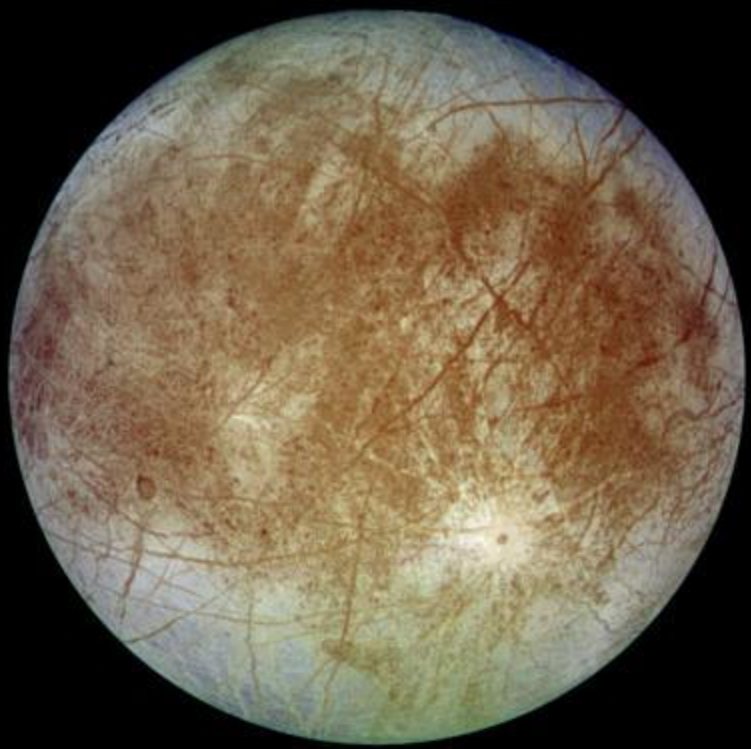
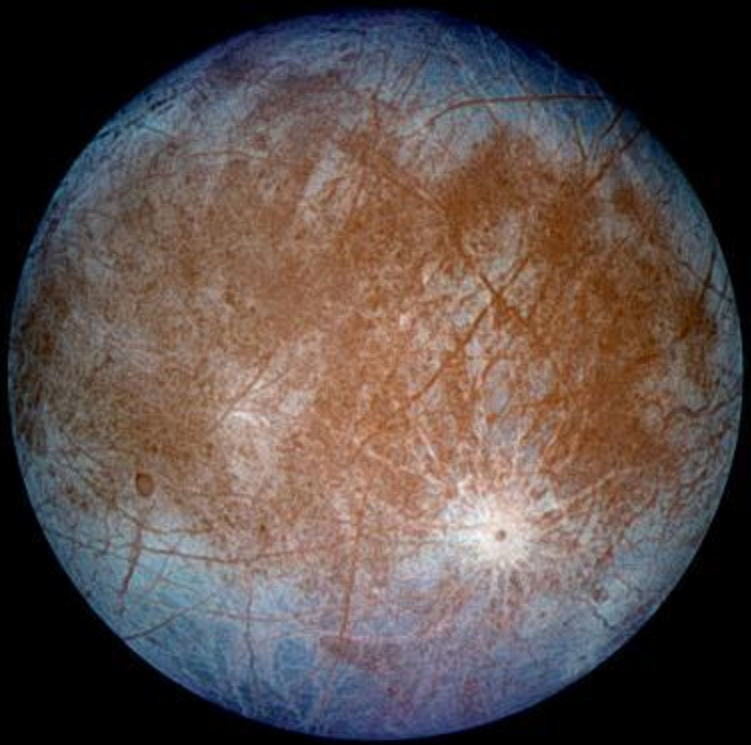
Curiosity at Gale Crater on Mars

Image courtesy of NASA.





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Defining Extremes 1

- Temp: -20 ° C to 121 ° C → Arctic sea-ice / hydrothermal vents
- pH: <1 to 13 → acid mine drainage basaltic aquifers / groundwater
- "Toxins": → Tutum Bay, PNG up to 70,000ppm Arsenic in vent sediments

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Junge et al., 2004

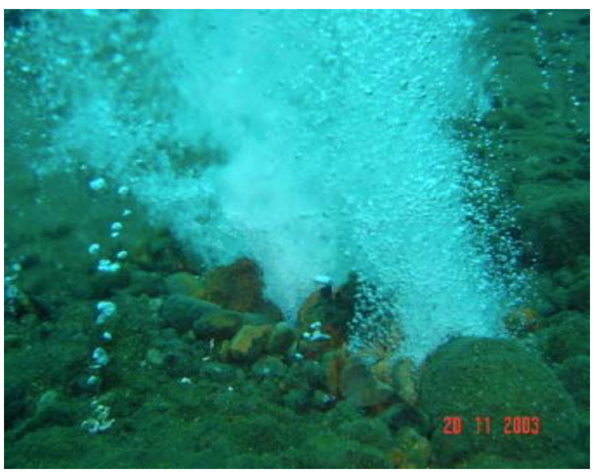

Image courtesy of D'Arcy Meyer-Dombard. Used with permission.

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Bond et al, 2000
"acidophiles" in Iron Mountain

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Kashefi & Lovley, 2003
Strain "121"

Defining Extremes 2

- Saline environments
  - "0" to saturation
  - Dead Sea 2.5M

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Please see http://www.jerichocosmetics.com/apage/33262.php.

- UV exposure
  - Deinococcus: spacecraft returns

Image courtesy of NASA.

- Pressure:

  seafloor HTV 40 MPa
  Challenger Deep 124 MPa
  *up to 1400 MPa (?)

Photograph of black smokers at a hydrothermal vent removed due to copyright restrictions.

Defining Extremes 3

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Extremophiles alter or cope with environmental "extremes"

Defining Habitability

What makes an environment habitable?

The Earth-centric view includes availability of

Water

Energy

Carbon

Scaling Habitability

✔

>>>

?

http://en.wikipedia.org/wiki/

http://photojournal.jpl.nasa.gov/index.html

Scaling Habitability

Image courtesy of D'Arcy Meyer-Dombard. Used with permission.

Photo: Meyer-Dombard

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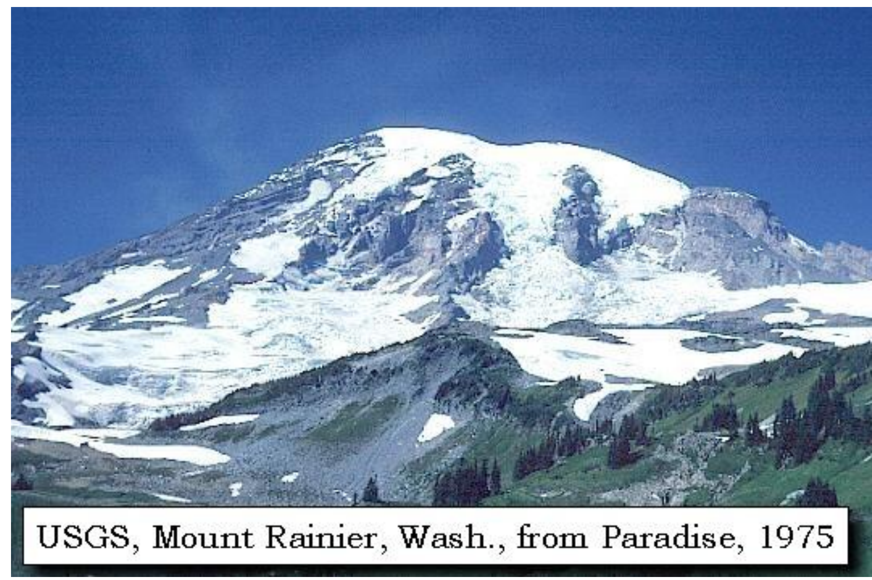

Image courtesy of USGS.

Scaling Habitability

Photograph of black smokers at a hydrothermal vent removed due to copyright restrictions.

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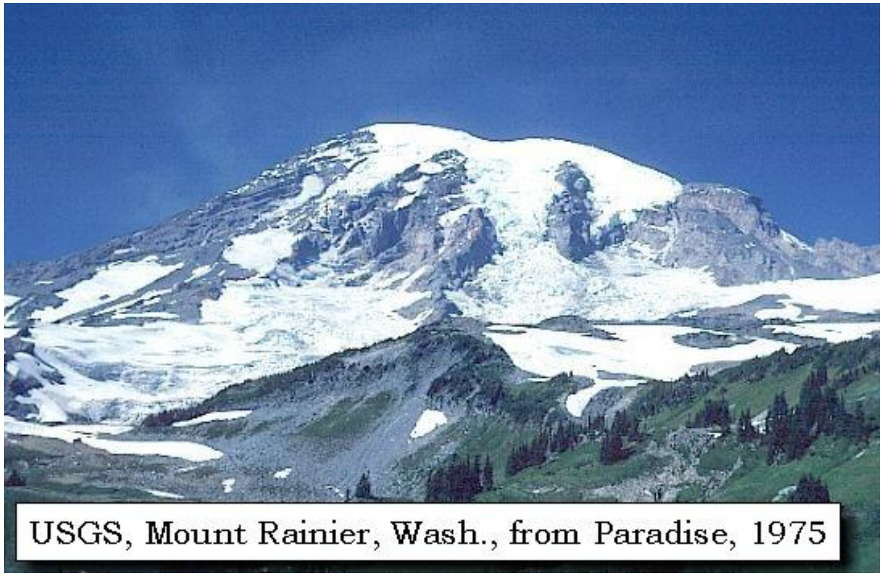

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Image courtesy of USGS.

Scaling Habitability

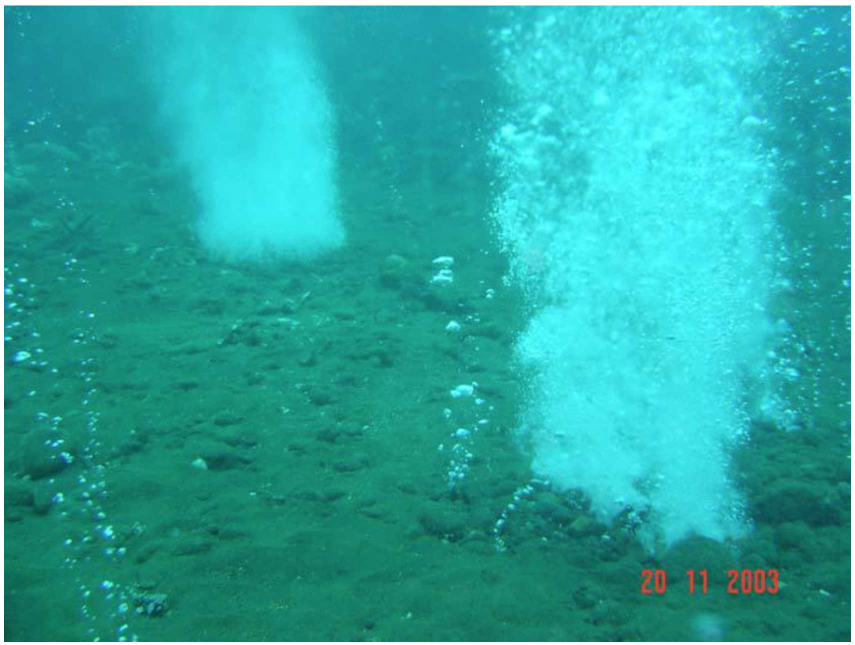

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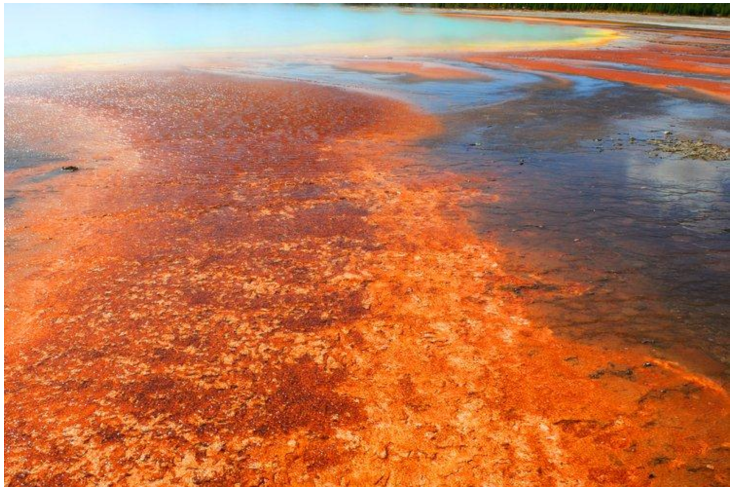
Photo: Meyer-Dombard

So what is Extreme?

cold

heat



Courtesy of NASA.

Courtesy of NASA.

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salt

http://www.flickr.com/photos/motorbikematt/4541461103/
by Matthew Reyes

Research Paper

Quantitative Habitability

EVERETT L. SHOCK[1,2] and MELANIE E. HOLLAND[1,*]

ABSTRACT

A framework is proposed for a quantitative approach to studying habitability. Considerations of environmental supply and organismal demand of energy lead to the conclusions that power units are most appropriate and that the units for habitability become watts per organism. Extreme and plush environments are revealed to be on a habitability continuum, and extreme environments can be quantified as those where power supply only barely exceeds demand. Strategies for laboratory and field experiments are outlined that would quantify power supplies, power demands, and habitability. An example involving a comparison of various metabolisms pursued by halophiles is shown to be well on the way to a quantitative habitability analysis.

Key words: Habitability-Extreme environments-Net power-Power supplies-power demands-Halophiles. Astrobiology 7, 839-851.

Life on Earth

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Please see the image on:
http://www.astro.rug.nl/~schuitert/De_zoektocht_naar_leven/deelvraag1.php

Habitability Continuum?

extreme

habitable

energy available
to an organism
per unit time

Shock, E.L., 2006. AbSciCon Presentation #165.

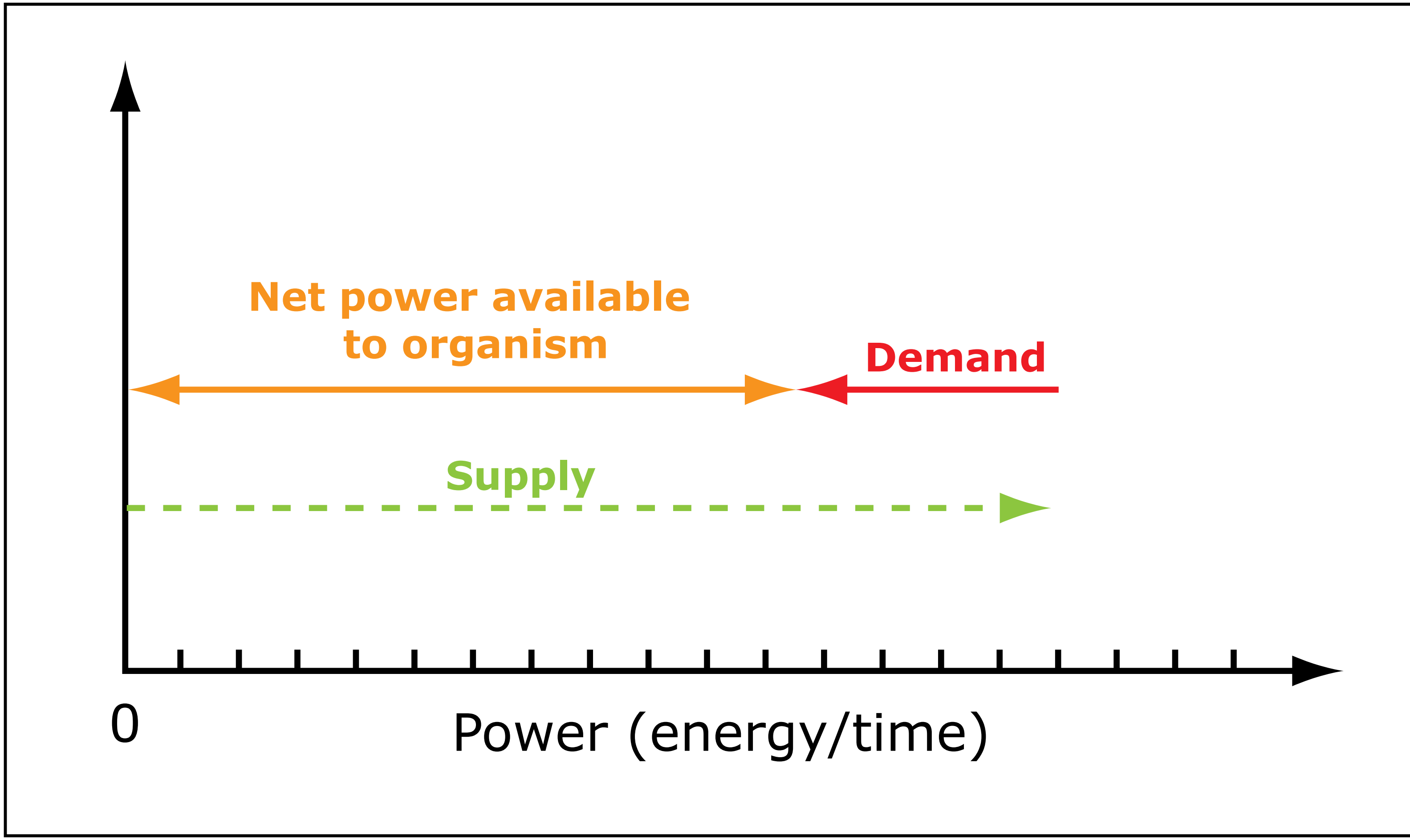
Habitability Continuum?

extreme → **habitable**

Power (watts)

Shock, E.L., 2006. AbSciCon Presentation #165.

Quantifying Habitability?



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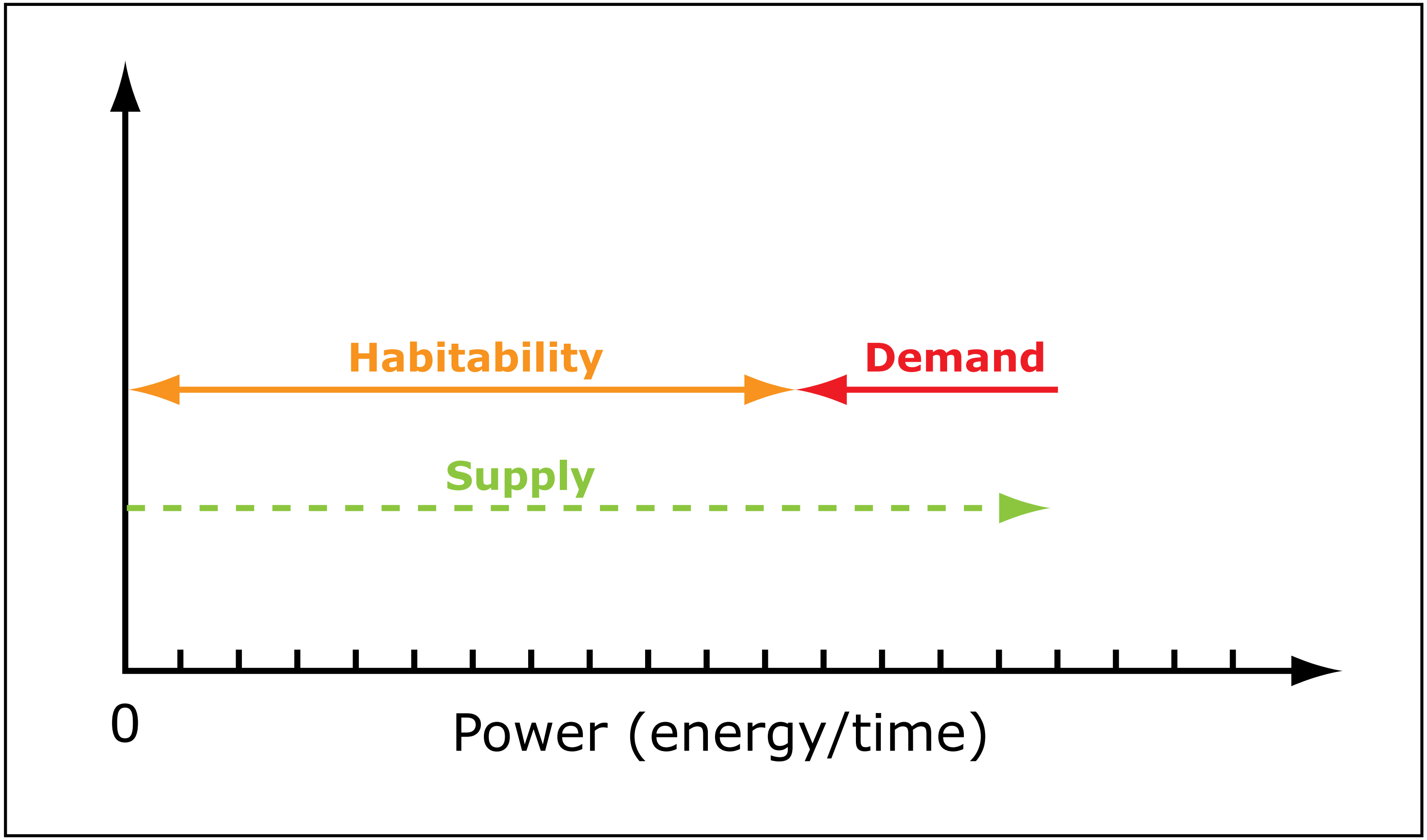
Quantifying Habitability?



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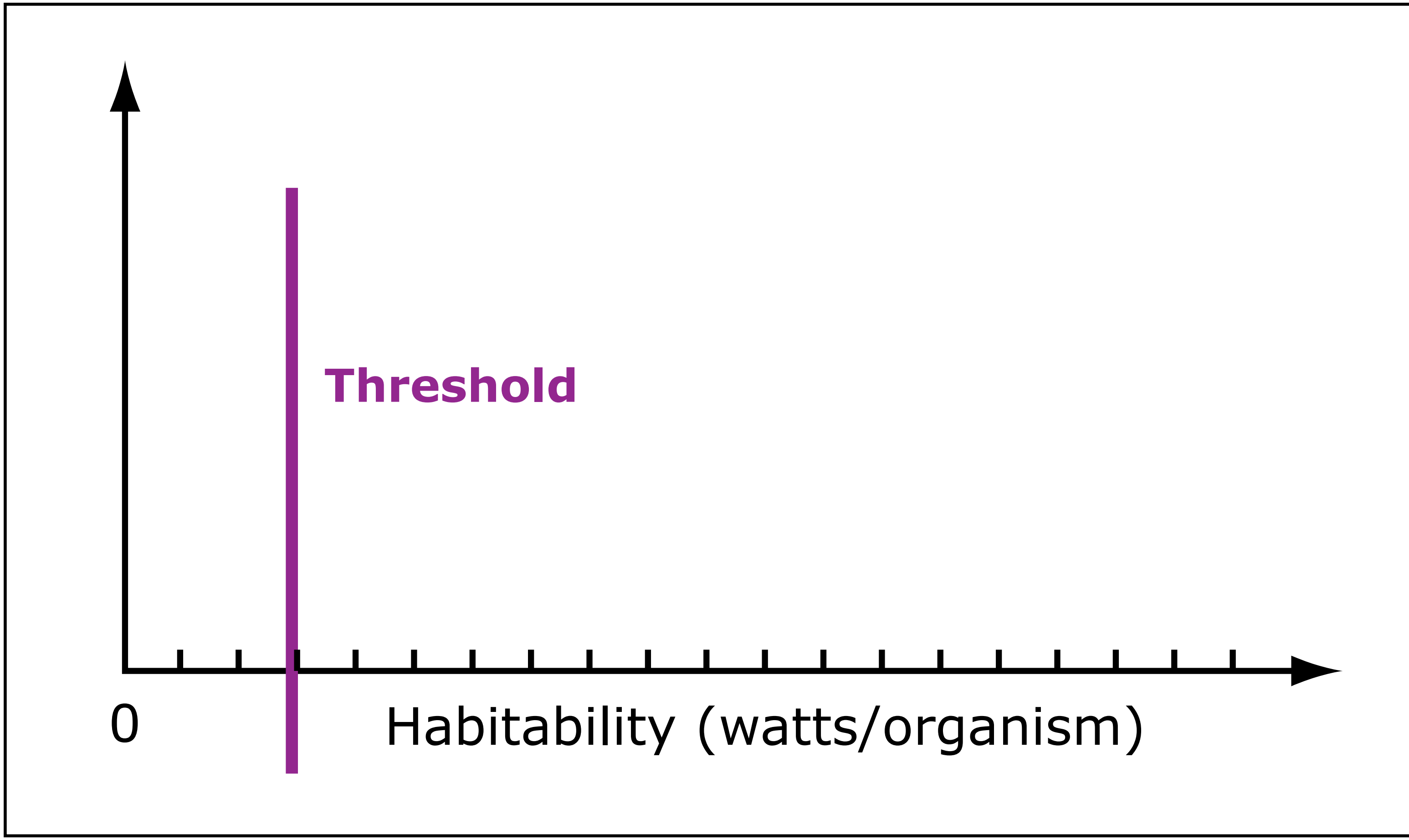

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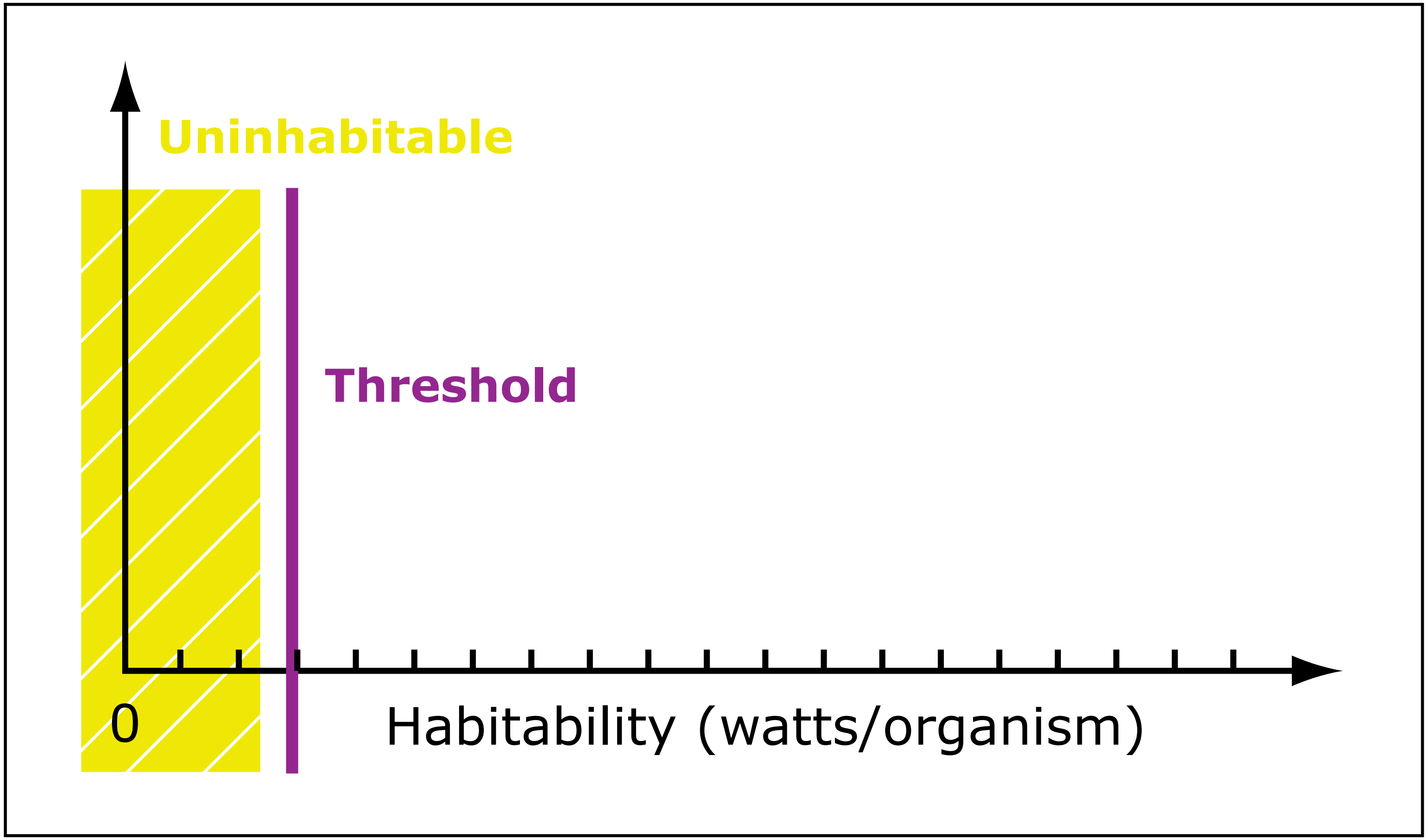

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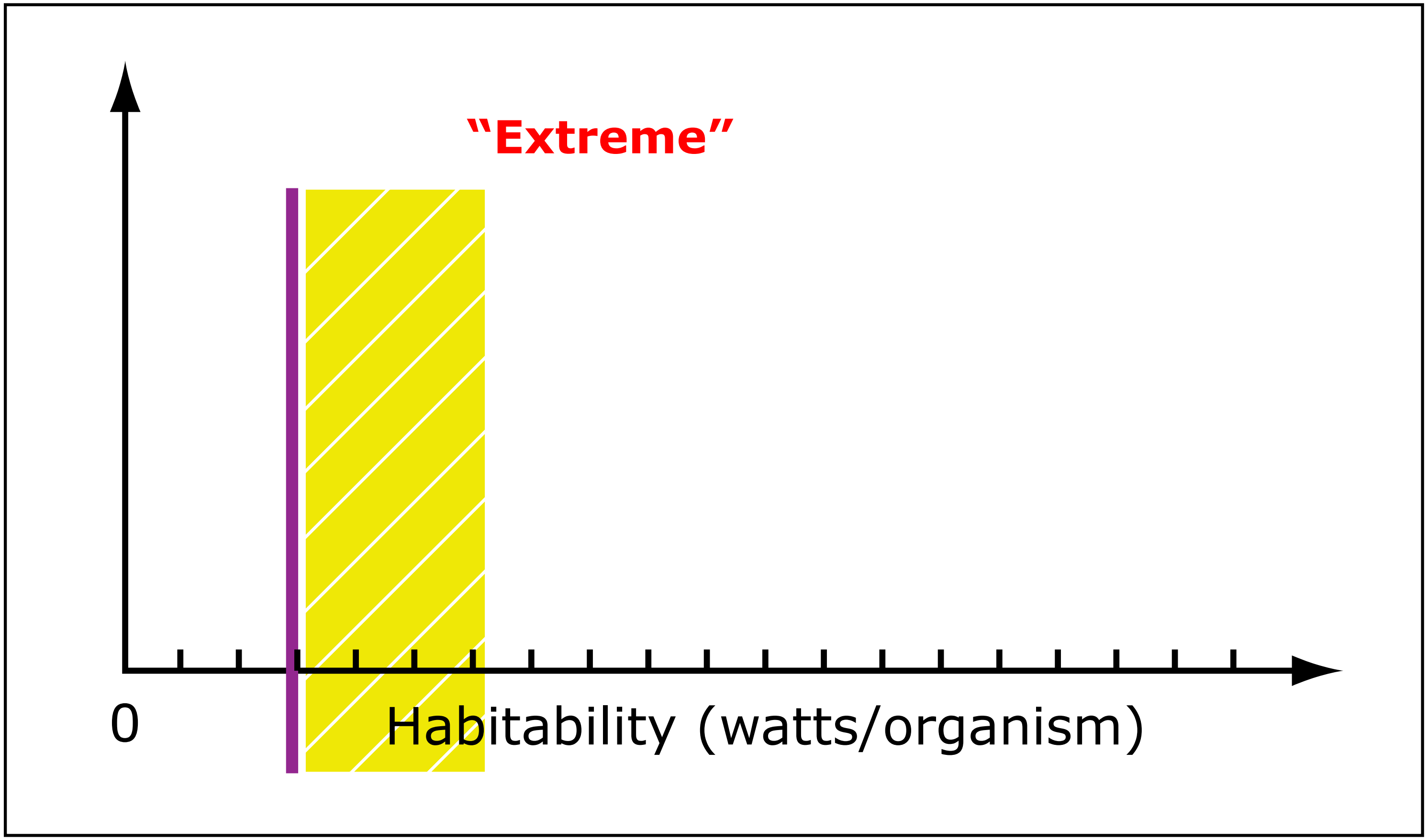

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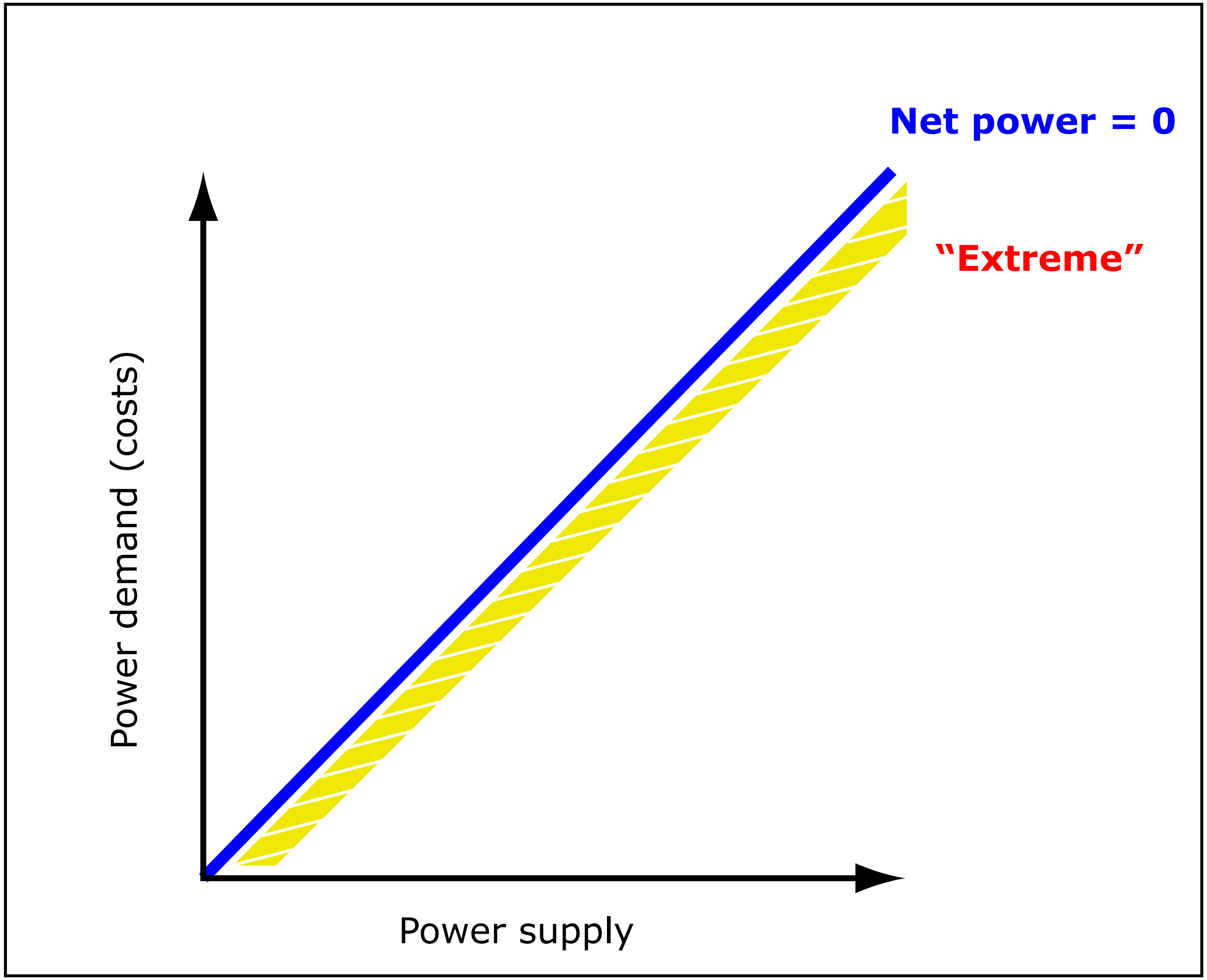

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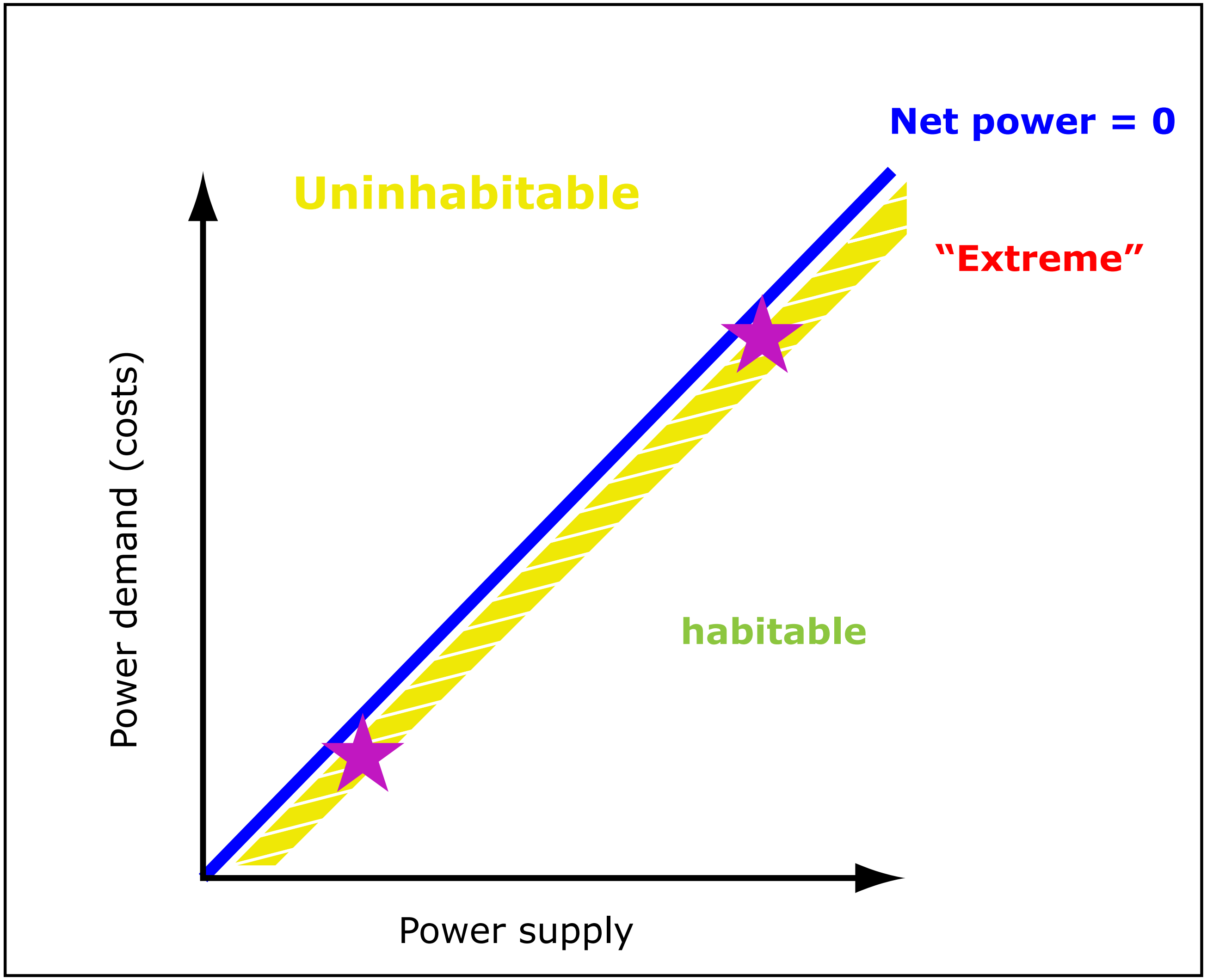

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Examining the chemotrophic 'buffet'

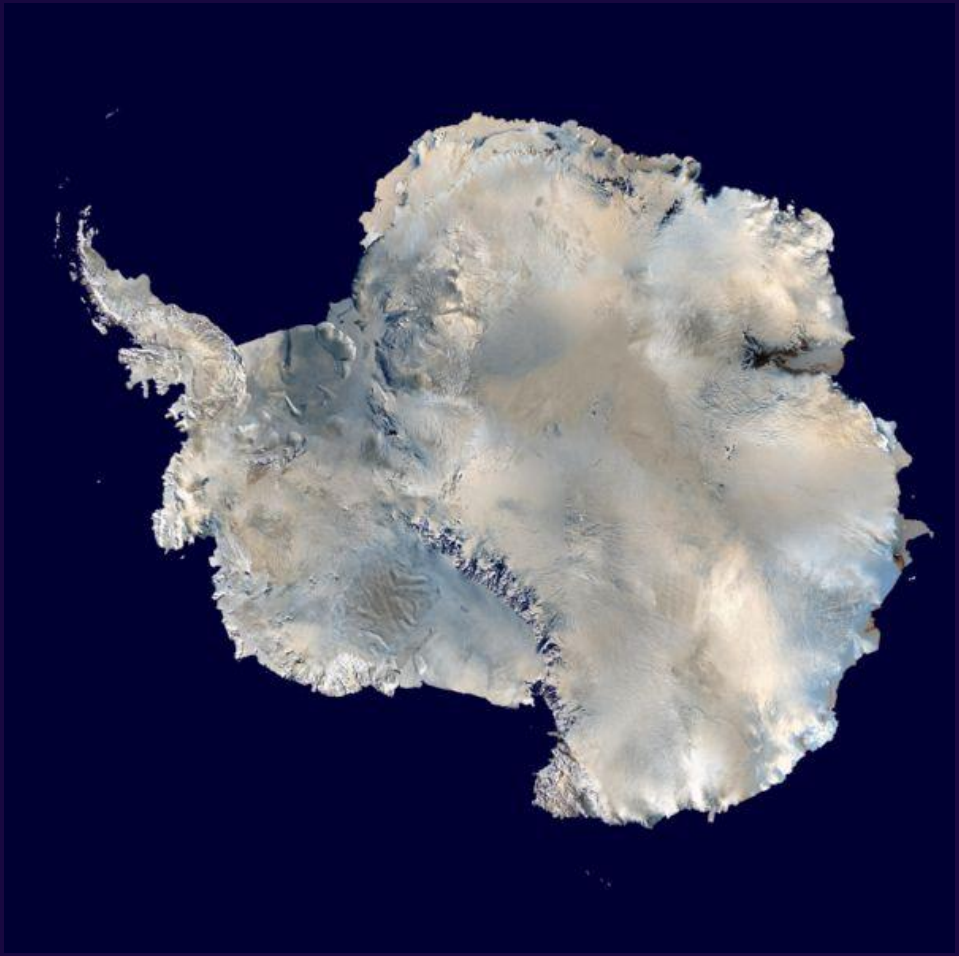
$$\Delta G_r = \Delta G_r^0 + RT\ln Q_r$$

↑ "activity product"

$$Q_r = \prod a_{(i,r)}^{V(i,r)}$$

$\Delta G_r < 0$ → energy yielding

- Example: $S^0 + H_{2(aq)} \rightarrow H_2S_{(aq)}$
- $Q_r = \dfrac{a_{H_2S(aq)}}{(a_{H_2(aq)})(a_{S^\circ})}$



http://visibleearth.nasa.gov/view_rec.php?id=2433

Endolithic Microorganisms in the Antarctic Cold Desert

E. Imre Friedmann

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Please see Figures 4, 5, and 7 on:
http://www.sciencemag.org/content/215/4536/1045.full.pdf

Endolithic Microorganisms in the Antarctic Cold Desert

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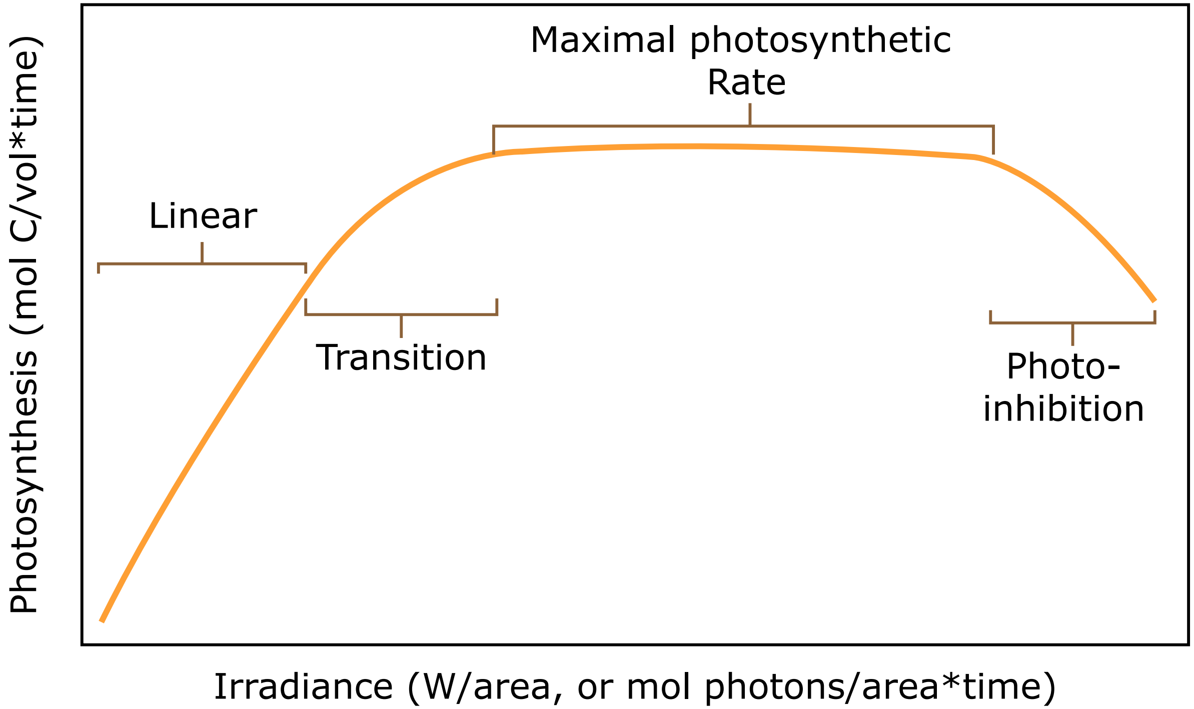

Photosynthetic productivity as a function of irradiance, showing a linear dependence at low irradiance, followed by a transition to a maximal rate, which then transfers into a range of high irradiance at which photosynthesis becomes inhibited.

Image by MIT OpenCourseWare.

SHOCK and HOLLAND, 2007

The Effects of Freezing and Desiccation on Photosynthesis and Survival of Terrestrial Antarctic Algae and Cyanobacteria

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Please see Figures 1 and 10 on:
http://link.springer.com/article/10.1007%2FBF00238287#page-1

Davey, 1989

Obligate psychrophile

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Please see the image on:
http://webadventures.rice.edu/games/302/materials/Magazine-302.pdf

Colwellia psychrerythraea

Photo: Richard A. Finkelstein / NCBI

Ice-active substances associated with Antarctic freshwater and terrestrial photosynthetic organisms

JAMES A. RAYMOND1* and CHRISTIAN H. FRITSEN*

ICE-NUCLEATION PROTEINS AND ANTIFREEZE SUBSTANCES

Antarctic Sea Ice-a Habitat for Extremophiles

D.N. Thomas and G.S. Dieckmann

The pack ice of Earth's polar oceans appears to be frozen white desert, devoid of life. However, beneath the snow lies a unique habitat for a group of bacteria and microscopic plants and animals that are encased in an ice matrix at low temperatures and light levels, with the only liquid being pockets of concentrated brines. Survival in these conditions requires a complex suite of physiological and metabolic adaptations, but sea-ice organisms thrive in the ice, and their prolific growth ensures they play a fundamental role in polar ecosystems. Apart from their ecological importance, the bacterial and algae species found in sea ice have become the focus for novel biotechnology, as well as being considered proxies for possible life forms on icecovered extraterrestrial bodies.

Image by MIT OpenCourseWare.

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Please see Figure 1 on:
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Please see Figure 3 on:
http://www.sciencemag.org/content/295/5555/641.full

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Deinococcus radiodurans

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Please see the image on:
http://www.scifun.ed.ac.uk/card/images/facts/d_radiodurans.jpg

Fenton's Reaction

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH\cdot + OH^-$$

OR

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + OOH\cdot + H^+$$

$OH\cdot$ and $OOH\cdot$ promote relatively **non-specific** oxidation of all organic compound classes (in water)

Commonly used to clean glassware, wastewater, degrade pesticides etc

Fenton's Reaction

Radical Addition: OH• + benzene → phenol + H•

Hydrogen Abstraction: OH• + CH_3OH → CH_2O + H_2O

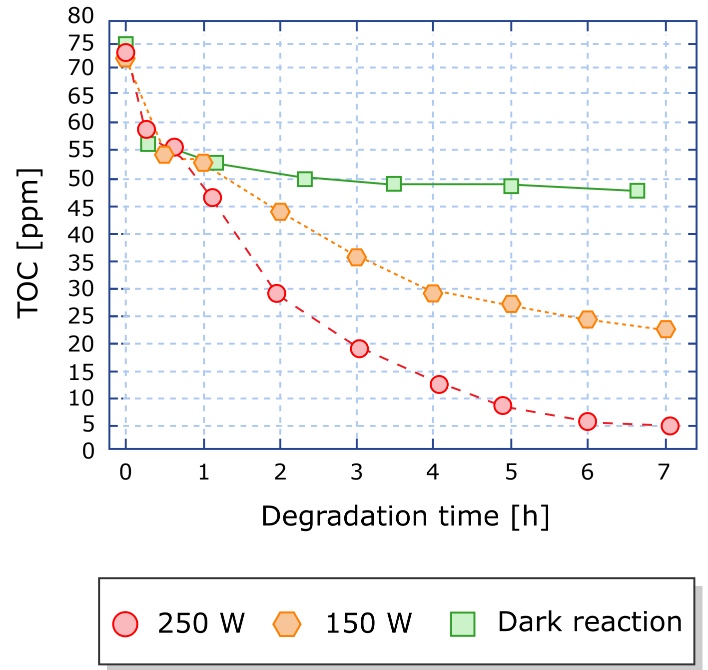
Oxidation: OH• + $[Fe(CN)6]^{4-}$ → $[Fe(CN)6]^{3-}$ + OH-

Radical Interaction: OH• + OH• → H_2O_2

Photo-Fenton Reaction in Aqueous Solution

$$Fe_{aq}^{3+} + H_2O \xrightarrow{h\nu} Fe_{aq}^{2+} + OH^{\bullet} \quad (< 400\text{nm})$$

$$H_2O_2 \rightarrow 2\ OH^{\bullet}$$



Effect of irradiation on the degradation of TOC (C_0(4-CP) = 1.01 x 10^{-3} mol l^{-1}, $C_0(H_2O_2)$ = 1.01x10^{-2} mol l^{-1}, $C_0(Fe^{2+})$ = 2.5x10^{-4} mol l^{-1}).

Image by MIT OpenCourseWare.

G. Ruppert, R. Bauer, G. Heisler

The photo-Fenton reaction — an effective photochemical wastewater treatment process

Journal of Photochemistry and Photobiology A: Chemistry, 73, 75-78 (1993)

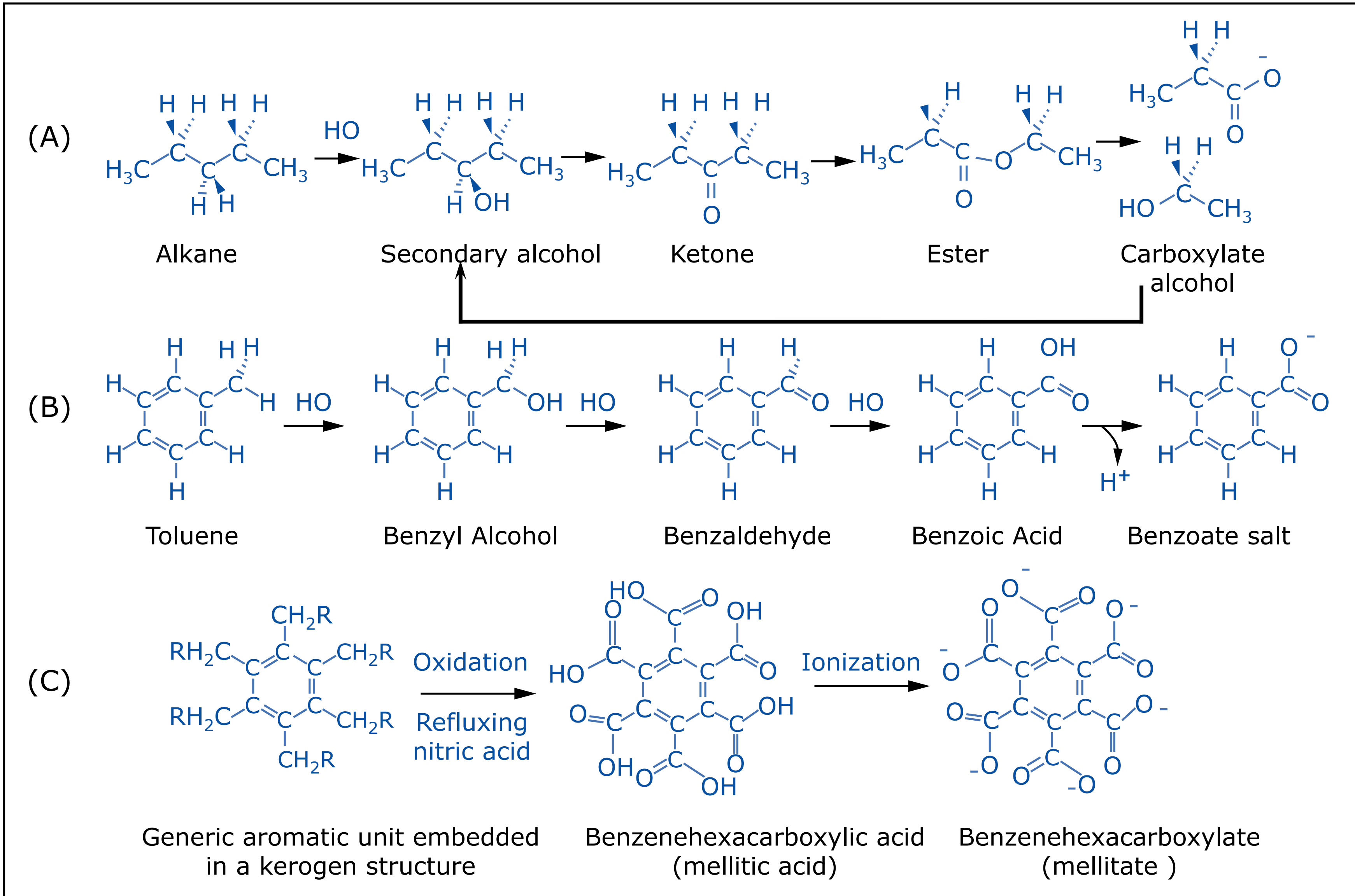
Photo-Fenton Reaction in Adsorbed Water

$$Fe_{aq}^{3+} + H_2O \xrightarrow{hv} Fe_{aq}^{2} + H^{+} + OH^{\bullet}$$

A photo-Fenton-like process on mineral surfaces that releases hydroxyl radicals and, thus, that oxidize any organic molecules may be responsible for the lack of organics of meteoritic origin in martian soil of the upper surface, as was concluded from the results of Viking mission experiments.

Adsorption Water-Related Potential Chemical and Biological Processes in the Upper Martian Surface, D. MÖHLMANN Astrobiology, 5, 770, 2005

Alkane degradation pathway



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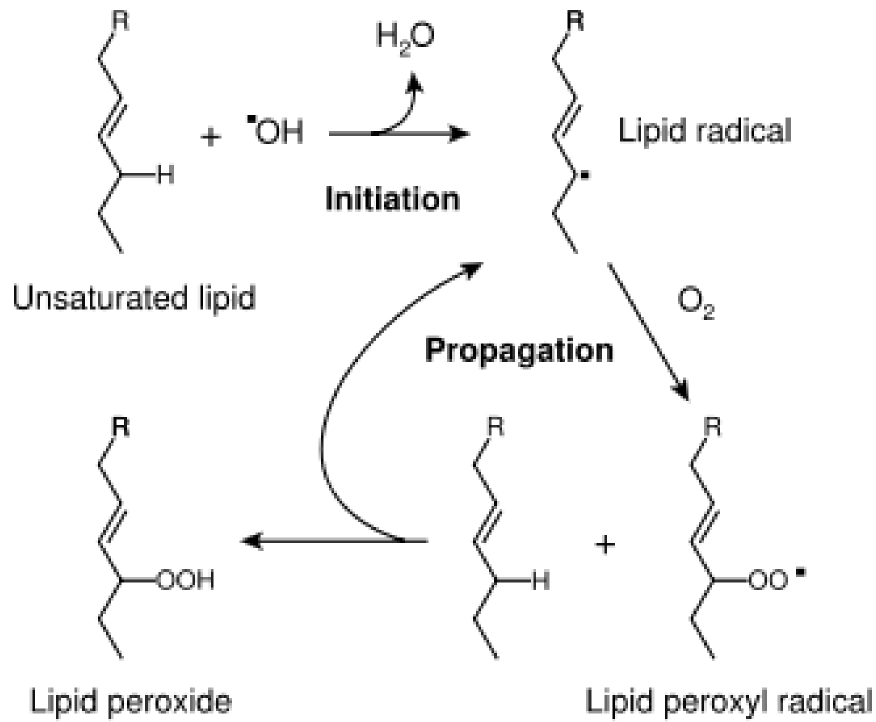
From Benner et al, 2000

Lipid radical formation



Accumulation of Mn(II) in Deinococcus radiodurans Facilitates Gamma-Radiation Resistance

D_{10} Survival values and intracellular Mn and Fe levels (12).

Strains	Radiation dose yielding 10% CFU survival	Desiccation dose yielding 10% CFU survival	^{59}Fe accumulation, atoms/cell	^{54}Mn accumulation, atoms/cell	Total Fe: ICP-MS/nmol Fe/mg protein	Total Mn: ICP-MS/nmol Mn/mg protein	Intracellular Mn/Fe (ICP-MS) concentration ratio
D. radiodurans	16 kGy	>30 days	2.7×10^3	1.08×10^5	1.49 (±0.39)	0.36 (±0.11)	0.24
Deinococcus geothermalis	10 kGy	>30 days	7.7×10^3 ($\pm 1.1 \times 10^3$)	2.17×10^5 ($\pm 3.7 \times 10^3$)	1.7 (±0.39)	0.78 (±0.15)	0.46
Enterococcus faecium	2.0 kGy	>30 days	ND	ND	6.3 (±2.8)	1.1 (±0.21)	0.17
E. coli	0.7 kGy	8 days	7×10^5 (16)	3.8×10^4 (16)	2.72 (±0.63)	0.0197 (±0.0027)	0.0072
Pseudomonas putida	0.25 kGy	1 day	ND	ND	6.8 (±0.70)	<0.001	<0.0001
S. oneidensis	0.07 kGy	<1 day	2.7×10^4	$<5 \times 10^2$	4.98 (±0.40)	0.0023 (±0.00005)	0.0005
D. radiodurans low-Mn DMM	10 kGy	ND	ND	ND	2.1	0.7	0.33
D. radiodurans high-Mn DMM	ND	ND	ND	ND	1.6	3.9	2.5

Image by MIT OpenCourseWare.

M. J. Daly, *et al.* 2008

Life in hot springs

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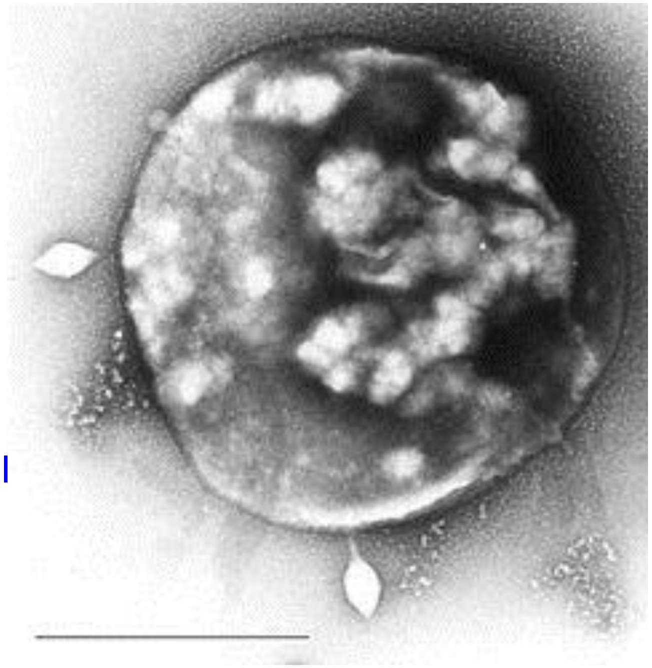
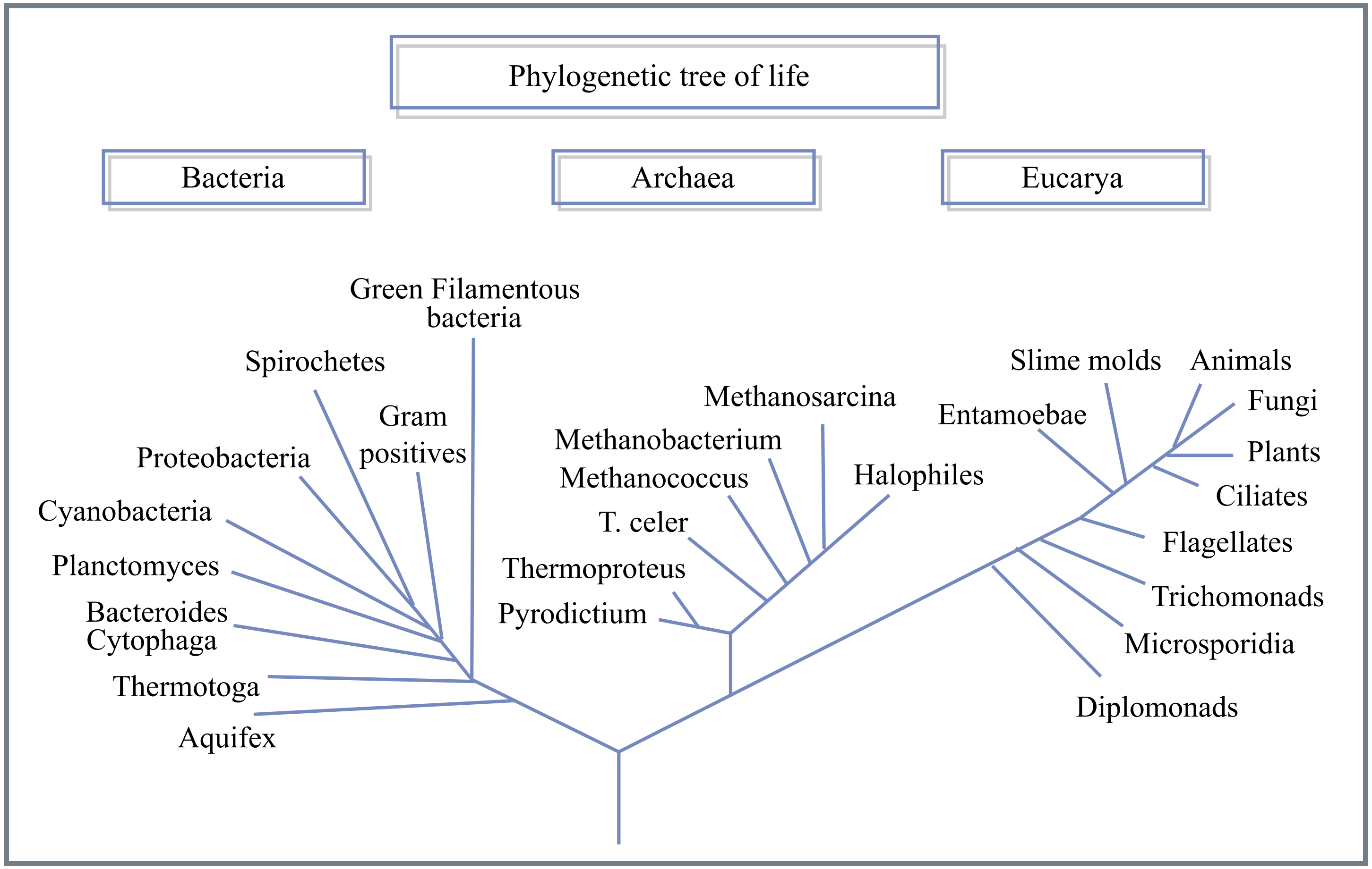


Sulfolobus solfataricus

pH 3, 80°C

Rothschild and Mancinelli, 2001



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Intact Microbial Lipids

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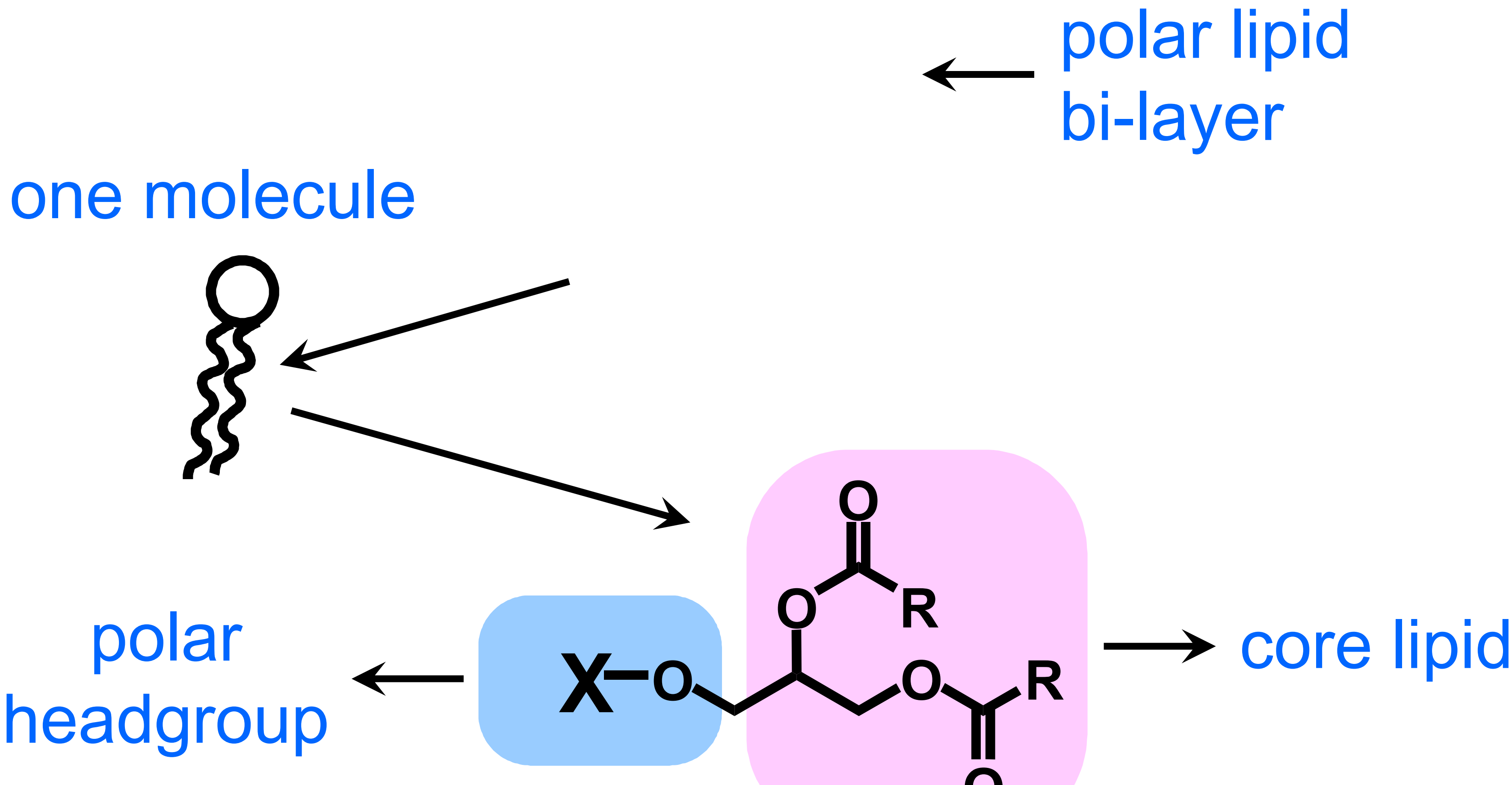
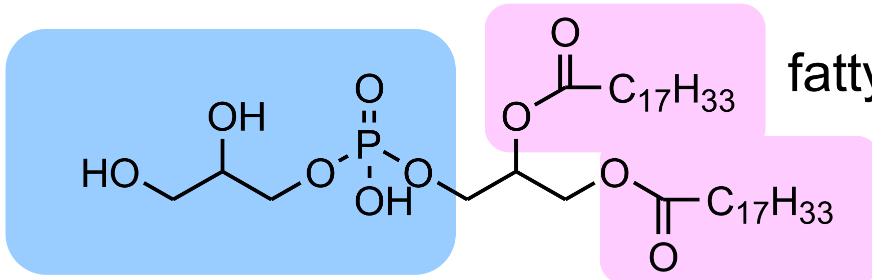


Figure 2: Generalized structure of an IPL

IPL variety analyzed by HPLC-ESI-MS

bacterial

10+ different headgroups identified…



fatty acids ~C_{12} to C_{24}

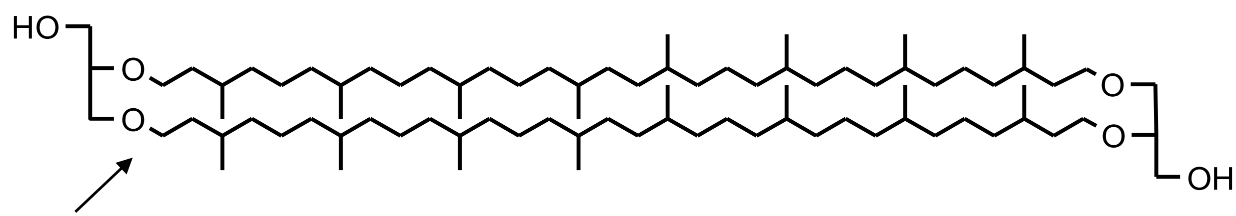
may also be alcohols

phospholipids & glycolipids, some highly specific

archaeal

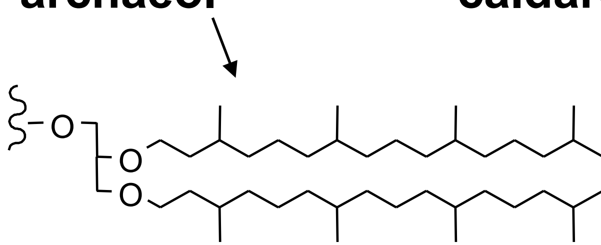
similar variety of headgroups but highly specific core lipids

2 basic types
with some variations

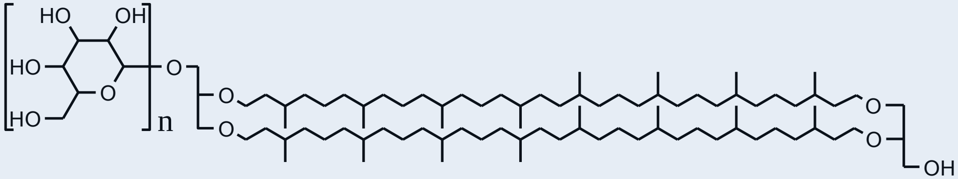


caldarchaeol (GDGT: glycerol dialkyl glycerol tetraether)

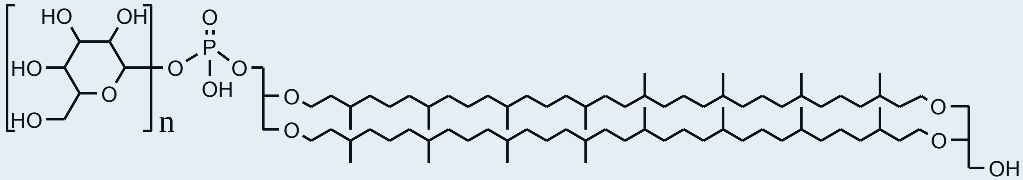
archaeol



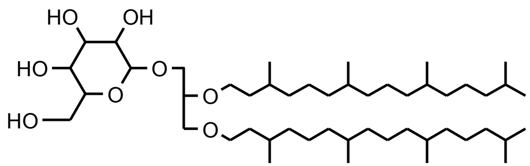
Data on IPL distributions in biogeochemically relevant prokaryotes are very sparse



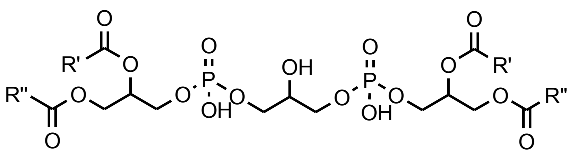
*n*G-GDGT
n = 1-4
Glycosyl glycerol
dibiphytanyl glycerol tetraether



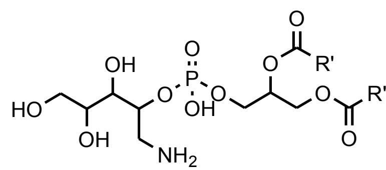
*n*G-PO_4-GDGT
n = 1-4



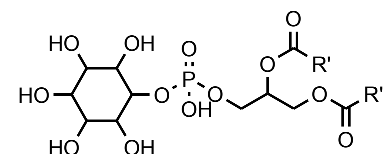
MG-archaeol



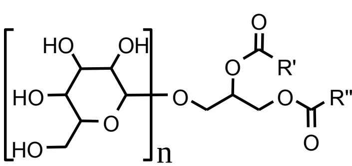
DPG
diphosphatidylglycerol



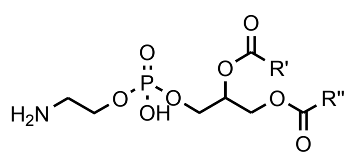
APT
aminopentanetetrol



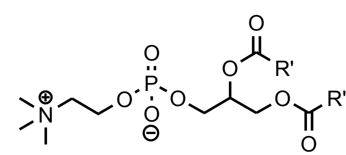
PI
inositol



MGDG,DGDG
mono, di-glycosyl diglyceride



PE
ethanolamine



PC
choline

Life in hot springs

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Thermotoga

K. Stetter

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Aquifex

Please see:
http://microbewiki.kenyon.edu/index.php/Image:Aquifex-pt1.jpg

Please see:
http://microbewiki.kenyon.edu/index.php/File:Aquifex_environment.jpg

Historical Perspective

PSC -filamentous bacteria living at 89ºC
Setchell, 1898

Filamentous bacteria colonised glass slide at 91ºC
Brock, ‘67

Microbiology/Genomics

Reysenbach et al., 1994 → 16S rRNA sequences → limited diversity - only 3 phylotypes of which
26/39 = Aquificales (EM17) → *T. ruber*
remainder Thermotogales (EM19) and an unknown group (EM3)

No Archaea detected

***Thermocrinis ruber* nov sp. isolated Huber, Eder et al. 1998**

Chemosynthetic Zone Clone libraries

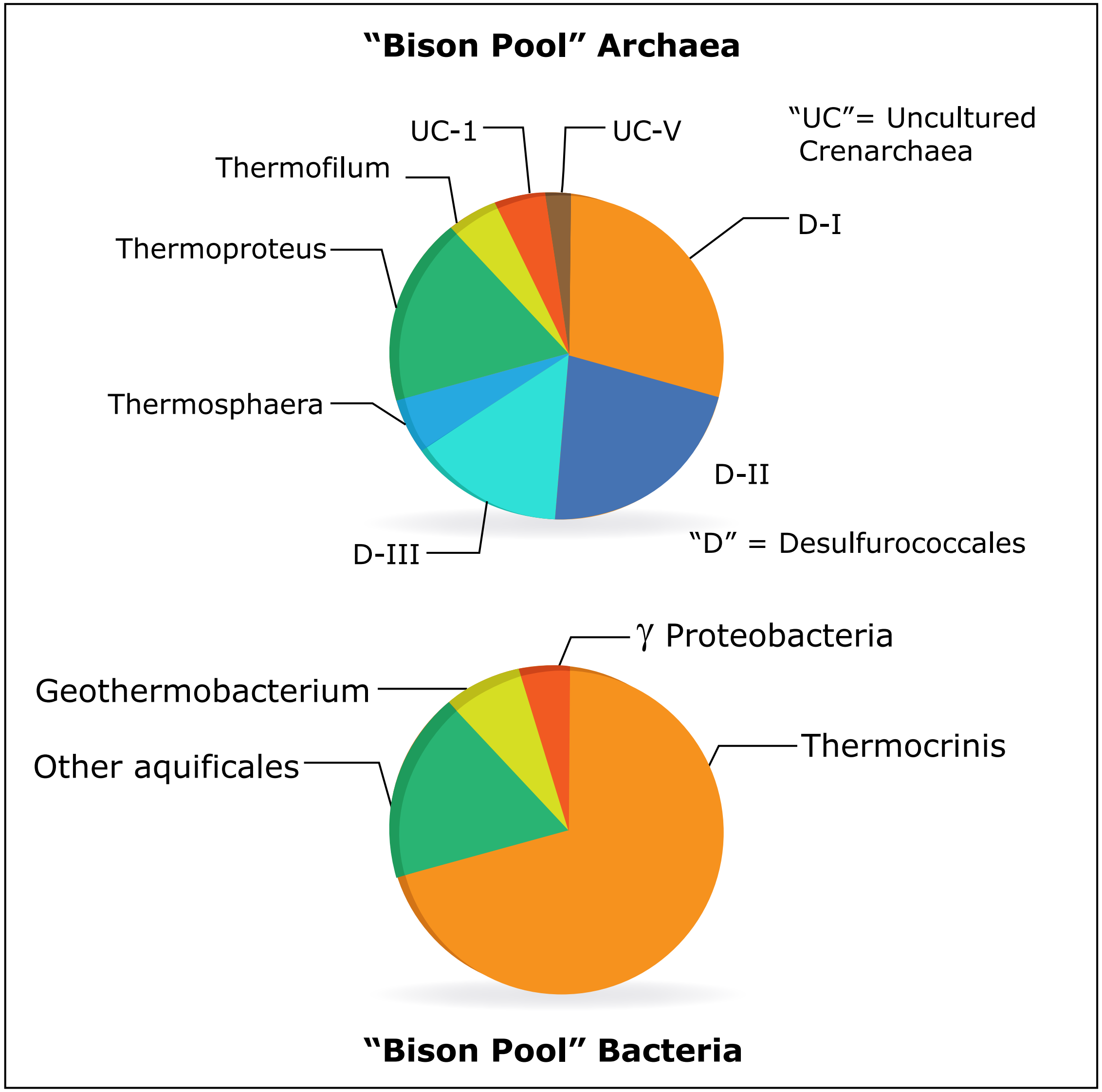

Image by MIT OpenCourseWare.

Archaeal Clones
100% Crenarchaea

- 66% Desulfurococcales
- 27% Thermoproteales
- 7% Uncultured Crens

Bacterial Clones
71% Thermocrinis

Meyer-Dombard et al., 2005 Geobiology

Life in hot springs

Aquifex

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Please see:
http://microbewiki.kenyon.edu/index.php/Image:Aquifex-pt1.jpg

Schubotz et al., in review

Photosynthetic extremophiles

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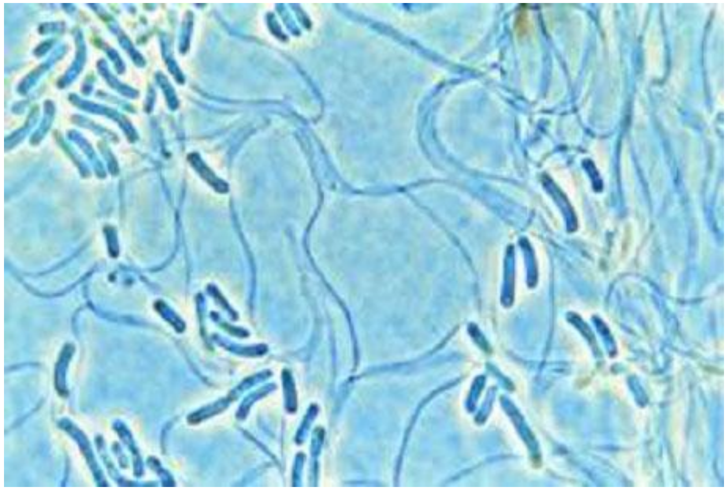
Please see Figure 5 on:
http://www.nature.com/nature/journal/v409/n6823/full/4091092a0.html

Cyanidium – red alga that lives at pH <4 and T ~ 42°C

Rotschild and Mancinelli, 2001



Castenholz

Cyanobacteria (*Synechococcus*) are found at pH > 4

Acid-mine drainage biota

Image courtesy of NASA.

$$H_2S + 2\ O_2 \rightarrow H_2SO_4$$
$$2\ H_2S + O_2 \rightarrow 2\ S^o + 2\ H_2O$$
$$2\ S^o + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4$$
$$Na_2S_2O_3 + 2\ O_2 + H_2O \rightarrow Na_2SO_4 + H_2SO_4$$
$$4\ Na_2S_2O_3 + O_2 + 2\ H_2O \rightarrow 2\ Na_2S_4O_6 + 4\ NaOH$$
$$2\ Na_2S_4O_6 + 7\ O_2 + 6\ H_2O \rightarrow 2\ Na_2SO_4 + 6\ H_2SO_4$$
$$2\ KSCN + 4\ O_2 + 4\ H_2O \rightarrow (NH_4)_2SO_4 + K_2SO_4 + 2\ CO_2$$
$$5\ H_2S + 8\ KNO_3 \rightarrow 4\ K_2SO_4 + H_2SO_4 + 4\ N_2 + 4\ H_2O$$
$$5\ S^o + 6\ KNO_3 + 2\ H_2O \rightarrow 3\ K_2SO_4 + 2\ H_2SO_4 + 3\ N_2$$
$$2\ FeS_2 + 2\ H_2O + 7\ O_2 \rightarrow 2\ FeSO_4 + 2\ H_2SO_4$$
$$4\ FeSO_4 + O_2 + 2\ H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2\ H_2O$$

Thiobacillus ferooxidans

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Please see the image on:
http://www.torinoscienza.it/img/200x200/it/s00/00/0004/0000048c.png

Life around black smokers

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Please see the animated image on:
http://www.laszloart.com/Vents.htm

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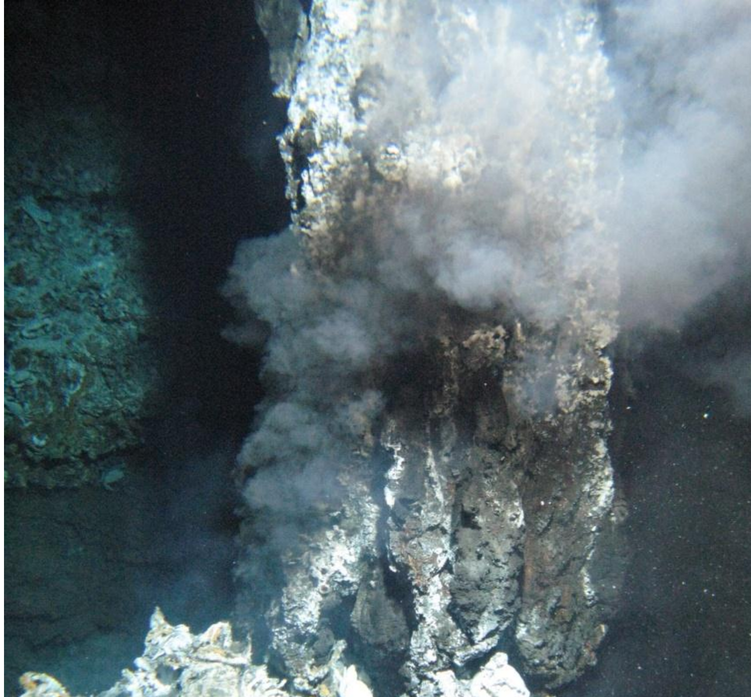
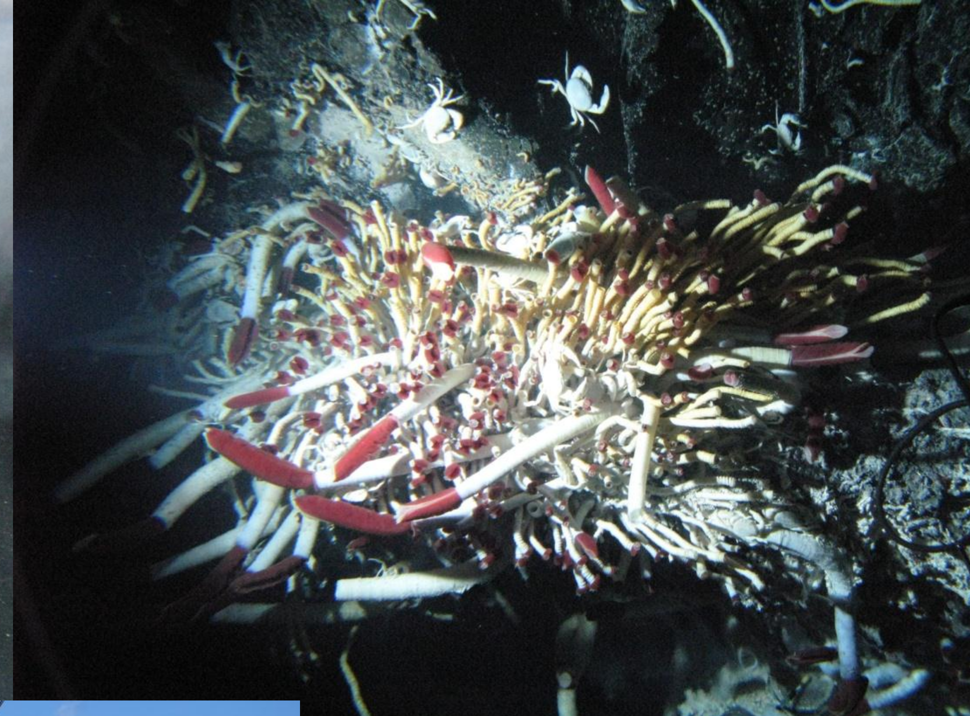
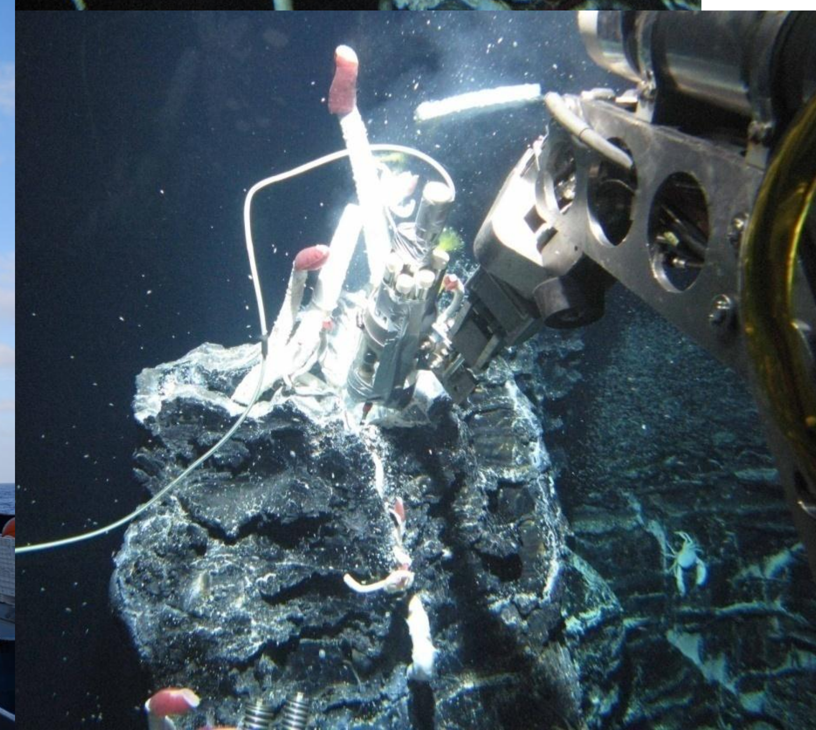
Please see the image on:
http://diversehierarchy.wikispaces.com/Archaebacteria+-+P.+fumarii

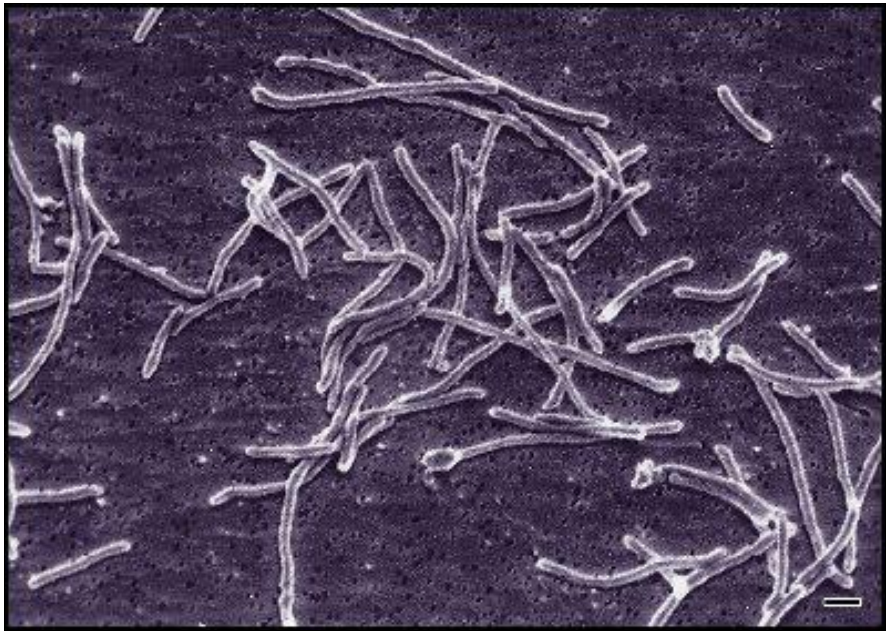
Pyrolobus fumarii



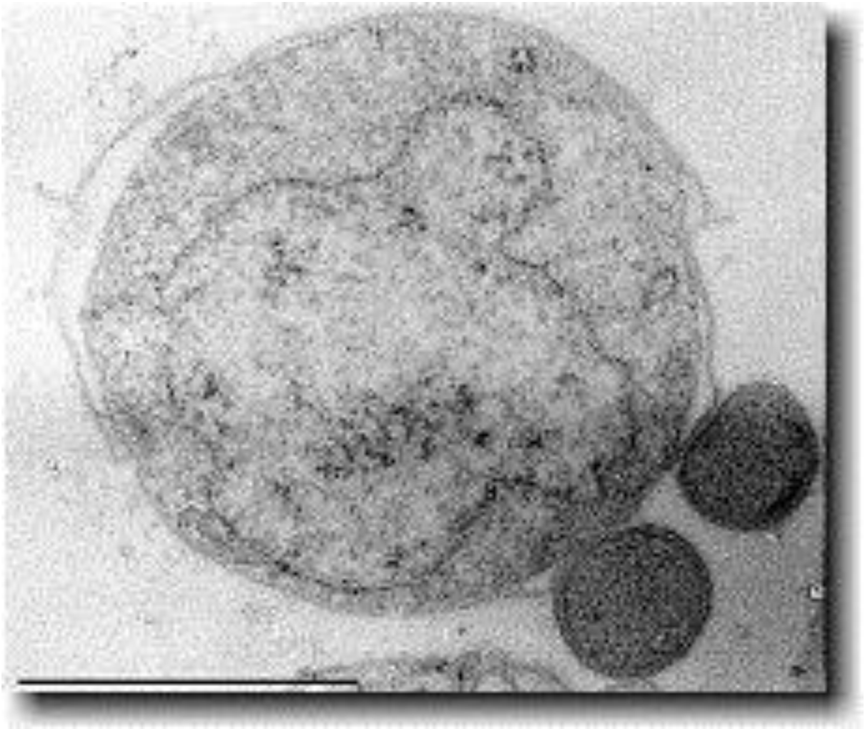
More hyperthermophiles

Pyrococcus furiosus



Thermus aquaticus

Archean parasite at near-boiling temperatures



Nanoarcheon equitans on Ignicoccus

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Life around black smokers

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Please see the images on:
http://www.accessexcellence.org/BF/bf01/arp/bf01p3.php

A Hot-Vent Gastropod with Iron Sulfide Dermal Sclerites

Anders Warén,[1*] Stefan Bengtson,[1] Shana K. Goffredi,[2]
Cindy L. Van Dover[3]

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Please see Figure 1 on:
http://www.sciencemag.org/content/302/5647/1007.full

The new gastropod. (A) Retracted in shell; scales and shell are rusty from storage in low grade ethanol. (B) Shell removed; front view of head-foot. Scales are in their normal, black color. (C and D) Longitudinal sections of scales, viewed with light microscopy (C) and scanning electron microscopy (D) photos. Sul, sulfide layers [black in (C), light in (D)].

Vampire squid: life at depth and low O_2

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Please see the images on:

http://www.pinterest.com/samurott/all-about-vampire-squids-book-project/

http://www.itsnature.org/sea/other/vampire-squid

http://www.seasky.org/deep-sea/deep-sea-menu.html

Loriciferans: life at depth and low or zero O_2

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http://culturingscience.files.wordpress.com/2010/04/snapshot-2010-04-07-14-39-34.jpg

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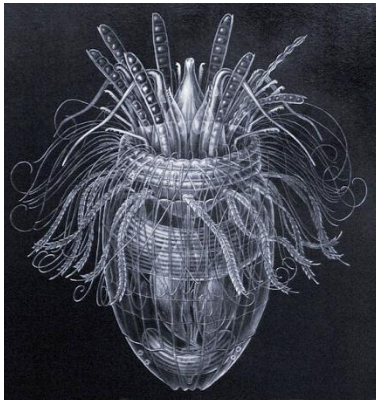
Please see the second image on:
http://www.benjamintseng.com/2010/06/life-without-oxygen/



L'Atalante basin, a brine lake west of Crete in the Med. Sea

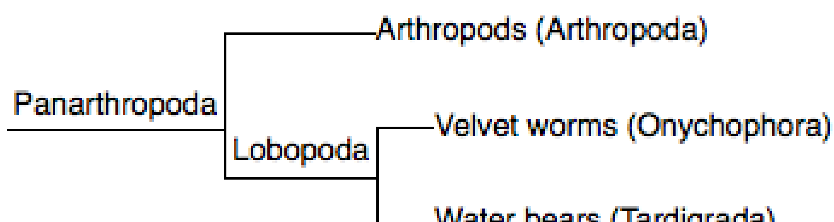
Image courtesy of NASA.

(Danovaro et al., 2010)

Tardigrades (waterbears or moss piglets): polyextremophiles

Image from
http://en.wikipedia.org/wiki/Hypsibiidae
by Bob Goldstein and Vicky Madden.

Survive desiccation, vacuum and radiation in space, high and low temperatures



Capable of suspended metabolism: Cryptobiosis

Life at high pressures

Photobacterium profundum

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http://microbewiki.kenyon.edu/images/e/e3/Photobacterium_profundum_flagella.JPG

Salt-loving organisms

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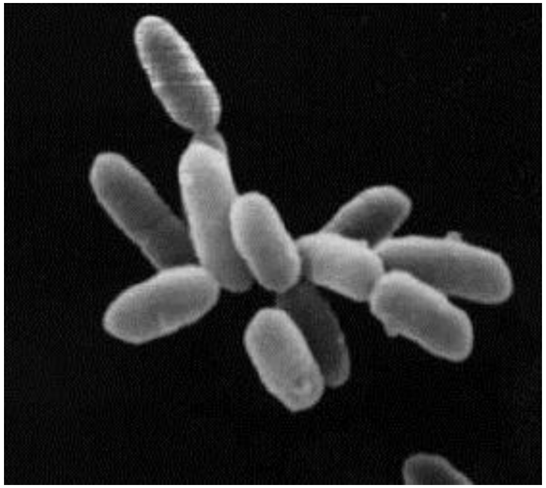
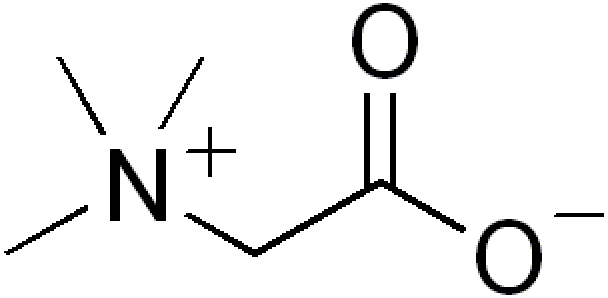
http://www.sas.upenn.edu/~pohlschr/

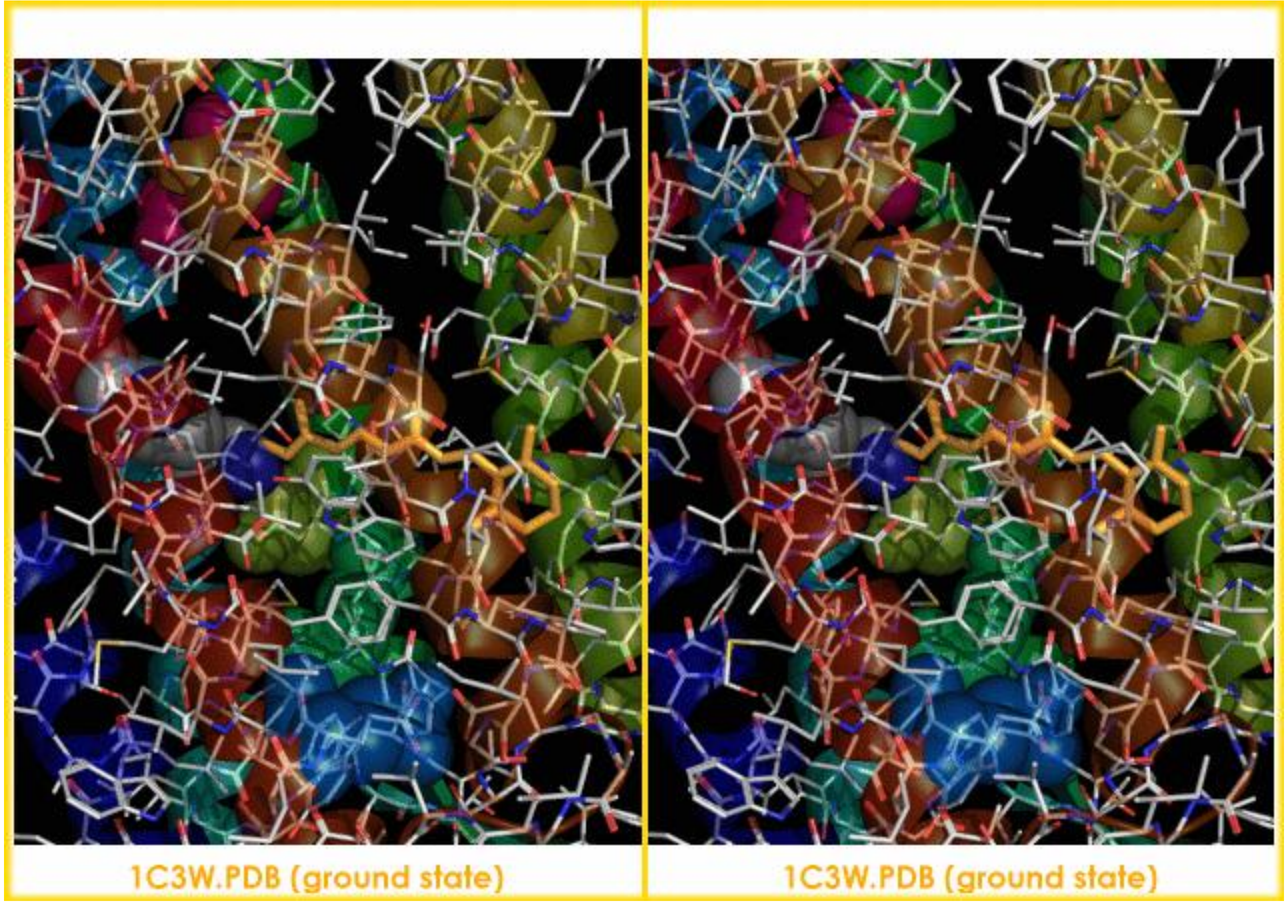


Halobacterium



Glycine betaine

Bacteriorhodopsin



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http://www.nature.com/nature/journal/v409/n6823/full/4091092a0.html

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Please see Table 3 on:
http://www.nature.com/nature/journal/v409/n6823/full/4091092a0.html

Rotschild and Mancinelli, 2001

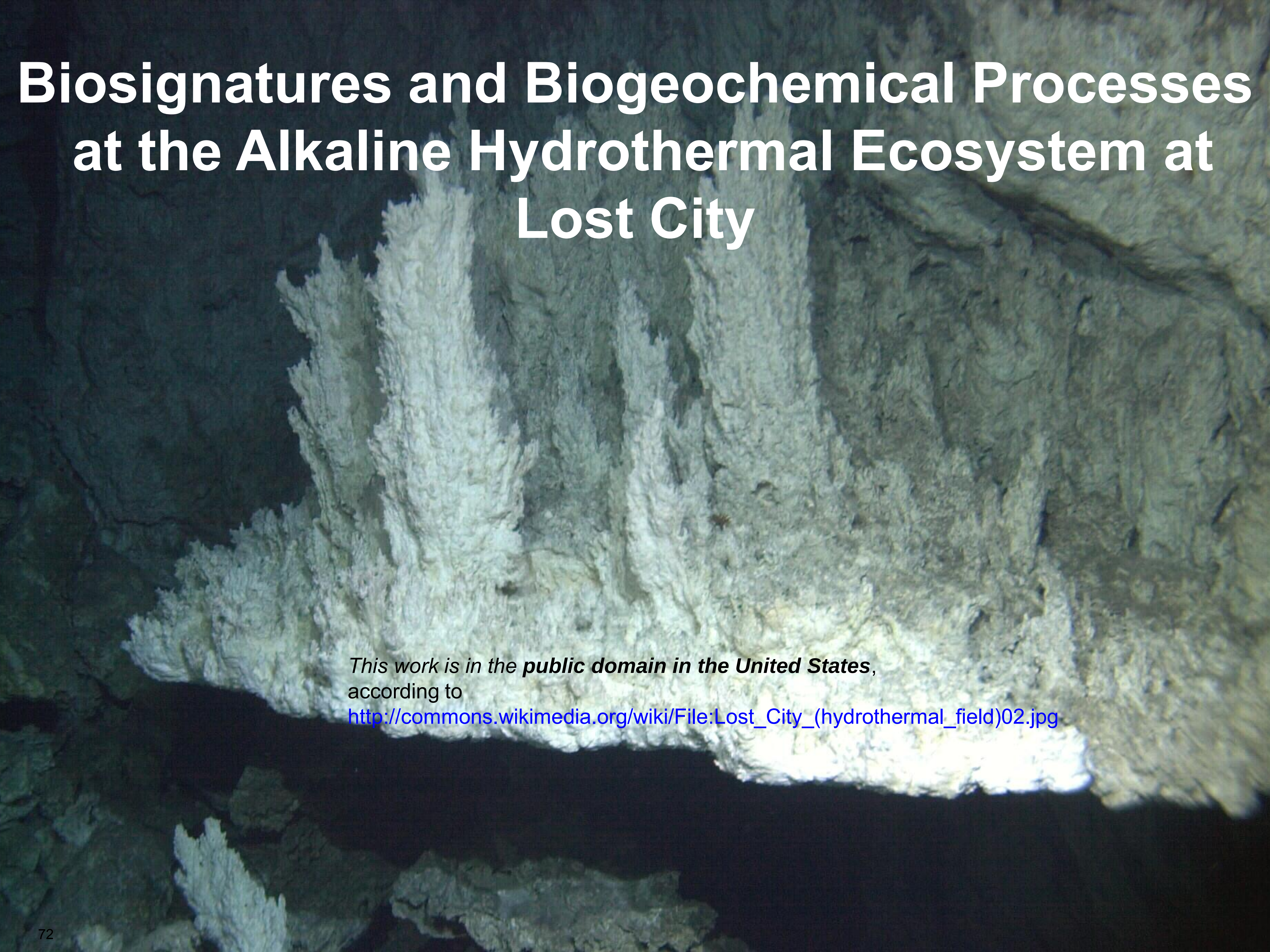
Serpentinization

Photograph of a carbonate chimney venting removed due to copyright restrictions.

Lost City

http://www.lostcity.washington.edu/file/Carbonate+chimney+venting+91%C2%B0C%2C+pH+11+fluids

Biosignatures and Biogeochemical Processes at the Alkaline Hydrothermal Ecosystem at Lost City

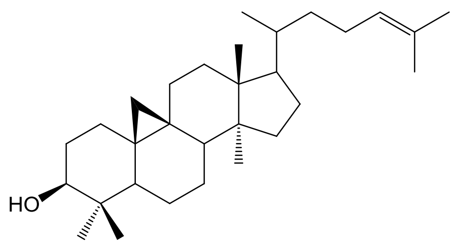


Overview

Overarching Goal: understand carbon cycling & microbial ecology in thermal environments

Approach: Apply tools of geochemistry and genomics

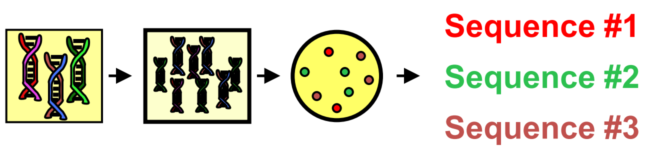
fluid chemistry



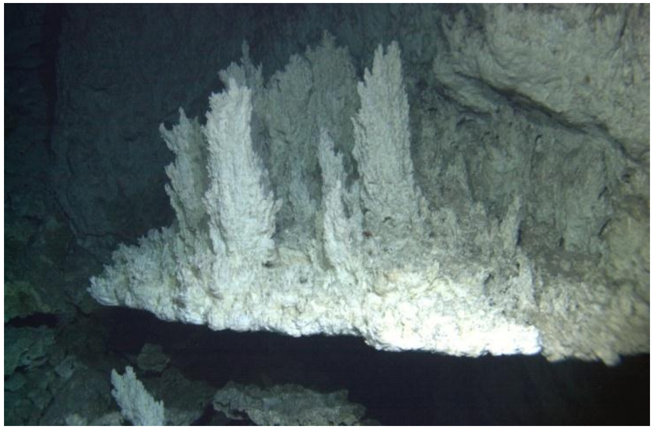
lipid structures

δ

stable isotopes



environmental DNA



Localities within the Lost City Hydrothermal Field

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Serpentinization: source of H_2 and alkalinity

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Photograph of a carbonate chimney venting removed due to copyright restrictions.

Olivine + water → Serpentine + brucite + magnetite + H_2

Lost City Hydrothermal Field

Photograph of a carbonate chimney venting removed due to copyright restrictions.

Vent Fluids

Hydrogen – up to 15 mmol/kg

Methane – up to 2 mmol/kg

Calcium – up to 30 mmol/kg

pH – 9 to 11

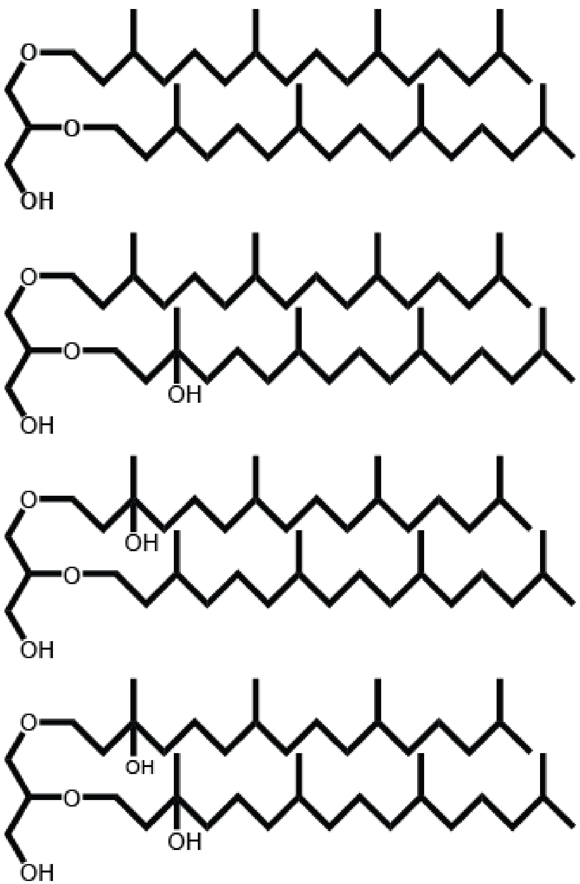
Low temp volatile production:
Proskurowski et al., Chem. Geology 2006

Abiogenic Hydrocarbon Production at Lost City Hydrothermal Field:
Proskurowski et al., Science 2006

Biomarkers at Lost City are dominated by diether lipids

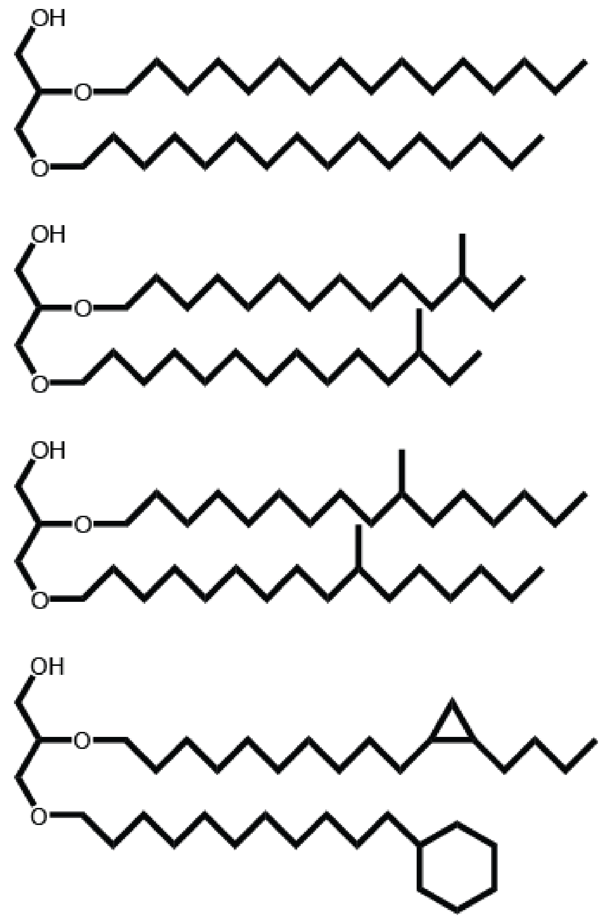
Archaeal diethers

Methanogens, ANME groups



Bacterial diethers

Aquificales, Ammonifex, Thermodesulfobacterium, δ-proteobacteria



Abiogenic Hydrocarbon Production at Lost City Hydrothermal Field

Giora Proskurowski,[1,2*] Marvin D. Lilley,[1] Jeffery S. Seewald,[2] Gretchen L. Früh-Green,[3] Eric J. Olson,[1] John E. Lupton,[4] Sean P. Sylva,[2] Deborah S. Kelley[1]

$$CO_{2aq} + [2 + (m/2n)]H_2 \rightarrow (1/n)C_nH_m + 2H_2O \quad (1)$$

Fischer-Tropsch

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Please see Figure 1 on: https://www.sciencemag.org/content/319/5863/604.full

Serpentinization in terrestrial environments: Cedars, CA

Please see the images on:
http://www.supertopo.com/climbing/thread.php?topic_id=1410539

12.007 Geobiology
Spring 2013