

Ch. 13: The Archaea

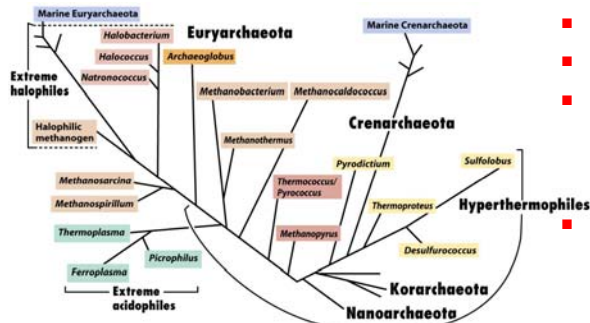


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Four phyla:

- Euryarchaeota
- Crenarchaeota
- Korarchaeota
 - Found in one spring In Yellowstone; no cultured representative
- Nanoarchaeota

13.2 Introduction

- Many Archaea are extremophiles
- With the exception of the methanogens, Archaea use similar metabolic pathways to those of the bacteria
- Chemoorganotrophy and chemolithotrophy are common
- Autotrophy by various pathways is common
- Do these life styles and metabolic pathways represent life on early Earth?

II Euryarchaeota

- **13.3** Extremely halophilic Archaea
- **Require** high salt concentration
 - > 1.5 M (~9%) NaCl
 - Most require 2-4 M
 - Some grow at 5.5 M (32%)
- Highly diverse metabolism and phylogeny reflecting the diversity in salt composition of saline environments

Table 13.1 Ionic composition of some highly saline environments^a

Ion	Concentration (g/l)		
	Great Salt Lake ^b	Dead Sea	Lake Zugm ^c
Na ⁺	105	40.1	142
K ⁺	6.7	7.7	2.3
Mg ²⁺	11	44	<0.1
Ca ²⁺	0.3	17.2	<0.1
Cl ⁻	181	225	155
Br ⁻	0.2	5.3	—
SO ₄ ²⁻	27	0.5	23
HCO ₃ ⁻	0.7	0.2	67
pH	7.7	6.1	11

^a For comparison, seawater contains (grams per liter): Na⁺, 10.6; K⁺, 0.38; Mg²⁺, 1.27; Ca²⁺, 0.4; Cl⁻, 19; Br⁻, 0.065; SO₄²⁻, 2.65; HCO₃⁻, 0.14; pH 7.8.

^b See Figure 13.2a.

^c Wadi El Natroun, Egypt (see Figure 13.2c).

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Microbial communities in saline environments:

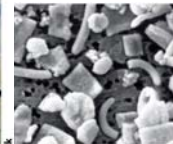
- Archaea are not alone:
 - Algae (*Dunaliella*) and anoxygenic phototrophic bacteria; a highly productive environment
 - Many halophiles are heterotrophs
 - Marine salterns - A “bloom” of halophilic archaea; red color is caused by the pigments of *Halobacterium* (bacterioruberins and bacteriorhodopsins)
 - Diverse and unique cellular forms are present in such blooms



Figure 13.2a Brock Biology of Microorganisms 11e
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Figure 13.2b Brock Biology of Microorganisms 11e
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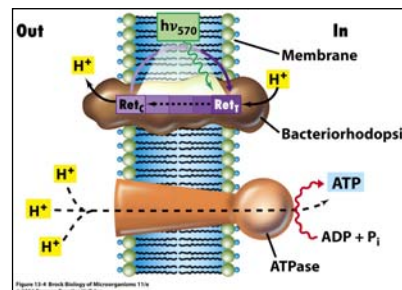
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What makes a halophile?

- Water balance is essential for maintaining cellular integrity; high salt means high osmotic pressure
- in *Halobacterium* spp.:
 - Instead of compatible solutes high internal concentrations of K^+
 - Cell wall integrity depends on high Na^+ concentration; contains glycoproteins rich in acidic amino acids (aspartate and glutamate) whose negative charges are neutralized by Na^+
 - Cytoplasmic proteins: hydrophilic (=charged); K^+ is required for ribosomes stability

Light mediated ATP synthesis in *Halobacterium* spp.

- When O_2 is depleted bacteriorhodopsin is produced and inserted into the membrane
- An associated retinol absorbs light at 570 nm \wedge conversion from a *trans* to a *cis* form and the release of H^+ to the outer surface of the membrane
- When the retinol returns to the trans form, a cytoplasmic H^+ is consumed \wedge the membrane is energized, PMF is formed and drives ATP production
- Bacteriorhodopsin-like proteins are also found in many marine bacteria



13.4 Methanogens

- **Methnogenesis:** discovered in the late 1770 by Alessandro Volta (“combustible gas”)
- Obligate anaerobes that use CO_2 as a terminal electron acceptor and produce CH_4
- The terminal oxidation step in many anaerobic environment (marshes, the GI tract, geothermal sources, sludge digesters - Table 13.4)



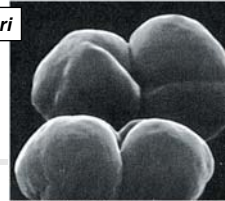
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John A. Breznak

Diversity and physiology

- Cell morphologies
- Cell wall chemistry: pseudopeptidoglycan, methanochondroitin, glycoproteins in different strains
- Metabolically: CO_2 or using simple organic molecules (Table 13.6)
- Environments: mostly mesophilic but hyperthermophiles, psychrophiles, acidophiles, and halophiles are known

Methanosarcina barkeri



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Methanobrevibacter ruminantium



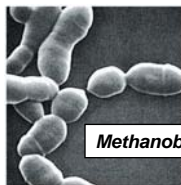
Alexander Zehnder

Mathanospirillum hungatii



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Methanobrevibacter arboriphilus



Alexander Zehnder



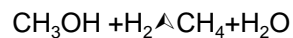
Methanogenic substrates

- Three types

- CO₂-type



- Methylated substrates



- Acetotrophic substrates



Table 13.6 Substrates converted to methane by various methanogenic *Archaea*

I. CO₂-type substrates
Carbon dioxide, CO ₂ (with electrons derived from H ₂ , certain alcohols, or pyruvate)
Formate, HCOO ⁻
Carbon monoxide, CO
II. Methyl substrates
Methanol, CH ₃ OH
Methylamine, CH ₃ NH ₃ ⁺
Dimethylamine, (CH ₃) ₂ NH ₂ ⁺
Trimethylamine, (CH ₃) ₃ NH ⁺
Methylmercaptan, CH ₃ SH
Dimethylsulfide, (CH ₃) ₂ S
III. Acetotrophic substrates
Acetate, CH ₃ COO ⁻
Pyruvate, CH ₃ COCOO ⁻

Table 13.6 from Biology of Microorganisms 11e
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Other Euryarchaeota:

- *Thermoplasmatales* (order; 13.5): highly acidophilic and thermophilic; *Thermoplasma* and *Ferroplasma* lack cell walls
- Hyperthermophilic (13.6): Branch at the base of the Archaea tree; optimal growth at 100 °C.
- *Archeoglobales* (order; 13.7): *Archeoglobus* and *ferroglobus* early H₂S reducers and Fe²⁺ oxidizers, respectively

III Crenarchaeota: introduction

- Live at temperature extremes (>100 °C - < -10°C)
- Isolates only from geothermally heated environments (**sulfataras**, heated industrial effluents, deep sea hydrothermal vents)
- Metabolism is associated with sulfur or sulfide as substrates for reduction and oxidation



A sulfataras in YNP

A acidic Fe²⁺ rich spring



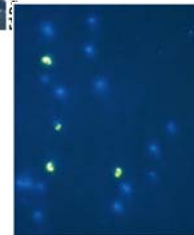
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Cold dwelling *Crenarchaeota*

- Found only in clone libraries of marine microbes
- Up to 10⁴ cells/ml mostly found in the nutrient poor and very cold oceans including sea ice (*Euryarchaeota* are found in more temperate regions of the ocean)
- Lipid analysis shows presence of ether-linked lipids - a confirmation



Ed DeLong



Ed DeLong

Energy metabolism - hyperthermophilic Archaea

Table 13.6 Energy-yielding reactions of hyperthermophilic Archaea			
Nutritional class	Energy-yielding reaction	Metabolic type	Example
Chemoorganotrophic	Organic compound + S ⁰ → H ₂ S + CO ₂	AnR	Thermoplasma, Thermococcus, Desulfurococcus, Thermofilum, Pyrococcus
	Organic compound + SO ₄ ²⁻ → H ₂ S + CO ₂	AnR	Archaeoglobus
	Organic compound + O ₂ → H ₂ O + CO ₂	AnR	Sulfolobus
	Organic compound → CO ₂ + H ₂ + fatty acids	F	Staphylothermus, Pyrodicticum
	Organic compound + Fe ³⁺ → CO ₂ + Fe ²⁺	AnR	Pyrodicticum
Chemolithotrophic	Pyruvate → CO ₂ + H ₂ + acetate	F	Pyrococcus
	H ₂ + S ⁰ → H ₂ S	AnR	Acidianus, Pyrodicticum, Thermoplasma, Staphylobus, Ignicoccus, Pyrobaculum
	H ₂ + NO ₃ ⁻ → NO ₂ ⁻ + H ₂ O (NO ₃ ⁻ is reduced to N ₂ by some species)	AnR	
	4 H ₂ + NO ₃ ⁻ + H ⁺ → NH ₄ ⁺ + 2 H ₂ O + OH ⁻	AnR	Pyrobaculum
	H ₂ + 2 Fe ³⁺ → 2 Fe ²⁺ + 2 H ⁺	AnR	Pyrobaculum, Pyrodicticum, Archaeoglobus
	2 H ₂ + O ₂ → 2 H ₂ O	AnR	Acidianus, Sulfolobus, Pyrobaculum
	2 S ⁰ + 3 O ₂ + 2 H ₂ O → 2 H ₂ SO ₄	AnR	Sulfolobus, Acidianus
	2 FeS ₂ + 7 O ₂ + 2 H ₂ O → 2 FeSO ₄ + 2 H ₂ SO ₄	AnR	Sulfolobus, Acidianus, Metallophasma
	2 FeCO ₃ + NO ₃ ⁻ + 6 H ₂ O → 2 Fe(OH) ₃ + NO ₂ ⁻ + 2 HCO ₃ ⁻ + 2 H ⁺ + H ₂ O	AnR	Ferroplasma
	4 H ₂ + SO ₄ ²⁻ + 2 H ⁺ → 4 H ₂ O + H ₂ S	AnR	Archaeoglobus
4 H ₂ + CO ₂ → CH ₄ + 2 H ₂ O	AnR	Methanopyrus, Methanocaldococcus, Methanothermobacter	

* AnR, anaerobic respiration; AeR, aerobic respiration; F, fermentation

Table 13-8 Brock Biology of Microorganisms 11/e
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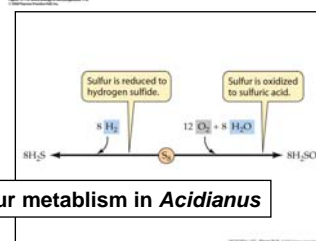
Both chemolitho- and chemoorganotrophs; mostly anaerobic respiration. Might these modes of microbial metabolism conditions on early Earth?

13.9 Sulfolobales

- *Sulfolobus* and *Acidianus* - hot and sulfur-rich terrestrial springs
- *Sulfolobus*: A hyperthermophilic aerobic chemolithoautotroph (can also grow chemoorganotrophically)
- *Acidianus*: A facultative anaerobe; interesting redox-dependent S⁰ utilization

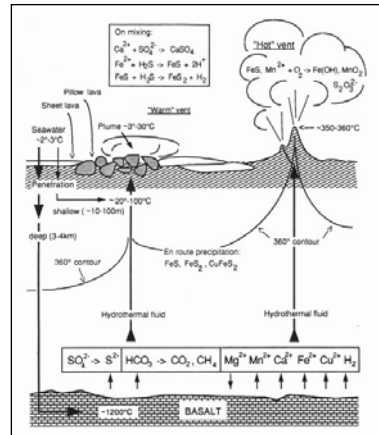


Sulfolobus acidocaldarius



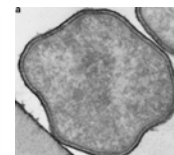
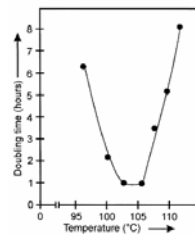
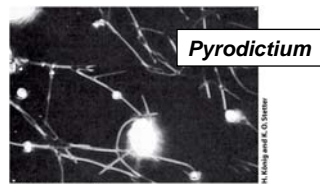
13.10 Hyperthermophiles from submarine (shallow and deep sea) hydrothermal vents

- Deep sea vents emit hot water that is highly enriched with reduced compounds
- Diverse and rich communities live in proximity to the vent; **life in absence of light!**
- The most extreme hyperthermophilic microbes are found in the vent environment



Pyrodicticum and *Pyrolobus*

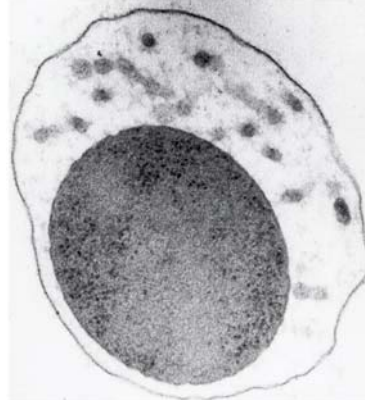
- **Optimum** growth temperature at 105 and 106 °C
- *Pyrodicticum*: disc shaped cells that grow a "mycelium"-like matrix with a role in attachment to crystals of S^0 , its electron acceptor, (either H_2 chemolitho- or an organotrophs)
- *Pyrolobus fumarii*:
 - The most extreme hyperthermophile (can still grow at 113 °C and survive > 121 °C)
 - H_2 oxidation with either NO_3^- , $\text{S}_2\text{O}_3^{2-}$ or O_2 as electron acceptors



Pyrolobus fumarii

Ignicoccus

- Optimal growth at 90 °C; H₂/S⁰ based metabolism
- Unique for its outer membrane (like bacteria) and a large periplasmic space
- Some are hosts to parasitic nanoarchaeons

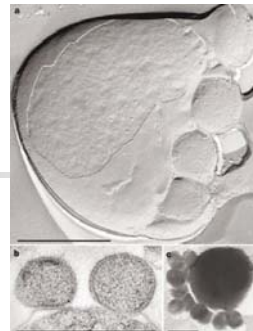


Reinhard Rachel and Karl O. Stetter

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IV Nanoarchaeota

- *Nanoarchaeum*: The smallest organism with the smallest genome (0.49 Mb)
- Can only grow as a parasite of *Ignococcus*; genome lacks genes that encode for the biosynthesis of amino and nucleic acids; similar to the obligate intracellular bacterial parasites?
- DNA replication, transcription, and translation, are carried out by *Nanoarchaeum*

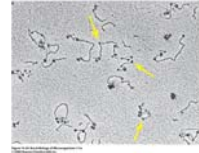


What is evolutionary significant of Nanoarchaeum?

- Branches at the bottom of the Archaea tree - Unique 16S rRNA with many modifications
- The smallest self replicating organism that has likely diversified early to establish a parasitic life style

V Evolution and life at high temperature

- 13.12 Heat stability of biomolecules - proteins:
 - It is all a matter of protein **folding** (hydrophobic core and more ionic interactions on the surface)
 - *Thermosom* - A chaperonin (in *Pyrodictium*); refolding post heating
- DNA:
 - High concentrations of protecting solutes (K cyclic 2,3-diphosphoglycerate); prevents loss of nucleotides by hydrolysis the glycoside bond)
- Reverse DNA gyrase - prevents DNA denaturation; only found among hyperthermophiles
- DNA binding proteins
 - *Sac7d* in *Sulfolobus* increases melting temp. by 40 °C
 - Histone-like proteins in the Euryarchaeota

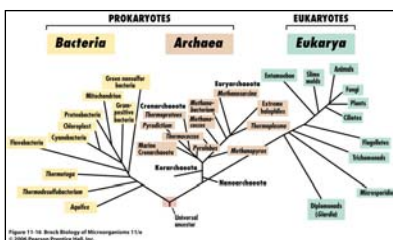


What makes a thermophile a thermophile (continue):

- Lipids: Presence of dibiphenyl tetraether: mono-, rather the bilayer, membranes
- Monomers: Instability of ATP and NAD⁺
- Is there a higher limits for life?
- “Black smoker” chimneys is where life occurs at the highest temperature
- Above 140-150 °C - essential molecules fall apart
- If life exists at > 150 °C, novel molecules must exist

13.13 Hyperthermophiles and microbial evolution

- Hyperthermophiles have evolved slowly
 - From phylogeny: Early but short “branches” in the tree of life
 - The establishment of beneficial mutations is less frequent under the extreme conditions of high temperatures as compared to mesophilic one



H₂ and chemolithotrophy as the primordial “life style” (?):

- By placing energy metabolism of cultured microbes against their maximal growth temperature:
 - H₂ (121 °C) > Fe²⁺, S⁰ (95 °C)
 - At >95 °C only Archaea (*Aquifex*: highest heat tolerance among the Bacteria)

