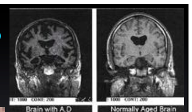
CYANOBACTERIA
The blue-green algae

Brain-destroying Algae?



The Chamorro people from Guam

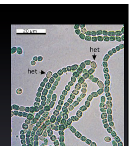
Large incidence of neuronal degeneration disease related to an excess of neurotoxin BMAA

How? Why?

Their diet include tortillas made of cycad seed flour and flying foxes

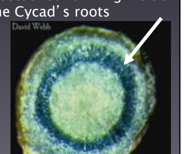
BMAA, a cyanotoxin, is produced in small amounts by glue-green algae or Cyanobacteria, in particular the genus *Nostoc*

But, what *Nostoc* has to do with brain-destruction?



Many cyanobacteria, including *Nostoc*, are symbionts with many organisms such as lichens, bryophytes, ferns, and vascular plants, including Cycads!

Nostoc found living inside the Cycad's roots



How people get BMAA in such amounts?

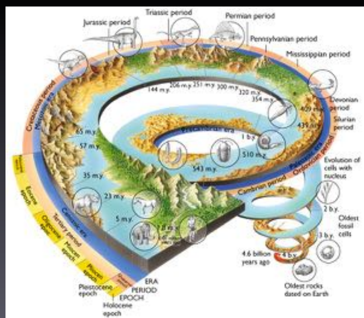
Is this problem only in Guam?

Is the cyanotoxin only found in *Nostoc*?

Are YOU at risk?

Do you want to know more about BG algae now?

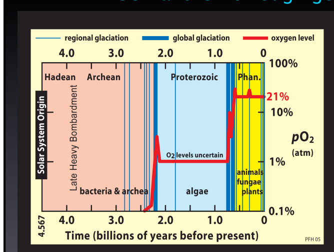
First algae to evolve



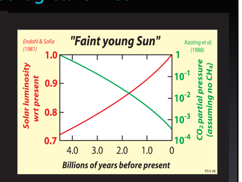
Dominant form of life for over 1 billion years!

Producing major changes in our planet!

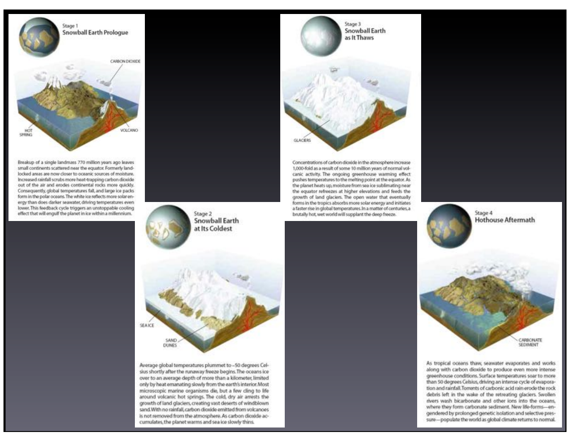
CO2 and O2 through geological times

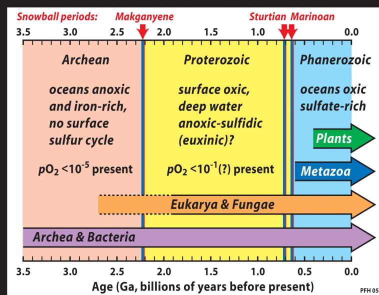


Rise in atmospheric oxygen over geological time and its relationship to ice ages (blue bars) and biological innovations.



Modeled increase in Solar luminosity over geologic time (Endahl & Sofia, 1981) and the compensatory decrease in atmospheric CO_2 partial pressure (assuming negligible methane) required if surface temperatures were quasi-stable over billions of years as is observed geologically.

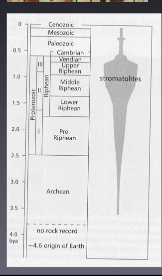




Snowball Earth episodes correlate broadly with major turning points in the chemical history of seawater and the evolution of life.

Paleontology: fossils 3.5 bya

Stromatolites



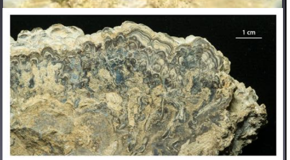


Figure 6.20 A fossil stromatolite. This stromatolite has been split open, revealing the layering typical of these formations. (Photo: L. W. Wilcox)

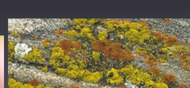
Ecology

They are ubiquitous and cosmopolitans, also found in extreme habitats

- Forming dark green slimy patches on walls or soils.
- Phytoplankton in marine and freshwater
- In Hot (thermophiles) or cold environments
- On Animals (epizoics)
- In Symbiotic associations
- Forming blooms

Microcoleus

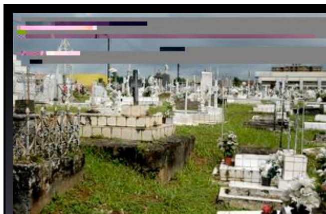
Aquatic fern *Azolla*

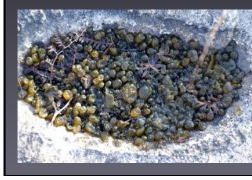


Lichen

Cyanobacteria inside rock

Cyanobacteria Bloom





Nostoc balls

Prokaryotes

Like other bacteria, they do not have "organelles" if you define organelles as membrane-bound structures with one or more special functions!

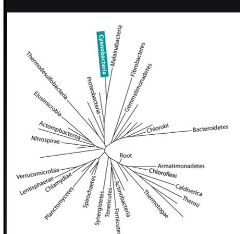


Figure 6.1 Tree showing that cyanobacteria form a phylum within the Domain Bacteria. They have a sister group in the non-photosynthetic Melainabacteria. © Copyright 2016 LLM Press

However, prokaryotes do have specialized membranes systems (thylakoids) and specialized structures!

Commonalities between Cyanobacteria and Bacteria:

✓Prokaryotic cell organization
✓Absence of organelles (flagella, nuclei, plastids, mitochondria, Golgi bodies)
✓Cell wall (Peptidoglycan)
✓Mucilaginous sheaths
✓Absence of histones
✓Small 70S ribosomes
✓Cell division by binary fission
✓Sexual reproduction absent

Differences between Cyanobacteria and Bacteria:

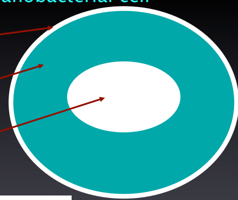
✓Cyanobacteria with Chlorophyll *a* (and *b* in some)
✓Oxygen producers

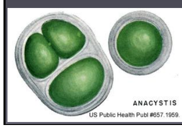
General structure of a cyanobacterial cell

Cell Wall: an inner rigid peptidoglycan and an outer mucilaginous sheath (similar to gram-negative bacteria) sometimes with pigments (scytonemin) as sunscreen protectors

Chromatoplasm: peripheral and blue-green in color

Centroplasm: granular and colorless where DNA is located (no nuclear membrane!)





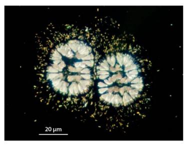


Figure 6.4 **Two *Gomphosphaeria* colonies, each with a halo of bacteria in the surrounding mucilage.** Note the heart-shaped cells. With darkfield microscopy, cyanobacterial cells may look pink or red, as is the case here. (Photo: L. W. Wilcox)

Figure 6.5 **Yellow-brown color of scytonemin in the sheath of a mat-forming cyanobacterium.** (Photo: M. E. Cook)

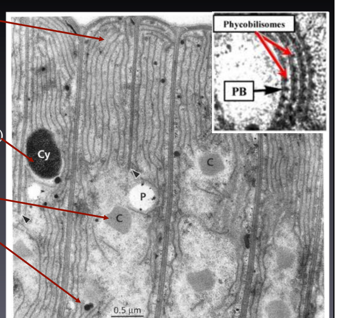
Chromatoplasma: With a system of membranes usually concentric, the THYLAKOIDS associated with the photosynthetic pigments

GRANULES Chromatoplasm or Centroplasm:

- Phycobilisomes (Pigments)
- Cyanophycin (Nitrogen, Aas)
- Polyphosphate or Volutin
- Carboxysomes (RuBisCo or Polyhedral Bodies)
- Lipids or β-granules

STORAGE PRODUCTS

Glycogen (Cyanophytan Starch)



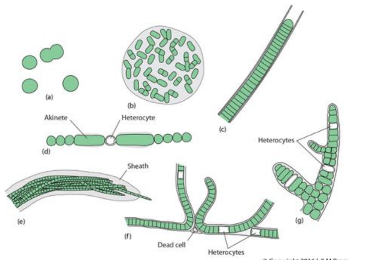
Binary Fission by infurrowing (centripetal cross wall formation)

No mitotic spindle

Cyanobacteria: Morphological diversity

@ 1,500 spp

Figure 6.3 Some of the morphological types present in modern-day cyanobacteria. (a) Unicells such as *Synechocystis*, (b) colonies of individual cells such as *Aphanothece*, (c) unbranched filaments including *Lyngbya*, (d) unbranched forms with heterocytes and akinetes such as *Anabaena*, (e) aggregations of multiple trichomes in a common sheath, as in *Microcoleus*, (f) false-branched forms including *Scytonema*, (g) true-branched forms such as *Stigonema*.



GROUP 1. Unicellular and Colonial forms lacking specialized cells or reproduction

Synechococcus

Figure 6.27 *Chroococcus turgidis*, a common bog-dwelling cyanobacterium. Following cell division, a few cells tend to remain attached to one another within the firm sheath. (Photo: L. W. Wilcox)

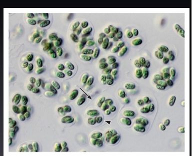


Figure 6.28 *Gloeocapsa*. Note that cells occur inside of concentric sheaths (arrow and arrowhead), reflecting the pattern of cell division. (Photo: M. E. Cook)

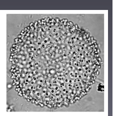


Figure 6.29 *Aphanocapsa*. Cells of this colonial cyanobacterium are spherical and without individual sheaths. (Photo: L. E. Graham)

Figure 6.32 *Microcystis* has numerous spherical cells that form variously shaped colonies. (a) A relatively small colony with numerous bacteria present in the ensheathing mucilage. In (b), two tortuous, perforated colonies are shown. The colony on the left has a less defined, textured mucilaginous matrix, while the one on the right has a firm, clearly delimited sheath. Note the dark appearance of the cells, which contain numerous gas vesicles. (Photos: L. W. Wilcox)

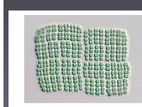


Figure 6.31 *Merismopedia*, whose cells occur in a flat sheet, often rectangular in outline. (Photo: M. E. Cook)

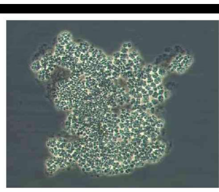
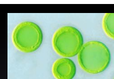


Figure 6.23 Colony of *Gloeobacter*, a cyanobacterium without thylakoids. (Image: NOAA)



Prochloron

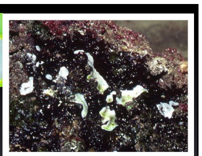


Figure 6.25 Ascidians (sea squirts) tinted green due to the presence of *Prochloron*. (Photo: L. E. Graham)

The earliest-diverging lineage of modern cyanobacteria is the genus *Gloeobacter*, which differs from all other known cyanobacteria and plastids in lacking thylakoids

- *Prochloron* is a unicell that lives primarily in association with marine didemnid ascidians, colonial tunicates also known as sea squirts
- It is unusual in possessing chlorophyll b in addition tochlorophyll a andlacking phycobilisomes.
- These cyanobacteria thus appear grass green.

GROUP 1. Unicellular and Colonial forms lacking specialized cells or reproduction

GROUP 2. Filamentous forms lacking spores, heterocysts, or akinetes

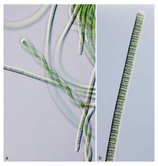


Figure 6.34 ***Oscillatoria.*** (a) A number of presumed *Oscillatoria* filaments, some of which have twisted about themselves or each other. (b) The tip of a filament at higher magnification. The cells are much wider than they are long. (Photos: M. E. Cook)

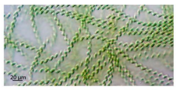
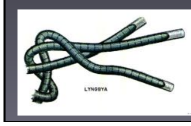
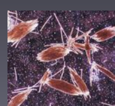


Figure 6.36 ***Spirulina.*** (Photo: L. W. Wilcox)

Microcoleus





Trichodesmium

Trichome: row of cells

Filament: row of cells enclosed in a sheath

GROUP 1. Unicellular and Colonial forms lacking specialized cells or reproduction

GROUP 2. Filamentous forms lacking spores, heterocysts, or akinetes

GROUP 3. Exospore-producing forms

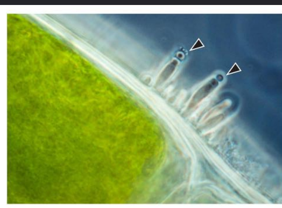


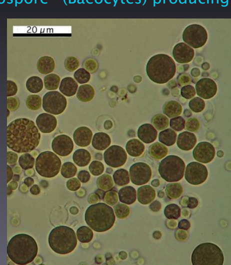
Figure 6.38 Cyanobacterial exospores. Exospores (arrowheads) have formed on two of these *Chamaesiphon* individuals that are growing on the green alga *Cladophora*. (Photo: L. E. Graham)

GROUP 1. Unicellular and Colonial forms lacking specialized cells or reproduction

GROUP 2. Filamentous forms lacking spores, heterocysts, or akinetes

GROUP 3. Exospore-producing forms

GROUP 4. Endospore- (Baeocytes) producing forms



Dermocarpa

GROUP 1. Unicellular and Colonial forms lacking specialized cells or reproduction

GROUP 2. Filamentous forms lacking spores, heterocysts, or akinetes

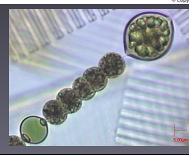
GROUP 3. Exospore-producing forms

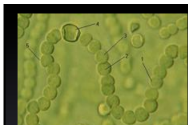
GROUP 4. Endospore-producing forms

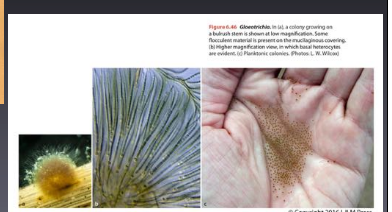
GROUP 5. Heterocyst and akinete-producing forms

Akinetes: “resisting” spore with thick walls

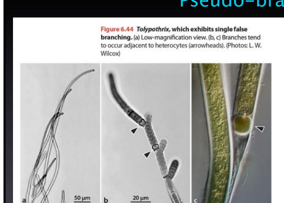
Heterocysts: clear and swollen cells with papillae







Pseudo-branched thalli



Simple pseudo-branching

Geminate pseudo-branching

GROUP 1. Unicellular and Colonial forms w/o specialized cells or reproduction

GROUP 2. Filamentous forms lacking spores, heterocysts, or akinetes

GROUP 3. Exospore-producing forms

GROUP 4. Endospore-producing forms

GROUP 5. Heterocyst and akinete-producing forms

GROUP 6. True branched forms

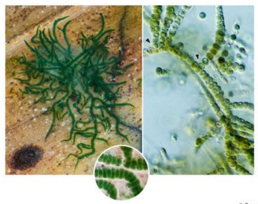
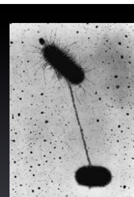


Figure 6.47 ***Stigonema.*** (a) A dissecting scope view of *Stigonema* growing on a bulrush stem (Inset: view with compound scope). The green alga *Chaetophora* can form somewhat similar growths on stems and other substrates in the same habitat but closer examination easily distinguishes the two organisms. (b) Note the true branches (arrowheads). (a: L. W. Wilcox; b: M. E. Cook)

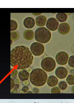
REPRODUCTION

- **Sex - yuk?**
  Probably bacteria-like
  - Transformation
  - conjugation (pili)
  - Transduction (CYANOPHAGES)



REPRODUCTION

- **Sex - yuk?**
- **Asexual reproduction**
  1. **Binary Fission**
  2. **Akinetes**: "resisting" spore with thick walls
  3. **Endospores**: multiple divisions within the cell
  4. **Exospores**: successive division at one end of the filament/cell
  5. **Fragmentation**: breakage of filaments
     a. hormogonium
     b. necridium



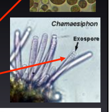


Figure 6.15 Reproductive structures. (a) Hormogonium. (b) Separation disks or necridia (arrows). (Photos: L. W. Wilcox)

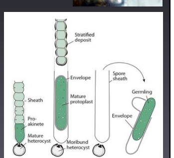
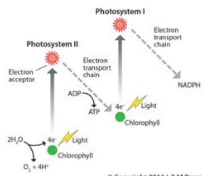


Figure 6.17 Development of the akinete of *Gloeotrichia echinulata*. (a) Differentiation begins near a heterocyte. (b) Akinetes enlarge, develop thick walls, and (c) separate from subtending vegetative filaments and heterocytes, leaving an empty sheath. (d) Germination of akinetes. (After Cmiech et al. 1984. Morphological and ultrastructural variability of planktonic cyanophyceae in relation to seasonal periodicity. I. *Gloeotrichia echinulata*: Vegetative cells, polarity, heterocysts, akinetes. *British Phycological Journal* 19:259–275)

Pigments: Three biochemical groups

- •Chlorophylls
- •Carotenoids
- •Phycobilins

Figure 6.10 Diagram of the light reactions of photosynthesis. In photosystem II, electrons derived from the splitting of water replace those transferred from a special chlorophyll *a* molecule to an acceptor molecule when light energy is absorbed. Oxygen is produced as a by-product, along with protons. Electrons then pass along an electron transport chain, producing ATP in the process. In photosystem I, electrons don't come from water but, rather, from the electron transport chain of photosystem II. They are similarly passed from a chlorophyll *a* molecule to an electron acceptor and along another electron transport chain, resulting in the production of NADPH, which, together with ATP, is used in the dark reactions of photosynthesis to produce chemical energy in the form of sugar.



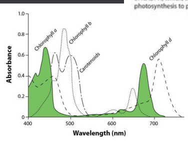
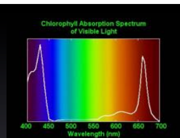


Figure 6.9 Absorption spectra for chlorophyll *a* (shaded curve), carotenoids, chlorophyll *b*, and chlorophyll *d*. Carotenoids and chlorophyll *b* act as "accessory" pigments, absorbing additional wavelengths of light and passing the energy along to chlorophyll *a*.

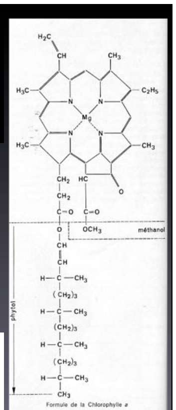
- Chlorophylls of cyanobacteria likely evolved from bacteriochlorophylls from other types of bacteria
- PSI is the ancestral reaction center
- PSII is thought to have originated from PSI by gene cluster duplication and divergence

Chlorophylls



Green pigments, soluble in alcohol and organic solvents

Absorbance at Blue and Red



Different types of chlorophylls: *a*, *b*, *c*, and *d*

Every algal group with particular chlorophylls

Structure

- •Tetrapyrrols with Magnesium (HEAD, hydrophyllic)
- •A Methanol group
- •A Phytol tail with twenty Carbon atoms (TAIL, hydrophobic)

Chlorophyll *a* the MOST IMPORTANT CHLOROPHYLL –present in all photosynthetic algae and plants

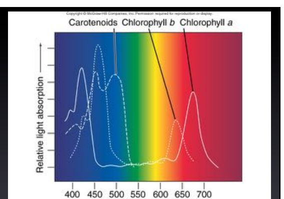
–directly responsible for photosynthesis

–All other pigments (chlorophylls [*b*,*c*,*d*], carotenoids, and phycobilins) are *ACCESORY* pigments

Carotenoids

Yellow and orange pigments, soluble in organic solvents and lipids

Absorbance at Blue λ



TWO TYPES Carotenes & Xanthophylls:

-Carotenes, hydrocarbons with a chain of long double bonds and one or two cyclic endings

β-carotene is the most common in all groups of algae

-Xanthophylls, oxygenated derivative of carotenes

Zeaxanthin is common in Cyanobacteria

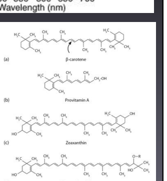


Figure 6.14 Structures of cyanobacterial carotenoids. (a) β-carotene, (b) provitamin A, (c) zeaxanthin, and (d) myxoxanthophyll. Provitamin A is formed by splitting β-carotene into two equal parts (at arrow). Zeaxanthin is a common xanthophyll and is also synthesized from β-carotene.

Phycobilins

Blue and red pigments, water-soluble

Open chain tetrapyrrols bound to proteins

Absorbance at yellow-orange λ

Three types in Cyanobacteria:

- C-Phycocyanin (blue)
- Allophycocyanin (blue)
- C-Phycoerytrhin (red)

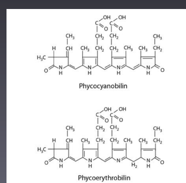


Figure 6.12 Phycocyanobilin and phycoerythrobilin. Note the open-chain tetrapyrrole structure.

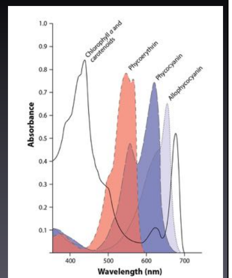
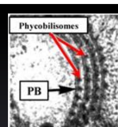


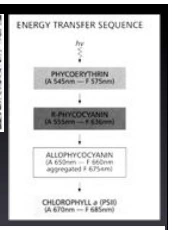
Figure 6.11 Absorption spectra for the phycobilin pigments found in non-chlorophyll *b*-containing cyanobacteria. These accessory pigments extend the range of wavelengths that can be used for photosynthesis, covering wavelengths where neither chlorophyll nor carotenoids show strong absorbances. (Re-drawn from Gantt 1975. Phycobilisomes: Light-harvesting pigment complexes. *BioScience* 25:781–788)

Phycobilisomes

- This granule consist of several phycobilins tightly bound to proteins on the outer surface of thylakoids
- Each phycobilisome consists of a core with allophycocyanin and radiating rods with phycocyanin and external phycoerythrins
- Phycobilisomes collect light which is transferred to a reaction center in the thylakoid, following a pathway:

PE ⟶ PC ⟶ APC ⟶ Chl *a*





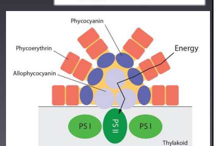
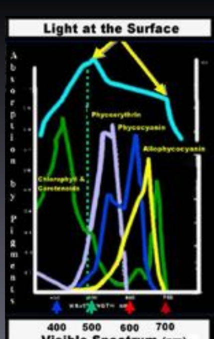


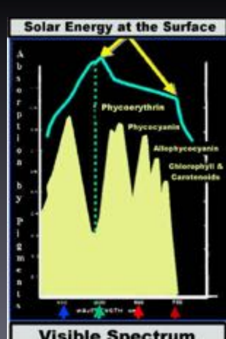
Figure 6.13 A cross-sectional model of the cyanobacterial phycobilisome. Note that light energy transfers from phycoerythrin to phycocyanin to allophycocyanin to chlorophyll *a* in photosystems I and II. The yellow areas represent linker proteins that hold the phycobilisome together to form an igloo-like, three-dimensional structure.

Only present in Cyanobacteria **with** Phycobilins

Absent in Cyanobacteria with chlorophyll *b* such as *Prochloron* (also lacking phycobilins)

The accessory pigments (chlorophylls *b*, *c*, *d*, carotenes, and phycobilins) **extend** the range of wavelength used for photosynthesis!



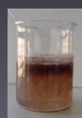


Chromatic Acclimation

Cyanobacteria can change the pigment composition according to the light quality:

- **Blue-Green light stimulates the synthesis of red Phycoerythrins**
- **Orange light promotes the synthesis of blue Phycocyanins**

Advantage to changing environments (seasonal, vertical, horizontal)



Motility: No flagella! But…..

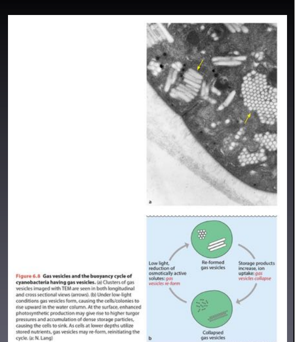
Oscillatoria et al. – gliding, rotation, oscillation

- Production of mucilage?
- Peripheral proteins?

Magnificent mysteries!!!!!
Secrets to be unlocked!!!!!
A Leitmotif for organismal biology!!!!

Cyanobacterial buoyancy

- Gas vesicles, gas vacuoles, pseudovacuoles
- "Membrane bound" by protein subunits
- Environmental control:
  - Low light stimulates gas vesicles
  - Storage products increase then gas vesicles collapse



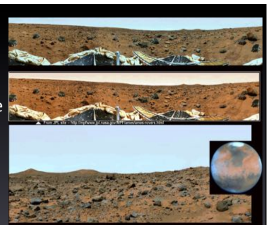
[Heterocysts]

Consider these conditions:

Paleolakes, no liquid water on surface

Temp -17 to -107°C

Low CO_2, vacuum



This happen in our planet!

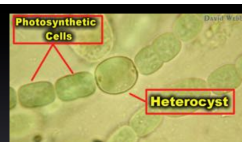
Mars analogues!

Where? Antarctica

Cyanobacteria represent great organisms to study how life in other planets can exist!

Cryptoendolithic algae

Nitrogen-fixation and Heterocysts

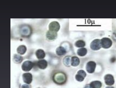


1. Cell enlargement
2. Thick cell wall and papillae
3. Decrease in granular inclusions (carboxysomes & cyanophycin)
4. Reorganization of thylakoids
5. Loss of phycocyanin (hence empty appearance & loss of photosystem II [Why?]
6. Increase in respiration [Why?]

BUT . . .

HETEROCYSTS are NOT required for nitrogen fixation:

• Most marine cyanobacteria lack heterocysts but many are active nitrogen fixers!



• *Synechococcus* - only fixes nitrogen at night (why?)

• *Trichodesmium* - It can conduct photosynthesis while fixing N!!! With lower O_2 tension in middle of bundles of filaments and very high rates of respiration

Economic Importance of Cyanobacteria

Biofertilizers in soils (nitrogen-fixing and mucilage)

Spirulina as food

Cyanobacterial blooms

Toxins (hepatotoxins and neurotoxins)

Drugs: anti-cancer, antibiotics, anti-inflammatory, neuroprotective

Figure 1.4 A conspicuous algal bloom produced by microalgae. This surface bloom in a hypereutrophic lake consists of several cyanobacterial species, which often produce toxins. Algal blooms involving other types of algae are often nontoxic and cause no significant problems. (Photo: L. W. Wilcox)

Evolutionary importance of Cyanobacteria

- Chloroplasts of eukaryotic algae are probably derived directly or indirectly from cyanobacteria!!!
- They were the first forms to produce Oxygen
- They are responsible for major ecological, biochemical, and evolutionary changes in our planet
  - ✓ cellular respiration
  - ✓ eukaryotic evolution
  - ✓ ozone layer!
  - ✓ us !!!!!

THE BIG FOUR FOR CYANOBACTERIA

1. **Pigments: Chlorophyll *a* and Phycobilins (in *Prochloron* Chl *a* and *b*, no phycobilins)**
2. **Storage products: Glycogen (Cyanophytan starch)**
3. **Cell wall: Peptidoglycans**
4. **NO FLAGELLA or other organelles!**