Wheaton Journal of

Cell Biology Research

Issue 7, Spring 2020:

"Living Architecture"

R.L. Morris, Editor. Wheaton College, Norton Massachusetts.

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A Comparison of Prokaryotic Thermophile Community Structure and Coastal Infrastructure Development

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BIO 298 / Principles of Cell Biology
Final Research Paper
27 April 2020

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Living Architecture Research Report written for
Wheaton Journal of Cell Biology Research
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Rule-to-Build-By:

Rule-to-build-by number four states *"to achieve the best design, continuously tinker with the building plans"* and biological communities and human built infrastructure uphold this rule (Morris, Lane, n.d.).

What:

The process of evolution in prokaryotes is displayed across many ecosystems, as is seen in the Grand Prismatic Spring community located in Yellowstone National Park, Wyoming, USA (Geiling, 2016). Similar to this biological evolution, human systems have also experienced evolution within city development and its proximity to water (Winiwarter, 2016).

How:

Thermophiles are prokaryotic organisms that are characterized by their tolerance for temperatures above 55°C. Thermophiles not only tolerate these high temperatures, but actually require high temperatures for growth (Noll, 2001). There are two classes of thermophiles: extreme thermophiles and hyperthermophiles. Extreme thermophiles have an optimal temperature of 65°C or above and hyperthermophiles have an optimal temperature of greater than 80°C (Noll, 2001). The Grand Prismatic Spring in Yellowstone National Park is home to a variety of extreme thermophiles and is known for its distinct coloration. The coloration displayed in Figure 1 is caused by various thermophilic bacteria and their distribution through the hot spring (Geiling, 2016). The Grand Prismatic Spring is divided into four zones that correlate with temperature variation. The inner yellow ring is the *Synechococcus* zone and is approximately 73°C. Next is the orange Chloroflexi zone that is approximately 65°C (Geiling, 2016). The third zone is the Phormidium zone and the farthest is the Calothrix zone; these zones are 55°C which is a much more habitable temperature for most prokaryotes (Geiling, 2016; Sindelar, 2018).

Photosynthetic pigments are very important to the colors in the Grand Prismatic Spring and also to the process of photosynthesis. These pigments are organized into photosystems that contain a light-harvesting complex composed of pigments and proteins that absorbs light energy.

This energy is transferred through the pigments into the reaction center where oxidation occurs, producing a free electron. The electrons then move through an electron transport system where energy molecules are created (Lumen Learning, n.d.). The photosynthetic pigments involved in this process range in color, causing the pigments to absorb different wavelengths of light (Figure 4). Bacteria will have pigments that optimize absorption for the light they are typically exposed to (Lumen Learning, n.d.).

The *Synechococcus* bacteria that are located in the yellow portion of the hot spring (Figure 1) are a type of cyanobacteria. Cyanobacteria (Figure 2) are photosynthetic prokaryotes. The *Synechococcus* cyanobacteria have adapted to the light and temperature conditions of Yellowstone. One adaptation is their light harvesting system called phycobilisomes or PBS (Larkin, 2019). PBS are clusters of light-harvesting proteins, named phycobiliproteins, that are attached to the thylakoid membrane (Figure 2) found within cyanobacteria (Larkin, 2019; Zilinskas, 1986). Phycobiliproteins are capable of binding different chromophores, regions of molecules that absorb different light wavelengths and produce different colors (Larkin, 2019; Chemistry LibreTexts, 2016). *Synechococcus* bacteria contain the phycobiliprotein phycoerythrin which absorbs blue and green wavelengths (Figure 4) and therefore reflects red. Properties for light-harvesting such as this allows *Synechococcus* bacteria to expand their niche further than organisms relying only on chlorophyll (Larkin, 2019). PBS harvest the primary light for photosynthesis, but in most cyanobacteria high temperatures cause the PBS to dissociate from the photosystem or denature, but *Synechococcus* have adaptations for this (Pedersen, 2017). *Synechococcus* utilize the enzyme RuBisCO (ribulose-1, 5-biphosphate carboxylase/oxygenase) within the Calvin cycle and this provides stability in high temperatures. The *Synechococcus* RuBisCO has amino acid changes that create stability in high temperatures (Miller, 2013). Another adaptation is the use of carotenoids that allow the *Synechococcus* to avoid photoinhibition (Larkin, 2019). Carotenoids produce a red, orange, or yellow color and this causes the yellow seen in Figure 1 (Geiling, 2016). Photoinhibition is caused by excessive electron transport. Through the process of photosynthesis sunlight energy is converted to chemical energy through the transport of electrons. When this is done in high volume it can lead to an increased reduction of oxygen and this create an imbalance in the photosystems (Lima-Melo, 2019).

Photosynthetic pigments are also critical to the Chloroflexi bacteria in the orange zone (Figure 1) (Geiling, 2016). Chloroflexi bacteria are part of a large group of filamentous anoxygenic phototrophic (FAP) bacterial organisms. FAP bacteria do not produce oxygen like cyanobacteria, they release sulfur compounds instead. These Chloroflexi bacteria are typically a dark green color (Biology LibreTexts, 2017). The bacteria located in Yellowstone are not dark green due to light adaptations. These FAP bacteria utilize chlorosomes as their light harvesting complexes. The chlorosomes attach to the membrane of the bacteria through a Fenna-Mathews-Olsen (FMO) complex (Figure 3) which is a protein complex that helps to transfer energy from the pigments to the reaction complex (Barroso-Flores, 2017; Pšenčík, 2009). These chlorosomes link to photosynthetic pigments including carotenoids. The carotenoids serve the same function in Chloroflexi bacteria as they do in *Synechococcus* bacteria, they act as protection (Pšenčík, 2009). These carotenoids protect the bacteria from photoinhibition and produce the orange color seen in Figure 1 (Geiling, 2016; Larkin, 2019).

This bacterial community can be compared to human-built infrastructure. Historically, bodies of water have been critical to the development of human civilization and infrastructure. Beginning in the Fertile Crescent, the start of city evolution was driven by the Tigris and Euphrates Rivers due to the resources they provided for agriculture (Facts on File, 2016). Modern cities still utilize proximity to waterways for shipping patterns (Figure 5) as is seen in the United States where large shipping corridors lead up to major cities such as New Orleans, Louisiana (Rodrigue, 2017). New Orleans' proximity to the ocean and the Mississippi River make it a critical location for human infrastructure. The Mississippi provides resources for cities such as a source of fresh water and transportation. The Mississippi is a critical resource for the Midwest economy and because New Orleans is adjacent to the Gulf of Mexico it is an important economic location (National Park Service, n.d.). Due to the economic value of the location the colonization of New Orleans was important, but it required infrastructure such as levees, canals, pumps, and drainage systems to make the land more habitable. While these initial changes began occurring in the 1800s, modern day infrastructure (Figure 6) must still be utilized to keep New Orleans dry (Campanella, 2018).

Why:

Through the use of various photosynthetic pigments for photosynthesis and cellular protection, these different types of bacteria have adapted to the ecosystem within Yellowstone National Park (Morris, Lane, n.d.). The most apparent adaptations that these thermophilic bacteria utilize is their temperature tolerance. The thermophiles living in the Grand Prismatic Spring must be able to withstand temperatures ranging from 55-73°C and these organisms have evolved proteins that allow them to thrive in such environments (Geiling, 2016; Noll, 2001). Thermophiles have developed very stable components such as thermostable enzymes that allow them to thrive where most organisms cannot (Pedersen, 2017). These organisms' ability to live in such environments was also critical to the evolution of life. Evolutionary evidence suggests that thermophiles were some of the earliest life forms (Noll, 2001).

Such evolutionary processes directly connect to the bacteria of the Grand Prismatic Spring. The bacteria found in this spring, specifically in the yellow and orange portions (Figure 1), utilize carotenoids as a protective measure from high light intensity (Geiling, 2016). Carotenoids protect photosynthetic pathways that are subjected to extreme light intensity from oxidative reactions that can be harmful to the functionality of the pathway. These carotenoids can be traced through the evolutionary history of a variety of organisms ranging from different bacteria to algae (Sandmann, 2002).

The combination of the evolution of both thermostable proteins and carotenoids in photosynthetic pathways have shaped the structure of the Grand Prismatic Spring in

Yellowstone. The organisms seen in Figure 1 have different coloration due to these adaptations to temperature and light intensity (Geiling, 2016).

Environmental adaptations are also seen in New Orleans, Louisiana. The location of New Orleans makes infrastructure adaptations a necessity. New Orleans sits below sea level and this poses an issue for flooding. There must be precautions in place, as is displayed in Figure 6, to prevent issues with flooding and wave damage (Campanella, 2018). Although the pressures of flooding require adaptations, there is important economic value for the location. Similarly, the bacteria in the Grand Prismatic Spring must adapt to the environment of Yellowstone, but these adaptations allow them to fill a niche that other species cannot (Pedersen, 2017).

Figures:

Figure 1: Grand Prismatic Spring Yellowstone, Wyoming, USA. This shows the coloration and the differentiation between bacterial species. Notice the division: (1) *Synechococcus* cyanobacteria, (2) Chloroflexi bacteria, (3) Phormidium zone, and (4) Calothrix zone (Sindelar, 2018). (Figure from Andrea Adobati, https://www.snowaddiction.org/2014/11/the-multicolored-hot-grand-prismatic-spring-in-yellowstone-usa.html, edited for clarity)

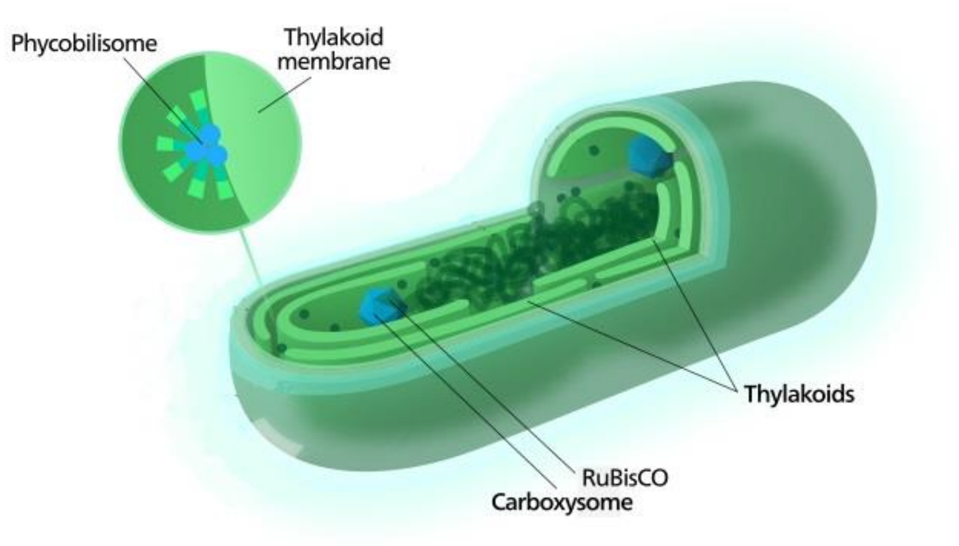

Figure 2: Cyanobacteria Photosystem. This displays the structure of cyanobacteria like the *Synechococcus* bacteria. Notice the carboxysome structure containing RuBisCO and its attachment to the thylakoid membrane. RuBisCO plays an important role in *Synechococcus* heat adaptations (Pedersen, 2017). (Figure from Kevinsong, https://en.wikipedia.org/wiki/Cyanobacteria#/media/File:Cyanobacterium-inline.svg, edited for clarity)

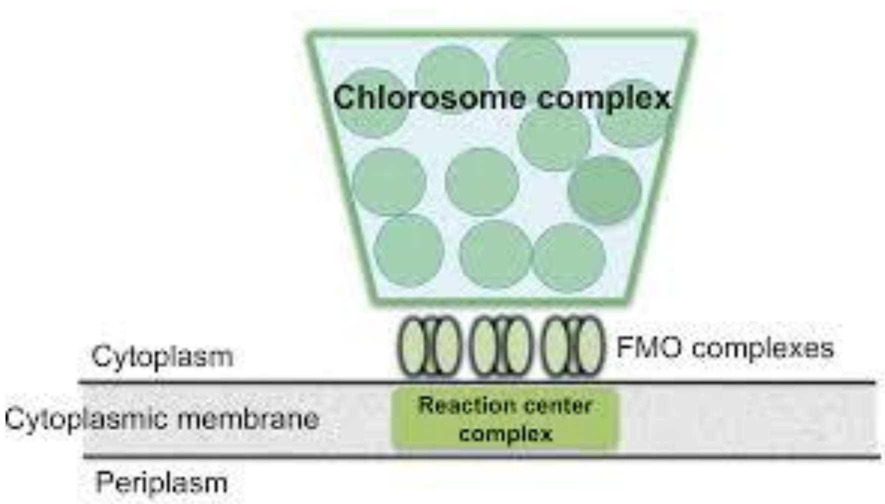

Figure 3: Chlorosome Complex Attachment. This displays the different complexes associated with chlorosomes in anoxygenic bacteria. Notice the green circles in the chlorosome complex, these are the pigments that are important to coloration. (Figure from K. Birgitta Whaley, http://online.kitp.ucsb.edu/online/qcontrolt-c13/whaley/pdf/Whaley_TeachersQuantumEra_KITP.pdf)

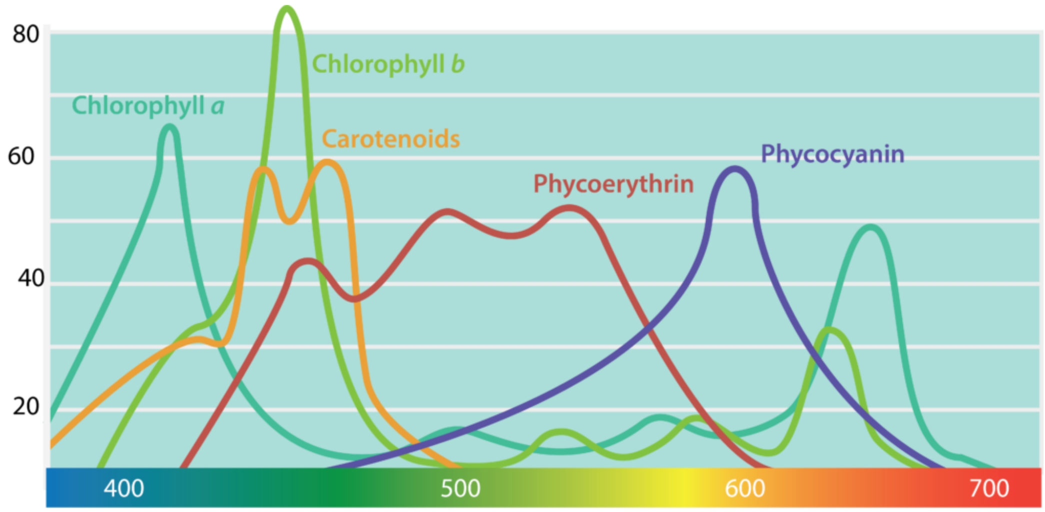

Figure 4: Photosynthetic Pigment Absorption Spectrum. This displays the absorbance spectrum of different photosynthetic pigments. The photosynthetic pigments in bacteria are specific for the light wavelengths that the organisms are typically exposed to (Lumen Learning, n.d.). Notice the phycoerythrin and carotenoid pigments which are important for the Grand Prismatic Spring bacteria colors. (Figure from Linda Bruslind, https://open.oregonstate.education/generalmicrobiology/chapter/phototrophy/)

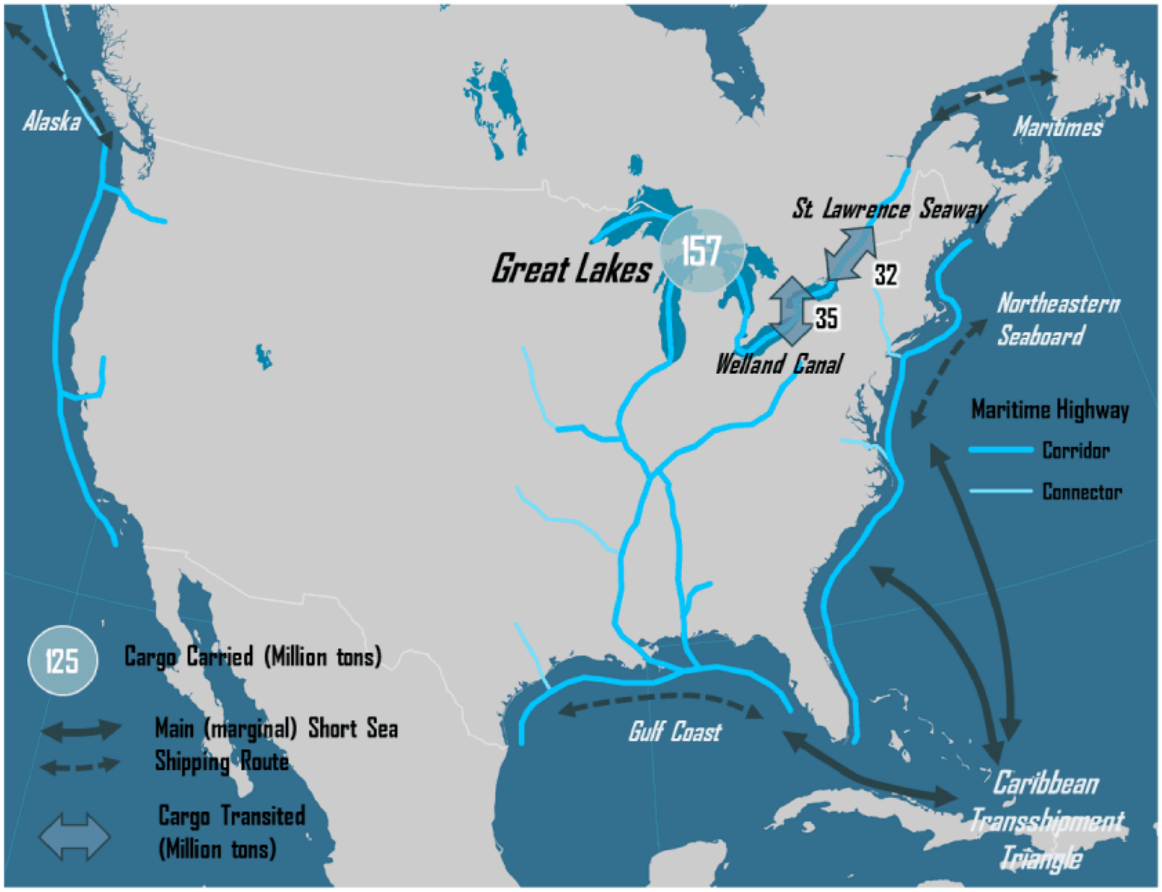

Figure 5: Cargo Route Correlation with Cities. This depicts the cargo routes through North America and the importance of the coastal proximity of cities. Notice the large influx of cargo in the Gulf Coast through Louisiana and up the Mississippi River. (Figure from Jean-Paul Rodrigue, https://transportgeography.org/?page_id=2263)

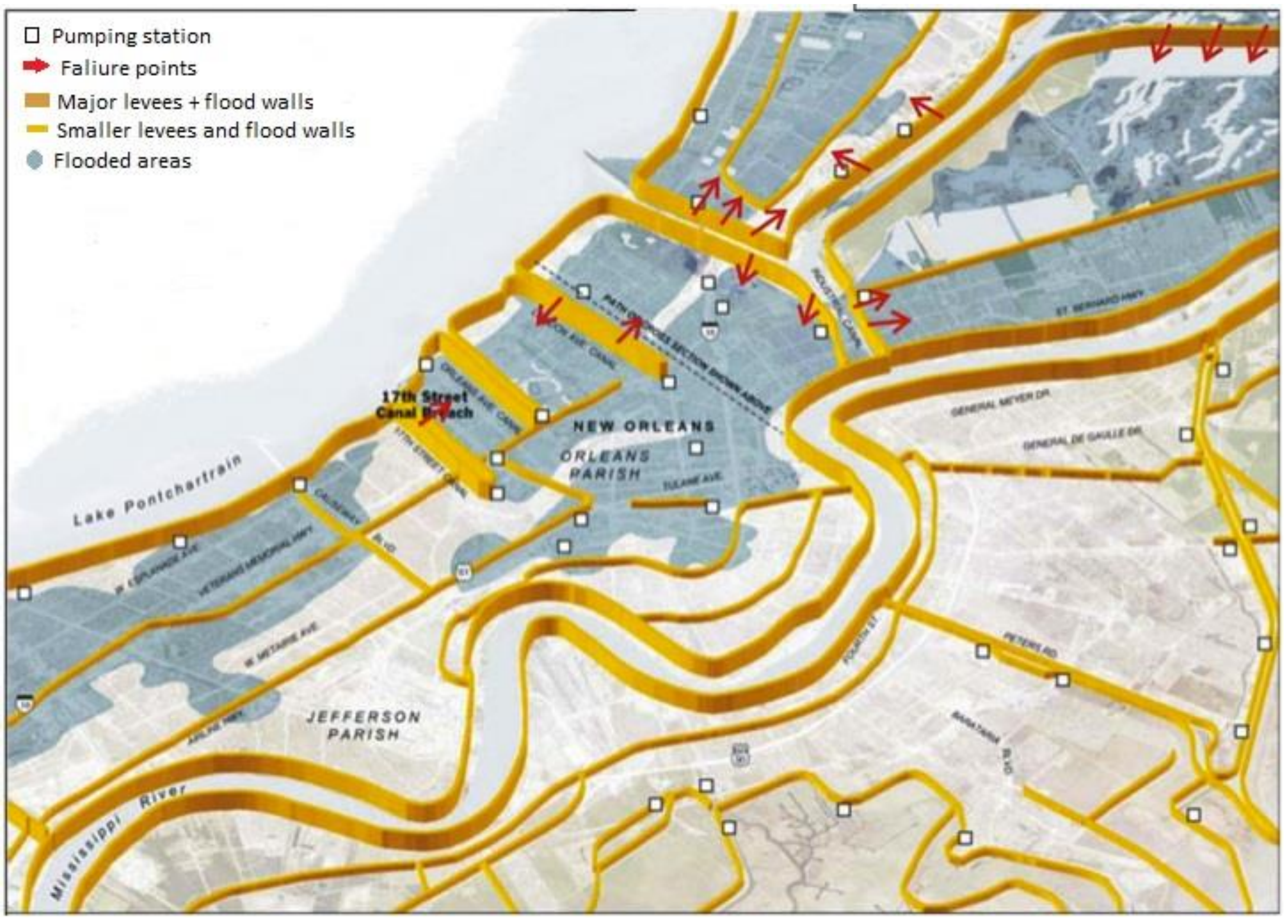

Figure 6: New Orleans, Louisiana, USA Coastal Infrastructure. This displays the levees and flood walls in New Orleans after Hurricane Katrina. Notice the need for such adaptations due to the high risk of flooding. (Figure from Independent Levee Investigation Team, https://www.e-education.psu.edu/earth107/node/1086, edited for clarity)

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