CORE
Metadata, citation and similar papers at core.ac.uk
Provided by University of St. Thomas, Minnesota

University of St. Thomas, Minnesota
UST Research Online

Biology Undergraduate Projects Biology

Fall 2017

Terraforming Mars using Cyanobacteria to produce the next Great Oxidation Event

Jennifer Walz
University of St. Thomas, Minnesota, jenny.walz@stthomas.edu

Follow this and additional works at: https://ir.stthomas.edu/cas_biol_ugpub

Part of the Biology Commons

Recommended Citation

Walz, Jennifer, "Terraforming Mars using Cyanobacteria to produce the next Great Oxidation Event" (2017). *Biology Undergraduate Projects*. 7.
https://ir.stthomas.edu/cas_biol_ugpub/7

This Paper is brought to you for free and open access by the Biology at UST Research Online. It has been accepted for inclusion in Biology Undergraduate Projects by an authorized administrator of UST Research Online. For more information, please contact libroadmin@stthomas.edu.

Terraforming Mars using Cyanobacteria to produce the next Great Oxidation Event

Jennifer Walz

Astrobiology HONR 480

Fall 2017

Astrobiology is the study of life around stars; it is a multi-disciplinary field that aims to discover how life started and evolved on the earth, whether life exists in space (and how we could know), and the potential for the spread of human life (Catling 2014). As we learn more about the sun's eventual engulfment of the earth, and the effects of climate change, the longevity of our time on earth seems to be dwindling. Naturally, a quest for increasing that longevity has become a vital concern to scientists around the world. One suggestion, of many, is a massive road trip to another planet, allowing for the existence and survival of humans as an interplanetary species. Before undergoing this massive road trip, a few preparations need to be made. Most importantly, the planet must be found either in a habitable state, or redesigned to support some form of life. Based off of the lack of habitable planets found so far (at least for humans), many researchers have instead focused on artificially adapting a planet to mimic Earth.

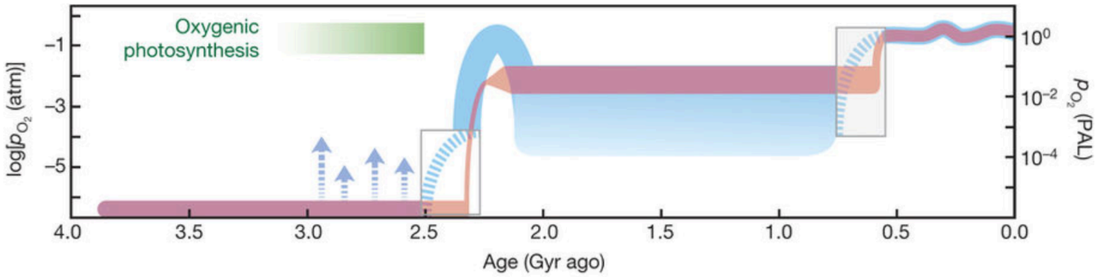
Billions of years ago, Earth looked significantly different than the home we know today. Devoid of life, with a drastically different atmosphere, Earth may have looked similar to other planets that could be candidates for human habitation. One major shift that pushed Earth towards habitability was the Great Oxidation Event (GOE). During this event there was a huge oxygen spike; leading to the oxygenated atmosphere that life thrives in today (Blaustein 2016). Some scientists believe it could be possible to recreate a GOE on another planet, more specifically: Mars. Theoretically, an inhospitable environment such as that located on Mars could be terraformed through an engineered GOE in order to allow for the evolution or inhabitation of life.

There are many ideas for various techniques that could be used to terraform Mars through an artificial GOE. One promising possibility is using cyanobacteria, an extremophile phototroph, to begin the process (Berkely website). Cyanobacteria played a crucial role in the GOE on Earth, and therefore could be vital to the success of a Martian GOE (Sessions, et al. 2009). This paper will further discuss these roles along with a summary of current research involving the use of cyanobacteria in space in order to determine the feasibility of creating a new habitable planet using cyanobacteria.

The Great Oxidation Event

The GOE was a widespread geological episode, which resulted in the buildup of oxygen in the atmosphere (Blaustein 2016). Scientists today still discuss the potential causes and timing of the GOE, though most agree it occurred sometime around 2.45 Ga (billion years ago). This transition took millions of years, occurring in stages (Holland 2006). Figure 1 depicts these stages, at first oxygen occurred transiently, until a tipping point was reached. At that point, oxygen accumulated in the atmosphere, stabilized for about two billion years, then peaked again, eventually leveling out to the oxygen level we experience today (Lyons, Reinhard, Planavsky 2014).

Figure 1:



Stages of oxidation on Earth, the arrows located between 3 and 2.5 Ga depict oxygen whiffs. The second peak shown around 0.7 Ga is associated with the development of animals (Lyons, Reinhard, Planavsky 2014).

In the very beginning of the GOE, it is likely that oxygen first began to accumulate in 'whiffs', or transient pockets of oxygen (Blaustein 2016). Whiffs were produced by oxygenic photosynthesis that accumulated oxygen in a small area, such as under a rock or in ocean surfaces. The atmosphere would then neutralize these whiffs before oxygen could accumulate in greater quantities (Blaustein 2016). These neutralizing molecules (such as iron) were one of the main buffers, or sinks, preventing oxygen build-up. Volcanoes greatly contributed to the buffer molecules in the atmosphere. When volcanoes underwent a fundamental shift caused by tectonic reorganization, the release of buffer molecules slowed (Lyons, Reinhard, Planavsky 2014). This decrease allowed oxygen to accumulate until reaching a tipping point, resulting in a massive peak in oxygen levels around 2.45 Ga. Another theory for the cause of this massive peak is the development of cyanobacteria, the first oxygen-producing bacteria, around the same time (Schirrmeister, Gugger, Donaghue 2015). These theories are not mutually exclusive, and most researchers support some combination of both (plus several others).

The GOE resulted in an oxygenated atmosphere, with significantly decreased methane and H_2 gases (Lyons, Reinhard, Planavsky 2014). This new oxygenated atmosphere was a huge driving mechanism behind evolution. Oxygen was toxic to many organisms, but cellular respiration was evolutionarily favored, as it is 16 times more efficient at creating ATP (stores and transports energy) than anaerobic fermentation (Sessions 2009). Any organism that managed to survive the oxygen peak, and adapt to take advantage of this vital life source would be favored. This advantage may have led to the development of eukaryotic cells, opening the possibility for the development of animals. From there on, we arrive at the world, as we know it.

Cyanobacteria as a cause of the GOE

The GOE was crucial to the evolution of humans, and therefore many astrobiologists have focused their careers studying potential causes of the GOE. Determining this cause is vital to repeating the GOE on another planet. The development of cyanobacteria may have been the main driver of the initial oxygen whiffs and eventual oxygen spike. Cyanobacteria are oxytrophic eubacteria, which get their name from the pigment phycocyanin, a bluish pigment used to absorb light in order to conduct photosynthesis (Speer 2006). This species of algae is the only organism that developed oxygenic photosynthesis, giving cyanobacteria a massive advantage over other organisms at the time of its development. All other photosynthesizing organisms developed the use of oxygen through endosymbiosis with cyanobacteria, forming modern day chloroplasts (Schirrmeister, Gugger, Donaghue 2015). Other photosynthesizing algae at the time used H_2, H_2S or Fe_2+ instead of H_2O to reduce CO_2 into organic matter (Holland 2006). This process used only photosystem I, a part of the photosynthesis process, to create the following reaction: $2H_2 + CO_2 \rightarrow C_{organic} + 2H_20$ (Holland 2006). Cyanobacteria were the first to begin using photosystem II in addition to photosystem I, which provided the tools to oxidize water using sunlight. In this way, the photosynthesis reaction developed: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$. This reaction used CO_2 and H_2O from the environment as a source, much more abundant molecules than H_2, H_2S or Fe_2+ around 3 Ga (Holland 2006). By using water cyanobacteria had a huge advantage over other organisms at the time, not only because of the abundance of water but also because of the efficiency of the reaction. Photosynthesis using both photosystems is much more efficient, and is the process used by phototrophs today harvest light energy. Relatively quickly, cyanobacteria began to dominate, creating oxygen as a waste product as the species excelled.

Cyanobacteria also fix nitrogen, making it unique among other algae species. Fixing nitrogen, or converting atmospheric nitrogen to an organic form, makes nitrogen available to nearby plants, acting as a natural fertilizer (Speer 2006). Many plants rely on nitrogen fixed by cyanobacteria, and form symbiotic relationships with cyanobacteria. This gives cyanobacteria an advantage over other algae, helping cyanobacteria to outcompete nearby species and thrive.

Through the oxytrophic characteristic of cyanobacteria, it seems that it should be obvious that cyanobacteria are the main cause of the GOE. On the contrary, there is still much controversy over the involvement of cyanobacteria in the GOE. The first huge peak of oxygen is believed to have begun around 2.45 Ga. This date is based off of multiple geologic sources. Mass-independent fractionation (MIF) of sulfur in sedimentary rocks indicates that oxygen levels were well below the present atmosphere level (PAL) before 2.45 Ga, then spiked around that time (Holland 2006). It is possible that the MIF of sulfur gives a much later time estimate than reality, as it may have taken millions of years of sedimentary rock weathering and burial for the MIF signals to appear (Lyons, Reinhard, Planavsky 2014). Additionally, the spike in oxygen would have caused a decrease in CH_4 in the atmosphere, resulting in an ice age. An ice age did occur around 2.9 Ga, supporting the assumption that the GOE occurred around 2.45 Ga. Finally, around the suggested time of the GOE, red-banded iron formations increase, indicating oxygen presence creating rust on iron in the rocks (Blaustein 2016). Based off of these indications, the timing of the GOE is fairly set in stone.

On the other hand, the date of the development of cyanobacteria and oxygenic photosynthesis is much more difficult to solidify. Some evidence points towards the evolution of cyanobacteria around 2.8-3 Ga, about 5 Ga before the GOE (Schirrmeister, Gugger, Donoghue 2015). The biomarkers that indicated the cyanobacteria development time might not be as conclusive as originally thought, causing many people to question the exact origin of cyanobacteria. Determining the development time of cyanobacteria using fossils may be possible, as cyanobacteria fossils are relatively reliable compared to other organisms (Schirrmeister, Gugger, Donoghue 2015). Despite the reliability, fossils presence is patchy, providing only glimpses into the cyanobacteria development. Based off of what fossil and genomic evidence can be found, it seems that cyanobacteria developed some time before 3 Ga. This evidence is not conclusive, and the time of development of cyanobacteria multicellularity is still unknown.

If cyanobacteria really did develop so much earlier than the GOE, then the connection between the two would be more complicated than previously thought. According to a detailed genomic study, there are two possible hypotheses to explain how cyanobacteria caused the GOE (Schirrmeister, Gugger, Donoghue 2015). First is that they caused the oxygen whiffs seen around cyanobacteria development time. The second is that the origin of multicellularity in cyanobacteria could be associated with the massive spike during the GOE. Figure 2 depicts the timeline of these two hypotheses.

Figure 2:

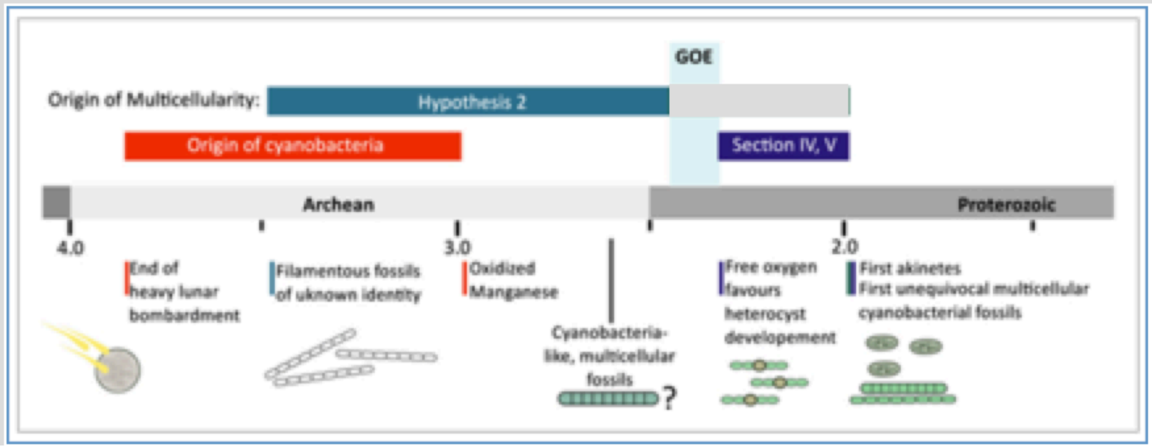


Figure 2 depicts a timeline of the GOE and the development of cyanobacteria. Hypothesis 2 depicts the theory that multicellularity developed before the GOE. The red bar in the picture depicts hypothesis 1, the theory that cyanobacteria caused oxygen whiffs (Schirrmeister, Gugger, Donoghue 2015).

The first hypothesis could very well be true, as oxygen whiffs did begin occurring around the time cyanobacteria developed. This hypothesis would not explain what caused the massive oxygen peak around 2.45 Ga. This issue could be explained by the combination of cyanobacteria and the shifts in volcanoes as described earlier (Lyons, Reinhard, Planavsky 2014). The second hypothesis relies heavily on the timing of the multicellularity development. Though it is a valid idea, the question can only be answered by further study about the specific timing. If this hypothesis is false, and multicellularity developed after the GOE, then it is very possible that the multicellularity was an adaptation in response to the GOE (Schirrmeister, Gugger, Donoghue 2015). Though the connection between cyanobacteria and the GOE may still be questioned, there are many theories that support the algae as the main cause of the GOE.

Cyanobacteria as Extremophiles

The success of cyanobacteria has been evident since its development. This success is due to their ability to adapt to many environments. Though cyanobacteria may be less productive than other organisms in ideal conditions, cyanobacteria are able to grow and repair better in almost all imaginable stressful environments. Cyanobacteria have a unique physiology, molecules called exopolysaccharides allow for repair of extensive damage (Quesada, Vincent 2012). These molecules reduce water loss, providing protection from droughts in both hot and cold environments. Exopolysaccharides also restrict ice crystals from forming within the cells, protecting the organism from extreme cold (Quesada, Vincent 2012). These physiological traits make cyanobacteria well adapted for the extraordinarily dry and cold climates seen on Mars.

In addition to physiological adaptations, cyanobacteria grow well in hypolithic and endolithic environments (under rocks). This protects organisms from extreme climates, trapping moisture, blocking excess sun exposure, and leaching nutrients from the substrate (Quesada, Vincent 2012). Cyanobacteria also have an impressive tolerance to UV radiation which is much more damaging on Mars than Earth (Cockell 2005). One species that exhibits the adaptability of cyanobacteria is *Chroococcidiopsis*, which is found in Antarctic rocks, hypersaline and arid habitats, and thermal springs (Friedmann, Friedmann 1995). This adaptability to a wide range of environments makes cyanobacteria fascinating to study on Earth, yielding a wealth of knowledge that can be applied to astrobiology.

Terraforming Mars

Due to the adaptability of cyanobacteria, astrobiologists are drawn to the idea that cyanobacteria could be used to terraform Mars. Terraforming is defined as: “a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate goal in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of the Earth – one that would be fully habitable for human beings” (Fogg 1995). In order to achieve the goal of terraforming, by definition, scientists start with a planet that is unsuitable for human habitation. This includes extreme climates, toxic atmospheres, strange gravities, and other unpredictable states. Choosing the most suitable planet to begin with is extraordinarily difficult. Currently, scientists have focused on Mars as a potential candidate due to evidence of a wetter and warmer environment (McKay, Marinova 2001). Furthermore, Mars is relatively near Earth and several space missions have already collected data on Mars, and so scientists have access to much information concerning Mars’ characteristics.

Based off of data collected so far, Mars is fairly different than Earth but remains the same in a few key characteristics. Table 1 depicts these comparisons side by side. The day length and obliquity (controls the season) are similar (McKay, Marinova 2001). Physical characteristics of Mars such as average temperature, atmospheric composition, and surface pressure are relatively similar to Earth, though will present challenges to terraforming. In terms of major differences, Mars has lower gravity, lower average sunlight and longer years/seasons compared to

Earth (McKay, Marinova 2001). None of these differences should present fundamental issues with conducting a planet-wide terraforming project. Therefore, Mars could be a candidate for terraforming, as any major differences should not prevent the survival of life.

Table 1: Mars and Earth Comparison

Parameter	**Mars**	**Earth**
Surface Pressure	0.5-1 kPa	101.3 kPa
Average Temp	-60°C	15°C
Composition	95% CO_2 2.7% N_2 1.6% Ar	78% N_2 21% O_2 1% Ar
UV light	>190 nm	>300nm
Surface gravity	0.38g	1g
Rotation Rate	24h 37m	24h
Year Length	687 days	365.25 days

Table 3 depicts a comparison of Mars' and Earth's characteristics (McKay, Marinova 2001).

Until recently, research concerning terraforming Mars has remained mostly theoretical. Through these thought exercises, scientists have sought to determine qualities a planet must have in order to be habitable for humans. Table 2 showcases the minimum characteristics for habitability.

Table 2: Habitability

Parameter	**Limits**
Global Temperature	0°C - 30°C
Composition for plants, algae, microorganisms	
Total Pressure	> 1 kPa
CO_2	>0.015 kPa
N_2	>0.1-1 kPa
O_2	>0.1 kPa
Composition for breathable air	
Total Pressure	
O2 pressure	>25 kPa
Air mixture pressure	>50 kPa
CO_2	<1 kPa
N_2	>30 kPa
O_2	13<kPa<30

Table 2 depicts the limits of human habitability, which are fairly different as compared to the characteristics of Mars (McKay, Marinova 2001).

There are two main issues that must be addressed through terraforming in order to make Mars match these requirements: surface temperature, and atmospheric pressure/nutrient balance. These two issues must be treated in two stages (Fogg 1998).

First, the surface temperature must allow for liquid water, as water is the key ingredient for photosynthetic and eventually respiratory life. Liquid water can be present at temperatures between 0-30°C, Earth currently averages 15°C, while Mars averages -60°C (McKay, Marinova 2001). In order to correct this issue, an initial terraforming project must be conducted. Even though cyanobacteria can withstand extreme cold (at the lowest around -5°C), their tolerance does not reach -60°C (Quesada, Vincent 2012). Therefore, this stage must precede the involvement of cyanobacteria or any other life forms (Fogg 1998). There are many theories about how to increase the temperature on Mars, though many researchers have focused on creating an artificial greenhouse effect using CO_2 that is trapped in the Martian surface. After an initial temperature increase, perhaps by the introduction of CFC's into the atmosphere, polar caps and Martian regolith (loose particles on the surface) will release more CO_2 (Fogg 1998, McKay and Marinova 2001). As simple as this theory may seem, researchers are not certain that Mars' surface actually contains enough CO_2 to create a full greenhouse effect. If the theory is effective, researchers estimate surface warming would take around 100 years, while deep warming could take up to 500 years (McKay and Marinova 2001). In an ideal situation, this theory would create a positive feedback loop, increasing the temperature of Mars, with minimum human involvement. The increase in temperature would melt frozen water present on Mars, making basic microbial life possible.

Next, atmospheric pressure and nutrient concentrations must reach the minimum requirements of human life (see Table 2). Mars contains a slightly lower total atmospheric pressure and concentrations of atmospheric nutrients are not balanced to support human life. Since the atmospheric pressure of Mars is lower than that on Earth, then the total number of molecules available would also be lower. Think of this like being on top of a mountain, there is lower pressure and therefore less oxygen molecules per breath, even though the concentration of oxygen is the same. In order to make Mars habitable, the atmospheric pressure must be increased through the release of nutrients trapped in Mars' surface. This may occur through digestion by organisms such as cyanobacteria and other larger plants.

On Mars, the main atmospheric molecule concentrations are: 95% CO_2, 2.7% N_2, and 1.6% Ar. In order to establish human life on Mars, the atmosphere needs to mimic that of Earth, containing: 78% N_2, 21% O_2, and 1% Ar (McKay and Marinova 2001). Once the surface temperature is improved and there is liquid water available, it may be possible to bring simple life forms to Mars in order to adjust these atmospheric differences. Theoretically, a photosynthesizing organism could digest the high CO_2 content atmosphere of Mars, releasing oxygen as waste. This way, as simple life forms grow and begin to thrive, more and more oxygen would build-up in the atmosphere, mimicking the GOE as it occurred on Earth. As discussed earlier, cyanobacteria are believed to have played a key role in the GOE. Therefore scientists have focused on the possibility of using cyanobacteria on Mars to create a Martian GOE.

Many scientists have created extremely detailed models to simulate the establishment of cyanobacteria on Mars, and how they could affect the Martian atmosphere. One model not only looked at Mars' atmosphere, but also factored in sun exposure, surface wind, and water vapor (Kuhn, Rogers, McElroy 1979). This model determined that cyanobacteria could feasibly survive on Mars, producing 10^-6 to 10^-7 mole of oxygen per cm per day. To put this in perspective, one person requires about 63 mole of oxygen per day. At this rate, it will take around 100,000 years to oxygenate Mars to the level of Earth (McKay and Marinova 2001).

Experimental Summaries

To discuss the feasibility of using cyanobacteria and their efficacy in oxygenating Mars, a few factors must be addressed. Even assuming the temperature of Mars is suitable for life, and water is present (either through melting, or transported from Earth), Mars may remain uninhabitable. Due to the lack of an ozone layer on Mars, UV radiation is significantly higher on Mars than on Earth (Cockell 2001). This radiation could kill any life on Mars, despite the increased temperature and presence of water. Additionally, Mars lacks nitrogen, a molecule that forms the backbone of DNA. Therefore, any plans to establish organisms on Mars may be rendered useless if they cannot access enough nitrogen to grow. The ability of cyanobacteria to repair damage and to fix nitrogen may make them the perfect fit as a pioneering organism on Mars.

Whether or not cyanobacteria can survive these issues is up for debate, and many experiments have focused on these two problems. The following sections will summarize a few of these experiments, detailing the results and their implications on the use of cyanobacteria to create a Martian GOE.

Resistance to UV Radiation:

Cyanobacteria have a unique reparative capability, allowing them to withstand damage from extreme temperatures and desiccation, then repair any damage to recover full functions (Quesada Vincent 2012). Experiments exposing cyanobacteria to UV radiation rely on this fact to prolong cyanobacteria survival. The research article *Effects of a Simulated Martian UV Flux on the Cyanobacterium, Chroococcidiopsis sp.* exposed cyanobacteria to UV radiation to determine their survival rate. Researchers found that after five minutes of UV exposure relative to that fond on Mars, there was a 99% loss of *Chroococcidiopsis* cell viability (Cockell 2005). Though viability was lost, evidence of life such as DNA and enzymatic activity remained after a full Martian day of UV exposure. Additionally, the cyanobacterium survived much longer than other organisms such as the spores, *B. subtilis*, which lost all viability after 15 seconds (Cockell 2005). This difference may have been due to the much larger size of *Chroococcidiopsis* and the polysaccharide sheaths that encapsulate cyanobacteria. When cells were covered in one mm of rock and exposed to UV radiation, cyanobacteria were able to remain viable for a full eight hours. In this way, the algae would be able to survive the daytime on Mars, repairing damage in the evening in order to continue to grow and thrive. This experiment implies that cyanobacteria may be able to survive on Mars, despite the high radiation, if they can grow under a thin covering (Cockell 2005).

To support this finding, cyanobacteria that are found in desert and cold environments are often found in hypolithic and endolithic growth forms (Friedmann, Friedmann 1995, Quesada Vincent 2012). Hypolithic growth is when an organism grows under a translucent stone, which reduces UV radiation and also conserves moisture (Friedmann, Friedmann 1995). Figure 5 depicts this growth habit. In a thought experiment concerning the survival of cyanobacteria on Mars using glass strips to protect from radiations, researchers theorize that cyanobacteria could not only survive, but also become a large-scale Martian farming technology. The hypolithic habitat would allow for temperatures that favor higher microbial growth, reduced water requirements, and protect from UV radiation. This experiment also suggests using *Chroococcidiopsis* due to its adaptability and resemblance to fossils found around the time of the GOE (Friedmann, Friedmann 1995).

Figure 5:

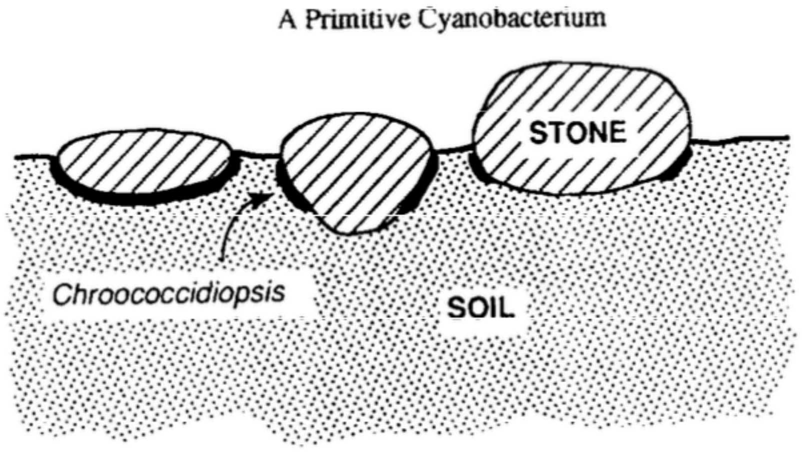


Figure 5 depicts the hypolithic growth habit of cyanobacteria (Friedmann, Friedmann 1995).

These articles show that cyanobacteria could in fact survive the UV radiation on Mars due to their ability to repair damage, and grow under protective rocks. There are several other articles that address this issue that could not be mentioned in this section (see Appendix A). Some other interesting experiments with cyanobacteria survival in space are the BOSS, BIOMEX and EXPOSE-R2 missions, that put cyanobacteria into space in order to test their ability to survive a vacuum, and other space related stressors (see Appendix B).

Soil Remediation using N-fixing:

Since cyanobacteria are nitrogen (N) fixing, they are less susceptible to N limitation in soil than other organisms. Due to the lack of nutrients in Martian soil, this means that cyanobacteria can fix N from the atmosphere, enriching the soil with N. Despite this advantage, the low amount of N in Mars' atmosphere would limit the amount of sediment biomass to 60g/cm (McKay 1991). This total amount of biomass can only release 40mbar of oxygen, far lower than what would be necessary to oxygenate Mars. Some researchers believe that enough nitrogen may be trapped in Mars' surface (McKay and Marinova 2001). If there is not enough nitrogen trapped in Mar's surface, the process of terraforming Mars to become inhabitable by humans would come to a complete halt, Mars would not be fully oxygenated, and therefore humans would not be able to breath on Mars. Therefore, determining the N content on Mars is essential before any terraforming projects on Mars can begin. Though cyanobacteria cannot add N to Mars' system, it can make N available through soil remediation, maximizing the N present on Mars.

An experiment determining the composition of cyanobacteria communities looked at nutrient contents in soil before and after cyanobacteria presence. The study found that the concentration of organic matter and nutrients were significantly higher in soils with cyanobacteria than without (Hu 2003). Though this soil remediation may take hundreds or thousands of years, cyanobacteria could significantly improve Martian soil structure. This would pave the way for the establishment of other plants such trees for larger oxygen release, and agricultural crops to feed the first human inhabitants (Hu 2003). In addition to remediating the soil for agricultural purposes, cyanobacteria themselves can be eaten, providing enough nutrition to make growing cyanobacteria worthwhile (Yokoshima 2014). The N-fixing and nutritional aspects of cyanobacteria makes the algae also useful for space travel as a fertilizer for food crops, or as food themselves (Stone 2015).

Another experiment focused on methods in order to best establish cyanobacteria in order to optimize establishment and N fixation. The experiment used mats inoculated with cyanobacteria to grow various vegetable crops, and found that cyanobacteria mats were just as effective in fertilizing crops as N fertilizers (Yokoshima 2014). These mats would also increase cyanobacteria viability on Mars, by preventing strong winds from blowing the species away.

In addition to simply fixing N, cyanobacteria could provide soil structure, reducing the amount of loose dust that would damage other plants. In deserts, cyanobacteria create crusts that help keep soil intact (Liu 2008). An experiment tested the abilities of cyanobacteria to withstand wind erosion at levels that would appear on Mars. After 15 days of growth, the cyanobacteria were able to successfully resist sand erosion (Liu 2008). Therefore, cyanobacteria could be used in greenhouses and habitats to minimize damage from dust on other important crops.

Terraforming Mars through an engineered GOE using cyanobacteria still lacks significant background research. The feasibility of this project is difficult to judge with such little practical research and only theoretical thought exercises. Based off of what we know now, there are a few problems that must be addressed. First, the exact processes behind the GOE must be determined in order to conclude the extent of cyanobacteria involvement. If cyanobacteria were not the main causers of the GOE, then using these algae for an engineered GOE may be useless. Additionally, the ability of cyanobacteria to survive in Martian conditions requires further research to determine the minimum qualities Mars must have achieved before the implementation of cyanobacteria. Finally, the total N content of Mars must be solidified, as the current atmospheric N total is not nearly sufficient to sustain human habitability.

In summary, cyanobacteria are amazing organisms. Due to their variety of habitat preferences, ability to repair damage, fix N and photosynthesize, cyanobacteria could be the perfect candidate as a pioneer organism on Mars. After initial warming, cyanobacteria could replay their role in the GOE in order to oxygenate Mars. With an oxygen rich atmosphere, humans could potentially move to Mars, becoming an interplanetary species. In this way, issues on Earth such as overpopulation and climate change would be solved.

Though many researchers have dedicated their careers to the research of Mars and the process of terraforming, there is still much to be done before such big dreams can be made possible. Most research so far has been theoretical, and it is necessary to create projects that can glean even more details about the surface and atmospheric makeup of Mars, in addition to the viability of cyanobacteria as a mechanism for a Martian GOE. Terraforming Mars is just one small part of astrobiology, and it is very possible that the solution to many of Earth's problems could be found somewhere out in space. It is a continual hope for these solutions outside of Earth that keeps astrobiologists motivated. Who knows, maybe terraforming Mars will be the one.

Appendix A

Baqué, Mickael, et al. "Biofilm and planktonic lifestyles differently support the resistance of the desert cyanobacterium Chroococcidiopsis under space and Martian simulations." *Origins of Life and Evolution of Biospheres* 43.4-5 (2013): 377-389.

Cockell, Charles S., et al. "Interplanetary transfer of photosynthesis: an experimental demonstration of a selective dispersal filter in planetary island biogeography." *Astrobiology* 7.1 (2007): 1-9.

Cockell, Charles S. "The martian and extraterrestrial uv radiation environment part II: further considerations on materials and design criteria for artificial ecosystems." *Acta astronautica*49.11 (2001): 631-640.

Cockell, Charles S., and John A. Raven. "Zones of photosynthetic potential on Mars and the early Earth." *Icarus* 169.2 (2004): 300-310.

Olsson-Francis, Karen, Rosa de la Torre, and Charles S. Cockell. "Isolation of novel extreme-tolerant cyanobacteria from a rock-dwelling microbial community by using exposure to low Earth orbit." *Applied and environmental microbiology* 76.7 (2010): 2115-2121.

Appendix B

Baqué, Mickael, et al. "The BOSS and BIOMEX space experiments on the EXPOSE-R2 mission: Endurance of the desert cyanobacterium Chroococcidiopsis under simulated space vacuum, Martian atmosphere, UVC radiation and temperature extremes." *Acta Astronautica* 91 (2013): 180-186.

Rabbow, Elke, et al. "EXPOSE-E: an ESA astrobiology mission 1.5 years in space." *Astrobiology* 12.5 (2012): 374-386.

Works Cited

Baqué, Mickael, et al. "The BOSS and BIOMEX space experiments on the EXPOSE-R2 mission: Endurance of the desert cyanobacterium Chroococcidiopsis under simulated space vacuum, Martian atmosphere, UVC radiation and temperature extremes." *Acta Astronautica* 91 (2013): 180-186.

Billi, Daniela, et al. "Cyanobacteria from extreme deserts to space." *Advances in Microbiology* 3.06 (2013): 80.

Canfield, Donald E., et al. "Oxygen dynamics in the aftermath of the Great Oxidation of Earth's atmosphere." *Proceedings of the National Academy of Sciences* 110.42 (2013): 16736-16741.

Carrapiço, Francisco. "The Azolla-Anabaena-bacteria system as a natural microcosm." *Proceedings of SPIE*. Vol. 4495. 2002.

Catling, David C. *Astrobiology: a very short Introduction.* Oxford University Press, 2014.

Cockell, Charles S., and John A. Raven. "Zones of photosynthetic potential on Mars and the early Earth." *Icarus* 169.2 (2004): 300-310.

Cockell, Charles S., et al. "Effects of a simulated martian UV flux on the cyanobacterium, Chroococcidiopsis sp. 029." *Astrobiology* 5.2 (2005): 127-140.

Cockell, Charles S., et al. "Interplanetary transfer of photosynthesis: an experimental demonstration of a selective dispersal filter in planetary island biogeography." *Astrobiology* 7.1 (2007): 1-9.

Fogg, Martyn J. "Terraforming Mars: a review of current research." *Advances in*

*Space Research*22.3 (1998): 415-420.

Fogg, Martyn J. "Terraforming: engineering planetary environments." *Warrendale, PA: Society of Automotive Engineers, c1995. 1st ed* (1995).

Friedmann, E. Imre, Maosen Hua, and R. O. S. E. L. I. Ocampo-Friedmann. "Terraforming Mars: dissolution of carbonate rocks by cyanobacteria." *Journal of the British Interplanetary Society* 46 (1993): 291-292.

Holland, Heinrich D. "The oxygenation of the atmosphere and oceans." *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 361.1470 (2006): 903-915.

Holland, Heinrich D. "Volcanic gases, black smokers, and the Great Oxidation Event." *Geochimica et Cosmochimica Acta* 66.21 (2002): 3811-3826.

Hu, Chunxiang, et al. "The vertical microdistribution of cyanobacteria and green algae within desert crusts and the development of the algal crusts." *Plant and Soil* 257.1 (2003): 97-111.

Joseph, Rhawn Gabriel. "Martian Mystery Structure May Be Composite Fungus and Cyanobacteria Organisms."

Katoh, Hiroshi, et al. "Utilization of the terrestrial cyanobacteria." 44th International Conference on Environmental Systems, 2014.

Kuhn, William R., S. R. Rogers, and R. D. MacElroy. "The response of selected terrestrial organisms to the Martian environment: A modeling study." *Icarus* 37.1 (1979): 336-346.

Kump, Lee R. "The rise of atmospheric oxygen." *Nature* 451.7176 (2008): 277-

278.

Liu, Yongding, et al. "Control of lunar and Martian dust—experimental insights from artificial and natural cyanobacterial and algal crusts in the desert of Inner Mongolia, China." *Astrobiology* 8.1 (2008): 75-86.Friedmann, E. Imre, and R.

Lyons, Timothy W., Christopher T. Reinhard, and Noah J. Planavsky. "The rise of oxygen in Earth/'s early ocean and atmosphere." *Nature* 506.7488 (2014): 307-315.

McKay, Christopher P., and Margarita M. Marinova. "The physics, biology, and environmental ethics of making Mars habitable." *Astrobiology* 1.1 (2001): 89-109.

McKay, Christopher P., Owen B. Toon, and James F. Kasting. "Making Mars habitable." *Nature*352.6335 (1991): 489-496.

Ocampo-Friedmann. "A primitive cyanobacterium as pioneer microorganism for terraforming Mars." *Advances in Space Research* 15.3 (1995): 243-246.

Olsson-Francis, Karen, and Charles S. Cockell. "Use of cyanobacteria for in-situ resource use in space applications." *Planetary and Space Science*58.10 (2010): 1279-1285.

Planavsky, Noah J., et al. "Evidence for oxygenic photosynthesis half a billion years before the Great Oxidation Event." *Nature Geoscience* 7.4 (2014): 283-286.

Quesada, Antonio, and Warwick F. Vincent. "Cyanobacteria in the cryosphere: snow, ice and extreme cold." *Ecology of cyanobacteria II*. Springer Netherlands, 2012. 387-399.

Schirrmeister, Bettina E., Muriel Gugger, and Philip CJ Donoghue. "Cyanobacteria and the Great Oxidation Event: evidence from genes and fossils." *Palaeontology* 58.5 (2015): 769-785.

Sessions, Alex L., et al. "The continuing puzzle of the great oxidation event." *Current Biology* 19.14 (2009): R567-R574.

Shields-Zhou, Graham, and Lawrence Och. "The case for a Neoproterozoic oxygenation event: geochemical evidence and biological consequences." *GSa Today* 21.3 (2011): 4-11.

Speer, B.R. "Cyanobacteria: Life History and Ecology." Life History and Ecology of Cyanobacteria, www.ucmp.berkeley.edu/bacteria/cyanolh.html.

Stone, Maddie. "The Key to Colonizing Mars Could Be These Tiny Green Microbes." *Gizmodo*, Gizmodo.com, 22 Sept. 2015, gizmodo.com/the-key-to-colonizing-mars-could-be-these-tiny-green-mi-1731268670

Yang, Wenbo, and Heinrich D. Holland. "The Hekpoort paleosol profile in Strata 1 at Gaborone, Botswana: soil formation during the Great Oxidation Event." *American Journal of Science*303.3 (2003): 187-220.