HIGH SCHOOL EDITION
Journal of Student Research

Volume 11 Issue 4 (2022)

Probability of Life on Mars Utilizing Biosignatures

Divya Krishna[1], Rajogopal Appavu[#] and Jothsna Kethar[#]

[1]Gifted Gabber
[#]Advisor

ABSTRACT

Biosignatures are key pieces of evidence of life on other planets, in this research paper we will be focusing specifically on Mars. This paper compiles research from other papers and highlights probabilities and improbabilities of life from data on Mars and terrestrial analogs on Earth. Hydrated areas likely to have liquid water exhibit a correlation with life as liquid water is commonly thought to be the "key" to an organism's survival. Analogs on Earth may also simulate similar conditions to that of Mars and illustrate various life forms that have inhabited these areas. Sources of energy observed in these analogs as well as Mars can be conducive to life. However, just because an environment is habitable does not mean life inhabited it. The paper also compares false biosignatures which may be misleading to the presence of life. The importance of this paper is to address the ambiguity and presence of microbial life on Mars.

Introduction

As an attempt to conclude traces of life outside of Earth, scientists have focused their attention on biosignatures with the relatively recent impetus from volumes of data collected from martian rovers. Both macro and microscopic biosignatures provide insight into previous life on Mars with a special focus on evidence regarding microorganisms. The word "biosignature" refers to a phenomenon, substance, object, and/or pattern whose origin is attributed to a biological agent (Des Marias et al., 2003). The Mars 2020 Science Definition Team identified key organizations of biosignatures (Organics, Minerals, Macro Structures/Textures, Micro Structures/Textures, Chemistry, and Isotopes—see Fig. 1). As the conquest to colonize the galaxy persists, the inherent curiosity of unknown life and possible isolation in the universe stimulates the search for these signatures of biological origin. Not only can a collection of evidence bring about the findings of otherworldly organisms, but pave the way for future missions. Biosignature preservation, however, is difficult on habitats such as Mars. Many chemical processes and compounds (e.g., radiation, oxidation, weathering) both in Mars' past, as well as present, prevent the preservation of such biosignatures. The small number of biosignatures still present on Mars may still lead to the findings of extraterrestrial life but may not provide the full picture of early to the present day Red planet.

An In-Depth Look at Biosignatures

Furthermore, excluding the destruction of biosignatures, abiosignatures, or a substance, object, and/or pattern with a nonbiological origin, aids in deducing the improbability of biosignatures. Characterizing abiosignatures allows for the ability to confirm the existence of biosignatures and if the environment is habitable. As well as abiosignatures, potential biosignatures are substances, objects, and/or patterns that fall into an ambiguous category as the origin of their existence cannot yet be determined. These potential biosignatures pose a difficulty to many "biosignature endeavors" as one cannot validate the biosignature. Despite the ambiguity of biosignatures themselves, another strategy to move around the "gray area" is to look for favorable conditions of life on Mars and afterward determine the feasibility of life actually being present with the support of biosignatures. Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, and Sulfur (CHNOPS), clement conditions, and sources of other trace essential nutrients are considered to be the basis of the majority of life as of now, with the higher probability of these materials resulting in the higher probability of life (Cockell, 2014). It has been hypothesized that the mid-Noachian to early Hesperian period was most conducive to life on Mars due to the higher probabilistic nature of essential nutrients and optimal conditions (Clark et al., 2021). Favorable conditions began to reduce during the bulk of the Hesperian period due to widespread volcanism, drastic loss of water, drying of the martian surface, and permafrost coverage (Clark et al., 2021). Although there are/were current and past missions on Mars such as the Perseverance and Curiosity Rovers, analog environments on Earth are additionally utilized to serve as a comparison and model of martian conditions. In an attempt to decipher and conceptualize martian life, geological features of Mars, defined biosignatures, Mars analog environments, presence of disequilibrium, manipulation of electromagnetic radiation, and probabilistic context of biosignatures are examined in this paper.

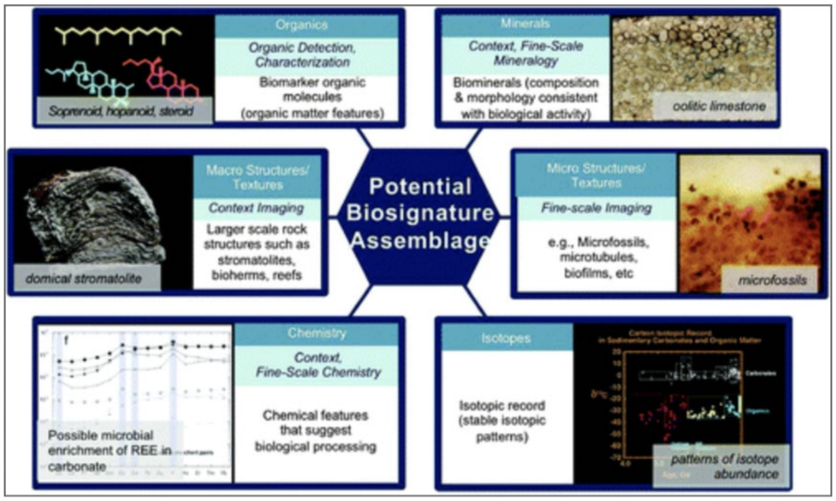

Figure 1. Above exhibits the efforts of the Mars 2020 Science Definition Team to classify the various types of biosignatures (From Mustard et al., 2013).

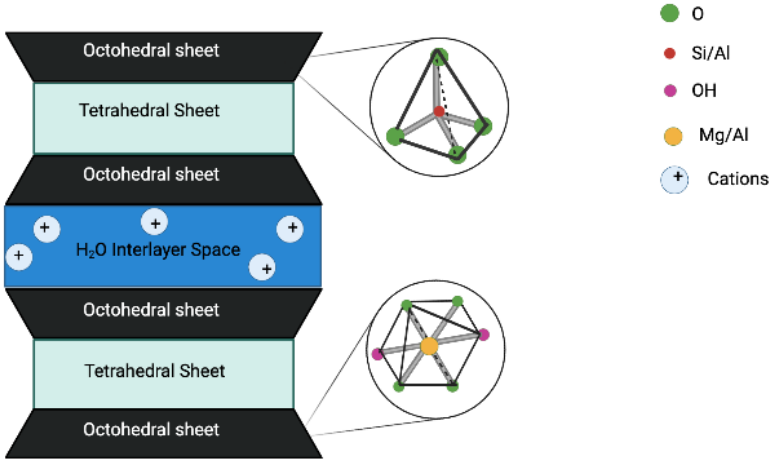

Figure 2. Smectite formation.

Evidence of Liquid Water

Water is often thought of as a hypothetical trail to the origin of life. H_2O is able to be incorporated into many biological processes such as photosynthesis, cooling mechanisms, breaking macromolecule bonds, and more. If Mars were to currently have liquid water on the surface, it would almost immediately vaporize because of its instability. Mars contains evidence such as the presence of Fe/Mg smectites, a type of clay that indicates aqueous conditions (Cockell, 2014). As exhibited in Figure 2, smectite formation is highly dependent on water in the interlayer space. Imaging spectrometers CRISM and OMEGA have helped identify various types of clays on Mars. A type of clay called phyllosilicates is associated with metal-OH absorptions with wavelengths from ~2.2-~2.4nm (Milliken, 2008.). With the Hesperian period of Mars characterized by the formation of sulfate deposits, no spectral evidence suggests acidic contamination of clay deposits near the Hesperian period. This indicates some areas during the period have the potential to be habitable. Other clays aside from smectites, including Kaolins, also appear to have their own distinct doublet at ~2.2μm and near ~1.4μm, as exhibited in Figure 3. Kaolins and other clays exhibit their own unique spectra and provide useful information about water-clay interactions on Mars (Milliken, 2008).

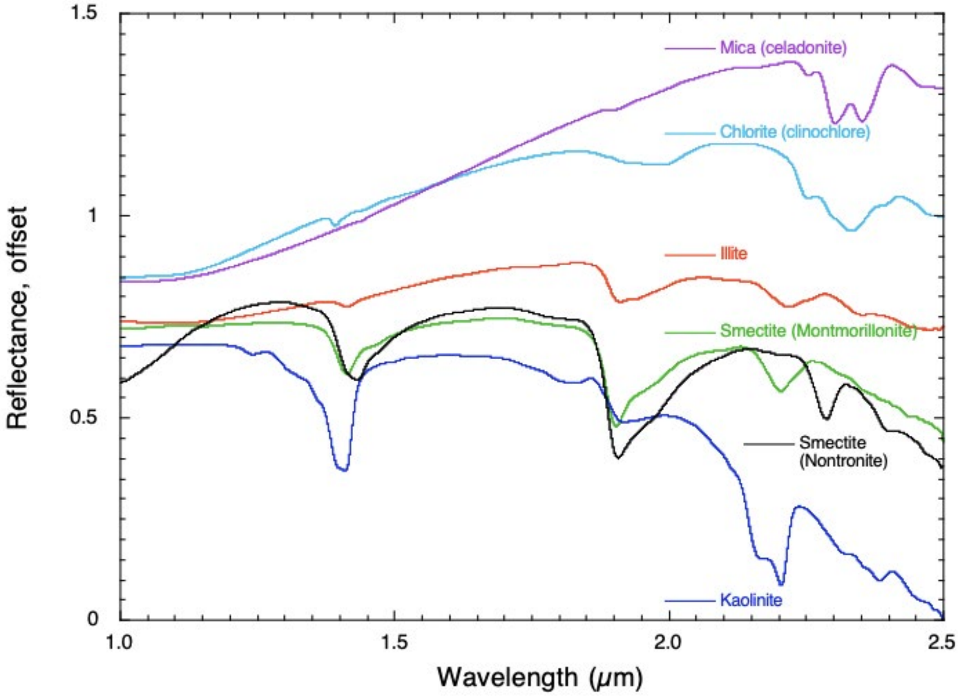

Figure 3. Spectra of various clays found on Mars in μm (From Milliken, 2008).

In addition to clays, geological features such as inverted fluvial networks found in the Antoniadi Crater depict past evidence of water. As shown in figure 4, the stubby branches of the network are hypothesized to be the result of groundwater sapping or the erosion of minerals by groundwater. Branching features represent stream channels as seen on Earth ("Inverted dendritic stream channels in Antoniadi crater (PSP_007095_2020)," n.d.). Gravel fragments and rounded pebbles yield evidence of vigorous water flow, resulting in their weathering (Nazari-Sharabian et al., 2020). Craters such as the Eberswalde Crater are home to deltas, posing strong support to lakes on Mars. It is considered a paleolake, especially with smectites found in the area. The Eberswalde Delta is thought to be formed by carrying sediment to the lake. After the sediment is carried, liquid water drops the sediments resulting in a delta (“Eberswalde Crater,” n.d.). Other areas also hint at water flow during the Noachian period. The Terra Sirenum, located at the Phaethontis and Memnonia quadrangles of Mars is suggested to be another dried-out lake. An Oxbow lake was located in the Phaethontis quadrangle. Its significance is attributed to the formation, where meanders or curves result in a "U" shape. This suggests flowing water for a relatively long period of time ("Terra Sirenum," n.d.).

Serpentinization reactions on Mars also pinpoint the origin of water. During serpentinization, olivines, a magnesium, iron silicate mineral, produce carbonates, serpentine, and talc as a byproduct when exposed to water containing carbon dioxide (Gronstal, 2020). Not only does serpentinization provide evidence for liquid water, but the reaction results in hydrogen liberation allowing for an invaluable source of electrons and energy for microbial organisms. Other processes such as that of Hematite Spherules otherwise referred to as "martian blueberries" are predicted to form similar to those on Earth. They are concretions formed by the precipitation of aqueous fluid (Misra et al., 2014).

Current water on Mars is found primarily in ice, if water were in its liquid state, it would immediately evaporate because of the high pressure on the Martian surface. The two polar ice caps, one in the north (Planum Boreum) and one south (Planum Australe) are composed of roughly 85% CO_2, 15% water ice, and scarps. In other words, scarps are the plains surrounding the ice cap consisting of primarily water and ice (Nazari-Sharabian et al., 2020). Ice is also found underground on Mars as exhibited in Figure 5. Most of the ice is distributed throughout the subsurface with almost none found in liquid form.

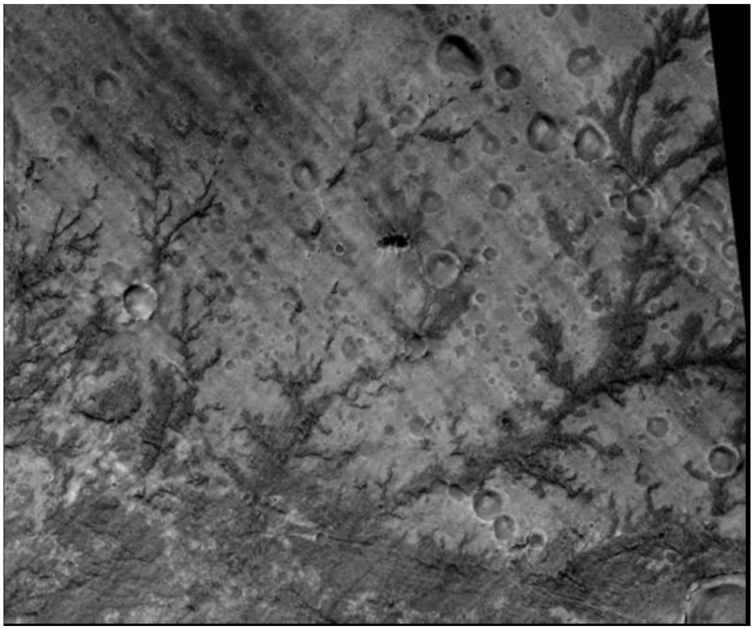

Figure 4. Martian inverted stream channels located at the Antoniadi crater in the Syrtis Major quadrangle from NASA's HiRISE (From Nazari-Sharabian et al., 2020).

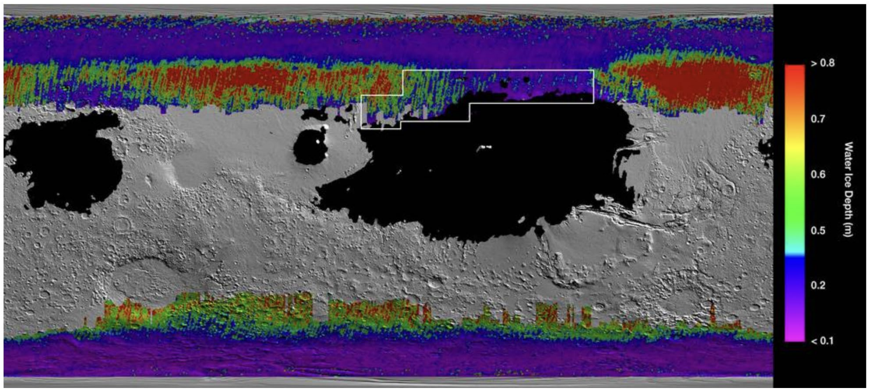

Figure 5 The image displays Martian underground water ice from many of NASA's orbiters. Cooler colors represent ~30cm below the surface and warmer colors at ~60cm below the surface. Black areas indicate spacecraft sinkage into fine dust and the outlined box displays the optimal region for astronauts to dig for water ice. Credits: NASA/JPL-Caltech/ASU

Mars Analogs on Earth

Part of understanding martian habitability is utilizing Earthly environments to simulate similar conditions on Mars. Various analogs such as hydrothermal vents, the Atacama desert, and Río Tinto allow for a greater understanding of microbial life on Mars.

Hydrothermal vents are fissures similar to geysers on the seafloor where heated water is transported from its interior. The Erdania basin is thought to be the location in which hydrothermal vents previously existed on Mars. Its concave structure indicates the basins were preserved by water or ice-covered water. At 1,100m the Ma'adim Vallis outflow channel lies, consistent with the elevation of the Erdania basin, indicating it was filled with water (Michalski et al., 2017). This evidence is significant as it had the potential to harbor vast amounts of microbial life. Hydrothermal vent activity may increase accessibility to water as it can melt nearby ground ice, form fumaroles or hot springs able to emit volcanic gasses and vapor in arid environments, and sustain hydrologic cycles (Hays et al., 2017). As valuable elements dissolve to form solutions, hydrothermal vents draw out the nutrients from rocks. Essential elements including CHNOPS and other trace elements are able to be drawn out from the host rocks during dissolution. Other elements are also provided through volcanic gasses released by hydrothermal vents, making this environment optimal for nutrient availability and life. However, many hydrothermal systems may be restricted due to their relatively small size. Additionally, due to the diverse conditions of hydrothermal vents, some areas may be inhabitable due to pH, temperature, and availability of nutrients (Hays et al., 2017).

Hydrothermal vents are one plausible environment for martian life, but other habitats, specifically microhabitats can be significant to life. As discussed in (Morgan et al., 2014) the Atacama Desert in Chile indicates evidence of alluvial fans on Mars. Alluvial fans are formed when sediment deposits fan out from one concentrated source of sediment. On Mars, the presence of these features suggests surface runoff from the Hesperian to Amazonian periods, thought to be uninhabitable to life. Also, the Atacama desert is reported to have a layer of smectites below the surface of the arid desert. Halophilic bacteria were found to live in the clay as it provided a distinct microenvironment and a source of protection from the majority of the desert (Azua-Bustos et al., 2020). Figure 6 exhibits the thirty salt-loving or halophilic bacteria in the layer of clay. Due to the abundance of clay on Mars, the Atacama desert analog illustrates the possibility of other archaeans or bacteria surviving on the Red Planet.

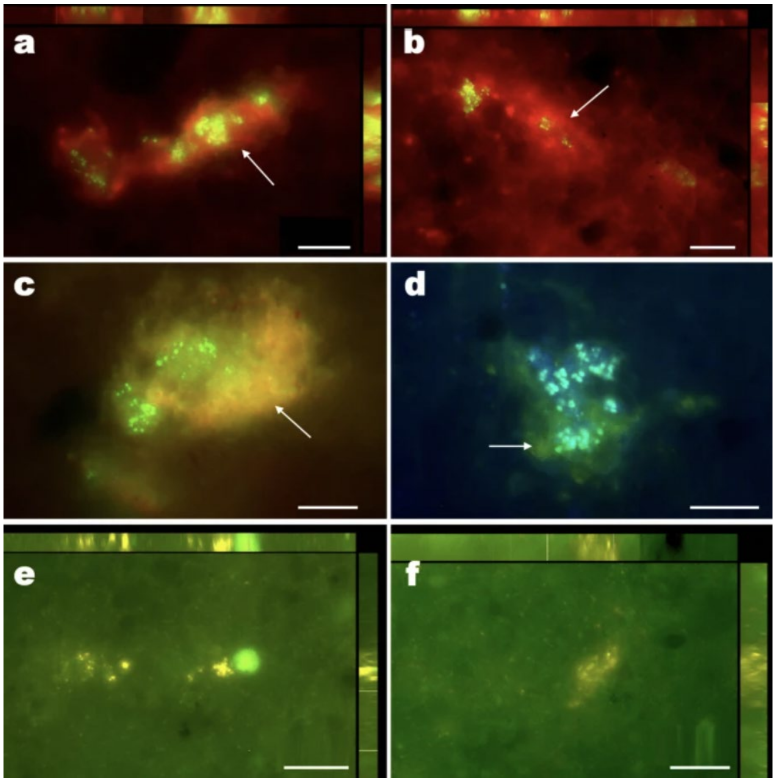

Figure 6. Atacama desert bacteria aggregates in subsurface clay from fluorescent imaging (From Azua-Bustos et al., 2020).

Other analogs include the Río Tinto or Red River in Spain, which is distinguished by low levels of oxygen and extremely acidic conditions close to Mars. This river is home to an abundance of microbial life and large amounts of iron and other minerals. The majority of microbes belong to three bacterial genera of *Acidithiobacillus*, *Leptospirillum,* and *Acidiphilium*, which all belong to the iron cycle. Each genus of bacteria respectively can oxidize iron in aerobic conditions, use ferric iron as an electron acceptor during anaerobic respiration, and use ferric iron as an electron acceptor aerobically. Other bacteria can utilize reduced sulfur as a source of energy (Amils et al., 2014). Pyrite is turned into dissolved iron and sulfuric acid, supporting energy usage for microbes.

Chemical Disequilibrium

Chemical disequilibrium is thought to support life on any planet. This process occurs when molecular compounds which would commonly react with one another essentially do not. For example, if CH_4 (methane) and $2O_2$ (oxygen) were to react, it would commonly produce CO_2 (carbon dioxide) and $2H_2O$ (water). However, in some atmospheres, methane and oxygen species exist without reacting, suggesting replenishment from a biological source. Earth currently has the largest disequilibrium in the solar system with a little over 1000 J/mol and Mars with 136 J/mol, a relatively high disequilibrium when comparing other planets in the solar system. The majority of the disequilibrium on Mars is attributed to the following reaction:

$$2CO + O_2 \rightleftharpoons 2CO_2$$

CO and O_2 are found to coexist on Mars when it is expected CO to lose electrons or become oxidized by O_2 (Krissansen-Totton et al., 2016). This leads scientists to believe the reaction is a potential biosignature, yet it is not regarded as one at all. In actuality, it is more likely that life would manipulate the reaction and metabolize the reactants and products as energy. Carboxydotrophic organisms are able to utilize aerobic CO dehydrogenase and consume the molecule (Wogan & Catling, 2020). Yet others may argue as to why Earth's disequilibrium supports evidence of a clear presence of life, illustrated by the reaction below:

$$2N_2(g) + 5O_2(g) + 2H_2O(1) \rightleftharpoons 4H^+(aq) + 4NO_3^-(aq)$$

The O_2-N_2-H_2O reaction is the largest contributor to chemical disequilibrium on Earth. It is hypothesized enzymes are unable to significantly decrease the activation energy through the use of enzymes and the disequilibria persist (Wogan & Catling, 2020). Oftentimes, disequilibria that cannot be consumed by organisms are far more valuable than those that are able to as it is more likely for a disequilibrium to be produced by a biological organism itself.

Sources of Nutrients on Mars

Carbon is commonly present as CO on Mars with 800 parts per million (ppm) compared to Earth's 0.3 ppm (Wall, 2015). Additionally, CO_2 is abundant in the martian atmosphere at 6 millibars (mbar) and Earth's 0.4 mbar and can be used in the synthesis of organic molecules (Clark et al., 2021). Carbon has also been found by the Curiosity Rover at the Vera Rubin Ridge in Gale Crater from powdered rock. The carbon detected in the sample were two different isotopes of the element, Carbon-12 and variable amounts of Carbon-13. Similar to the 2.7 billion-year-old Tumbiana Stromatolite from Australia, there were depleted Carbon-13 levels. But, in the Tumbiana Stromatolite methane consumption by microbial mats resulted in the sample. One could argue a process similar to that of Mars, but scientists remain unsure due to the different conditions and composition of Mars (Whitt, 2022). The discovery of Carbon-12 is of significance as it is incorporated into photosynthesis. Other sources of Carbon can be found in meteorites such as the Tissint martian meteorite where carbonaceous particles were found (Wallis et al., 2012), carbonaceous structures in the Nakhla meteorite (Gibson et al., 2006), and carbonate globules in the ALH84001 meteorite (Becker et al., 1999).

Hydrogen can be extracted from previous water molecules that may have existed on the surface or in the form of hydroxyl ions. The water molecules may have come into contact with the martian surface and split due to radiolysis (Cockell, 2014). Although hydrogen is commonly sourced from water, previous atmospheric conditions would have exhibited hydrogen in methane (CH_4), ammonia (NH_3), hydrogen gas (H_2), hydrogen cyanide (HCN), and more. Some species of hydrogen were discovered by Curiosity Rover's Dynamic Albedo of Neutrons (DAN) by neutrons entering martian ground from cosmic rays, which then bounce off hydrogen's energy levels. The hydrogen was interpreted to be in the form of H_2O or OH^- ("Curiosity Finds Hydrogen-Rich Area of Mars Subsurface," 2015).

Most of the nitrogen is predicted to be in its diatomic form (N_2), but living organisms are unable to utilize nitrogen gas. Living organisms use fixed nitrogen gas which can be found in the martian soil in the form of nitrates and ammonium salts. Nitrogen fixation may have occurred through volcanic activity, meteorite impacts, and lightning events (Cockell, 2014). But, a few organisms called diazotrophs are found to be able to fix dinitrogen using nitrogenase enzymes based on Fe-S-Mo or V-. Currently, nitrogen composes ~2.7% of the martian atmosphere. However, in early Mars, it is proposed that N_2 concentrations were 13-200 times more than the present concentrations. This is due to the loss of gas from the atmosphere and to the soil in the form of fixed nitrogen (Clark et al., 2021).

Mars has a composition of ~0.13% oxygen, which is difficult to support copious amounts of life. But oxygen may be found in other compounds like liquid water, CO_2, perchlorates, sulfates, and ferric oxides (Cockell, 2014). Modeling suggests episodic periods of higher O_2 concentrations which, although providing more instances of oxygen incorporation could have acted as a limiting factor to life (Wordsworth, 2021). Nevertheless, seasonal changes have been attributed to the amount of oxygen available on Mars. During the spring and summer seasons, oxygen rises to a concentration of 400 parts per million (ppm). Some scientists believe this spike is due to abiotic processes. Such processes include the separation of CO_2 and water vapor into their subsequent parts, including oxygen. Additionally, the breakdown of perchlorates due to cosmic radiation may release diatomic oxygen (although too fast to result in large spikes). Life may also be viable in underground oxygen reservoirs composed of hydrogen peroxide diffused into the soil and could host organisms such as sponges (Greshko, 2019).

Phosphorus is commonly found in its volatile form on Mars as opposed to Earth's less volatile phosphorus. Phosphorus is commonly found in minerals in the Gusev crater. For example, Wishtone class rocks of P_2O_5 abundances were found in the crater (more than 5%). Also, alkaline basalts in the Gale crater (less than 1% weight abundance) were found to contain phosphorus. Minerals classified as merrillite, whitlockite, and chlorapatite are P-containing minerals that were able to be extracted from shergottite meteorites as other sources of phosphorus (Clark et al., 2021). Similar to Earth, microbial organisms and fungi are able to absorb nutrients such as phosphorus from rocks.

The last of the CHNOPS essential elements include sulfur. Sulfur is highly concentrated in the soil attributed to the oxidation of sulfides by water and volcanic degassing (Greenwood & Blake, 2006). Mars as a sulfur-rich planet also contains concentrations of sulfate salts namely gypsum, jarosites, etc. (Cockell, 2014). Furthermore, sulfur is prevalent as magnesium sulfate, which is able to provide essential cations (Mg^{2+}) for RNA and stimulate life for microbes (Franz et al., 2019). As previously mentioned, sulfur dominance on Mars suggests a distribution from the mantle to the surface. The components of the sulfur distribution may include SO_2 or H_2S which are accessible to microbes (Cockell, 2014).

Chirality

Chirality is essential to early life as the shape of molecules is crucial to their function. Take amino acids and sugars as an example, amino acids are strictly "left-handed," with the exception of glycine, (L-amino acids) and sugars "right-handed" (D-sugars). On Mars, preservation of these chiral molecules is quite high as the environment is cold and dry resulting in slower rates of racemization (conversion of L-amino acids to D-amino acids) and hydrolysis (Glavin et al., 2020). However, no chiral molecules to date have been discovered on Mars, but its importance as a potential biosignature is crucial to finding new life on Mars. On Earth, biological macromolecules are homochiral, meaning they possess the same type of chirality. In outer space, there have already been signs of potential chirality such as in the interstellar cloud of Sagittarius B2. Here, the molecule propylene oxide or its chemical formula CH_3CHOCH_2 is one of the only molecules scientists have found in space with chiral properties (Carroll et al., 2016, p. 1449-1451). This finding suggests a possibility for chirality on Mars.

Conclusion

Therefore, despite current evidence and possible biosignatures, non-microbial life cannot be completely supported. With the growing questions of life aside from Earth, turning to nearby planets such as Mars may pose a greater probability of living beings. From massive craters to microscopic atoms, no stone will be unturned to impede our search. Continuing to observe Earthly analogs and their set of microbial life is one of the best ways to minimize the costliness and time consumption of missions to Mars. Areas, especially with evidence of hydrated elements and geological features, may be the prime location to explore in future conquests. It is important to realize the gravity of discovering biosignatures as they can provide an understanding of habitability on other planets and potential colonization of humans in the Solar System. The discussed biosignatures do not "confirm" life, but rather lead to a strong hypothesis of life. In conclusion, as further research is uncovered a greater understanding of the vast world above Earth is in the near future.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

Works Cited

1. Amils, R., Fernández-Remolar, D., & The IPBSL Team. (2014). Rio Tinto: A geochemical and mineralogical terrestrial analogue of Mars. *Life*, *4*(3), 511-534. https://doi.org/10.3390/life4030511
2. Azua-Bustos, A., Fairén, A. G., Silva, C. G., Carrizo, D., Fernández-Martínez, M. Á., Arenas-Fajardo, C., Fernández-Sampedro, M., Gil-Lozano, C., Sánchez-García, L., Ascaso, C., Wierzchos, J., & Rampe, E. B. (2020). Inhabited subsurface wet smectites in the hyperarid core of the Atacama desert as an analog for the search for life on Mars. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-76302-z
3. Becker, L., Popp, B., Rust, T., & Bada, J. L. (1999). The origin of organic matter in the Martian meteorite ALH84001. *Advances in Space Research*, *24*(4), 477-488. https://doi.org/10.1016/s0273-1177(99)00090-3
4. Carroll, B., Blake, G., Remijan, A., Jewell, P., Finneran, I., Loomis, R., & McGuire, B. (2016). Discovery of the first interstellar chiral molecule: Propylene oxide. *Proceedings of the 71st International Symposium on Molecular Spectroscopy*, *352*(6292), 1449-1451. https://doi.org/10.15278/isms.2016.wh06
5. Clark, B. C., Kolb, V. M., Steele, A., House, C. H., Lanza, N. L., Gasda, P. J., VanBommel, S. J., Newsom, H. E., & Martínez-Frías, J. (2021). Origin of life on Mars: Suitability and opportunities. *Life*, *11*(6), 539. https://doi.org/10.3390/life11060539
6. Cockell, C. S. (2014). Trajectories of Martian Habitability. *Astrobiology*, *14*(2), 182-203. https://doi.org/10.1089/ast.2013.1106
7. *Curiosity Finds Hydrogen-Rich Area of Mars Subsurface.* (2015, August 19). NASA. https://www.nasa.gov/jpl/msl/pia19809/curiosity-finds-hydrogen-rich-area-of-mars-subsurface
8. Des Marais, D. J., Allamandola, L. J., Benner, S. A., Boss, A. P., Deamer, D., Falkowski, P. G., Farmer, J. D., Hedges, S. B., Jakosky, B. M., Knoll, A. H., Liskowsky, D. R., Meadows, V. S., Meyer, M. A., Pilcher, C. B., Nealson, K. H., Spormann, A. M., Trent, J. D., Turner, W. W., Woolf, N. J., … Yorke, H. W. (2003). The NASA Astrobiology Roadmap. *Astrobiology*, *3*(2), 219-235. https://doi.org/10.1089/153110703769016299
9. *Eberswalde crater*. (n.d.). Marspedia. https://marspedia.org/Eberswalde_Crater
10. Franz, H. B., King, P. L., & Gaillard, F. (2019). Sulfur on Mars from the atmosphere to the core. *Volatiles in the Martian Crust*, 119-183. https://doi.org/10.1016/b978-0-12-804191-8.00006-4
11. Gibson, Jr., E. K., McKay, D. S., Clemett, S. J., Thomas-Keprta, K. L., Wentworth, S. J., Robert, F., Verchovsky, A. B., Wright, I. P., Pillinger, C. T., Rice, T., Van Leer, B., Meibom, A., Mostefaoui, S. M., & Le, L. (2006). Identification and analysis of carbon-bearing phases in the Martian meteorite Nakhla. *SPIE Proceedings*. https://doi.org/10.1117/12.690503
12. Glavin, D. P., Elsila, J. E., McLain, H. L., Aponte, J. C., Parker, E. T., Dworkin, J. P., Hill, D. H., Connolly, H. C., & Lauretta, D. S. (2020). Extraterrestrial amino acids and L-enantiomeric excesses

in the <scp>CM</scp> 2 carbonaceous chondrites Aguas Zarcas and Murchison. *Meteoritics & Planetary Science*, *56*(1), 148-173. https://doi.org/10.1111/maps.13451

13. Greenwood, J. P., & Blake, R. E. (2006). Evidence for an acidic ocean on Mars from phosphorus geochemistry of Martian soils and rocks. *Geology*, *34*(11), 953. https://doi.org/10.1130/g22415a.1
14. Greshko, M. (2019, November 18). *Mysterious oxygen spike seen on Mars puzzles scientists*. National Geographic. https://www.nationalgeographic.com/science/article/mysterious-oxygen-spike-seen-on-mars-puzzles-scientists
15. Gronstal, A. (2020, April 9). *NASA Astrobiology*. Astrobiology. https://astrobiology.nasa.gov/news/serpenitinzation-and-astrobiological-potential-of-the-mars-2020-landing-site/
16. Hays, L. E., Graham, H. V., Des Marais, D. J., Hausrath, E. M., Horgan, B., McCollom, T. M., Parenteau, M. N., Potter-McIntyre, S. L., Williams, A. J., & Lynch, K. L. (2017). Biosignature preservation and detection in Mars analog environments. *Astrobiology*, *17*(4), 363-400. https://doi.org/10.1089/ast.2016.1627
17. *Inverted dendritic stream channels in Antoniadi crater (PSP_007095_2020)*. (n.d.). HiRISE | High Resolution Imaging Science Experiment. https://hirise.lpl.arizona.edu/PSP_007095_2020
18. Krissansen-Totton, J., Bergsman, D. S., & Catling, D. C. (2016). On detecting biospheres from chemical thermodynamic disequilibrium in planetary atmospheres. *Astrobiology*, *16*(1), 39-67. https://doi.org/10.1089/ast.2015.1327
19. Michalski, J. R., Dobrea, E. Z., Niles, P. B., & Cuadros, J. (2017). Ancient hydrothermal seafloor deposits in Eridania basin on Mars. *Nature Communications*, *8*(1). https://doi.org/10.1038/ncomms15978
20. Milliken, R. E. (2008, October). *Which Clays are Really Present on Mars and How Did They Form?* Lunar and Planetary Institute. https://www.lpi.usra.edu/meetings/aqueous2008/pdf/7009.pdf
21. Misra, A. K., Acosta-Maeda, T. E., Scott, E. R., & Sharma, S. K. (2014). Possible mechanism for explaining the origin and size distribution of Martian hematite spherules. *Planetary and Space Science*, *92*, 16-23. https://doi.org/10.1016/j.pss.2014.01.020
22. Morgan, A., Howard, A., Hobley, D., Moore, J., Dietrich, W., Williams, R., Burr, D., Grant, J., Wilson, S., & Matsubara, Y. (2014). Sedimentology and climatic environment of alluvial fans in the Martian Saheki crater and a comparison with terrestrial fans in the Atacama desert. *Icarus*, *229*, 131-156. https://doi.org/10.1016/j.icarus.2013.11.007
23. Nazari-Sharabian, M., Aghababaei, M., Karakouzian, M., & Karami, M. (2020). Water on Mars—A literature review. *Galaxies*, *8*(2), 40. https://doi.org/10.3390/galaxies8020040
24. *Terra Sirenum*. (n.d.). Marspedia. https://marspedia.org/Terra_Sirenum
25. Wall, M. (2015, March 23). *More ingredients for life identified on Mars*. Space.com. https://www.space.com/28899-mars-life-nitrogen-carbon-monoxide.html
26. Wallis, J., Wickramasinghe, N. C., Wallis, D. H., Miyake, N., Wallis, M. K., Di Gregorio, B., & Hoover, R. (2012). Possible biological structures in the Tissint Mars meteorite. *SPIE Proceedings*. https://doi.org/10.1117/12.2013827
27. Whitt, K. K. (2022, January 21). *Scientists find carbon-12, life's most crucial isotope, on Mars*. EarthSky | Updates on your cosmos and world. https://earthsky.org/space/scientists-find-carbon-12-13-isotope-on-mars/
28. Wogan, N. F., & Catling, D. C. (2020). When is chemical disequilibrium in earth-like planetary atmospheres a Biosignature versus an anti-biosignature? Disequilibria from dead to living worlds. *The Astrophysical Journal*, *892*(2), 127. https://doi.org/10.3847/1538-4357/ab7b81
29. Wordsworth, R. D. (2021). Modeling terrestrial planetary atmospheres. *Encyclopedia of Astrobiology*, 1-15. https://doi.org/10.1007/978-3-642-27833-4_5442-1