Microbial life under Martian permafrost layer

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Aromatic compounds have been detected by the Curiosity and Perseverance rovers, suggesting their familiar presence on the Martian surface.[1] These organic compounds were previously attributed to water-rock reactions. However, according to our knowledge, no experimental or theoretical evidence substantiates the formation of aromatic compounds purely through water-rock reactions in natural conditions. Here, we propose that the aromatic compounds on Mars are the products of microbial metabolism (Figure 1). These microbiomes inhabit warm regions under the Martian permafrost layer and are fertilized by methane and ammonia formed through water-rock interactions. Most organic compounds on the Martian surface are easier to decompose, leaving behind residual aromatic compounds preserved in Martian soil due to their chemical stability. This model can be further tested using carbon isotope signals of the aromatic compounds.

ORGANIC MATTER DISCOVERED ON MARS

Potentially habitable environments on the Martian surface have attracted much attention since the 1990s, especially with regard to the formation of organic matter and H_2O activities that are crucial to exploring the presence of alien life. Recently, Sharma et al. reported aromatic compounds in the Máaz and Séítach formations of Jezero Crater by *in situ* measurements with the Perseverance rover.[1] Combined with previous research on Martian meteorites and surfaces,[2] it was found that organic matter is primarily located with water-related minerals, such as serpentine, carbonates, phosphates, and sulfates. Thus, the organic matter is interpreted as forming in abiotic aqueous organic synthesis.[3] However, thus far, no evidence in experimental petrology explicitly proves that aromatic compounds can be formed through water-rock reactions. Aromatic compounds on Earth are commonly found in fragrant plants and some microbiomes, which indicates the tight connection between aromatic compounds and biological activity.

The discovery of organic matter on Mars is a vital step in exploring alien life. The achievements in searching for organic matter on Mars have been achieved primarily by the exploration of Mars rovers and the analysis of Martian meteorites.

Since the 1970s, the Soviet Union, the United States, and China have launched more than 20 Mars landers and rovers to investigate the Martian surface environment and explore potential life signals.[4] Hindered by instrumental technology and interference from perchlorates on the Martian surface, early Mars rovers did not detect organic matter.[2] In 2010, Navarro-González and his colleagues reanalyzed data from similar samples obtained by the Viking 1 rover (1976–1982),[5] demonstrating that thermal decomposition of perchlorates in the samples produced oxygen, which subsequently combusted or destroyed organic matter, thereby preventing the detection of organic carbon signals. Navarro-González et al. estimated that samples measured by the Viking 1 rover contained approximately 0.7–6.5 ppm of organic carbon. The subsequent Curiosity rover (landed in 2012), with its improved gas chromatography-mass spectrometer, effectively avoided interferences from perchlorates during detection. *In situ* measurements by the instruments on the Curiosity rover indicated various organic matter in the Rocknest aeolian deposits on the Gale Crater, primarily including chloroalkanes and aromatic compounds, which was the first report of organic matter on the Martian surface being discovered *in situ*.

Scientists further improved *in situ* detection instruments on the Perseverance rover (landed in 2021), which used deep ultraviolet lasers to detect the abundance and types of organic matter without destroying the samples. Data from the Perseverance rover indicated a wide variety of aromatic compounds in the Jezero crater.[1] More crucially, this rover has collected samples on Mars that will be returned to Earth for comprehensive analysis in the future.

Various forms of organic carbon have also been discovered in Martian meteorites. For example, the most famous Martian meteorite, ALH84001, carries graphite or diamond created by transient high-pressure events caused by impact, macromolecular carbon or graphite created by hydrothermal reactions, macromolecular carbon created by igneous processes, and exogenous inputs of polycyclic aromatic hydrocarbons, amino acids, fatty acids, etc from meteorites.

WATER-ROCK REACTIONS ON MARS

Previous studies have proposed that the extensive water-rock reactions on the Martian surface produced H_2, which forms aromatic compounds through the electrochemical reduction of aqueous CO_2 due to interactions of spinel-group materials, sulfides, and brine.[1] Extensive water activities may have occurred on the Martian surface before the wet Hesperian period. The widespread distribution of valleys, alluvial fans, and the relics of ancient lakes all indicate that liquid water existed on the Martian surface until the Noachian period, when only groundwater systems remained active. Water activity on the surface decreased during the Hesperian period, and the Martian surface finally dried in the Amazonian period, possibly due to consumption in water-rock reactions. Extensive water-rock reactions have left widespread water-related minerals, including sulfides, sulfates, carbonates, and clay minerals, on the Martian surface, leaving behind a dry environment due to complete consumption of water through these reactions.

Synthesis of organic matter through water-rock reactions has been a hot topic for decades. However, laboratory experiments based on serpentinization have only synthesized simple molecules such as alkanes, formate, and ammonia.[3] It has been proposed that the products of water-rock reactions could further react to yield simple organic matter, such as producing amino acids from ammonia and methane under discharge conditions.

Complex organic matter can be synthesized through multiple inorganic reactions under strict conditions (pressure, temperature, pH, salinity, etc.) in addition to biological activities. For example, aromatic compounds were synthesized during Fischer-Tropsch synthesis with special artificial catalysts in the presence of H_2 and CO. However, such conditions are unlikely on the Martian surface.

The significance of water-rock reactions is intrinsically intertwined with the origin of life.[3] Water is a vital medium for life, while the energy generated by water-rock reactions also supports microbiome activities. Water-rock reactions, especially serpentinization on Mars, can provide energy and essential raw materials such as methane and ammonia for microbiome activity. Serpentinization generates H_2 through water-rock reactions at the expense of ferrous iron oxidation. Once CO_2 and N_2 are involved in serpentinization, methane (CH_4), formate ($HCOO^-$), and ammonia (NH_3) can be synthesized. Based on hydrothermal experiments, serpentinization may have converted large amounts of CO_2 and N_2 into CH_4 and NH_3, forming a thick layer of amino acids, potentially augmented by lighting and thus providing sufficient raw materials for microbial metasomatism and/or maintaining heterotrophic life.[3]

LIFE ON MARS

The Martian surface is cold and dry now. The average temperature of the Martian surface is $-63°C$, and no rover has directly found any extant liquid water. However, temperature increases with depth on terrestrial planets, so water may

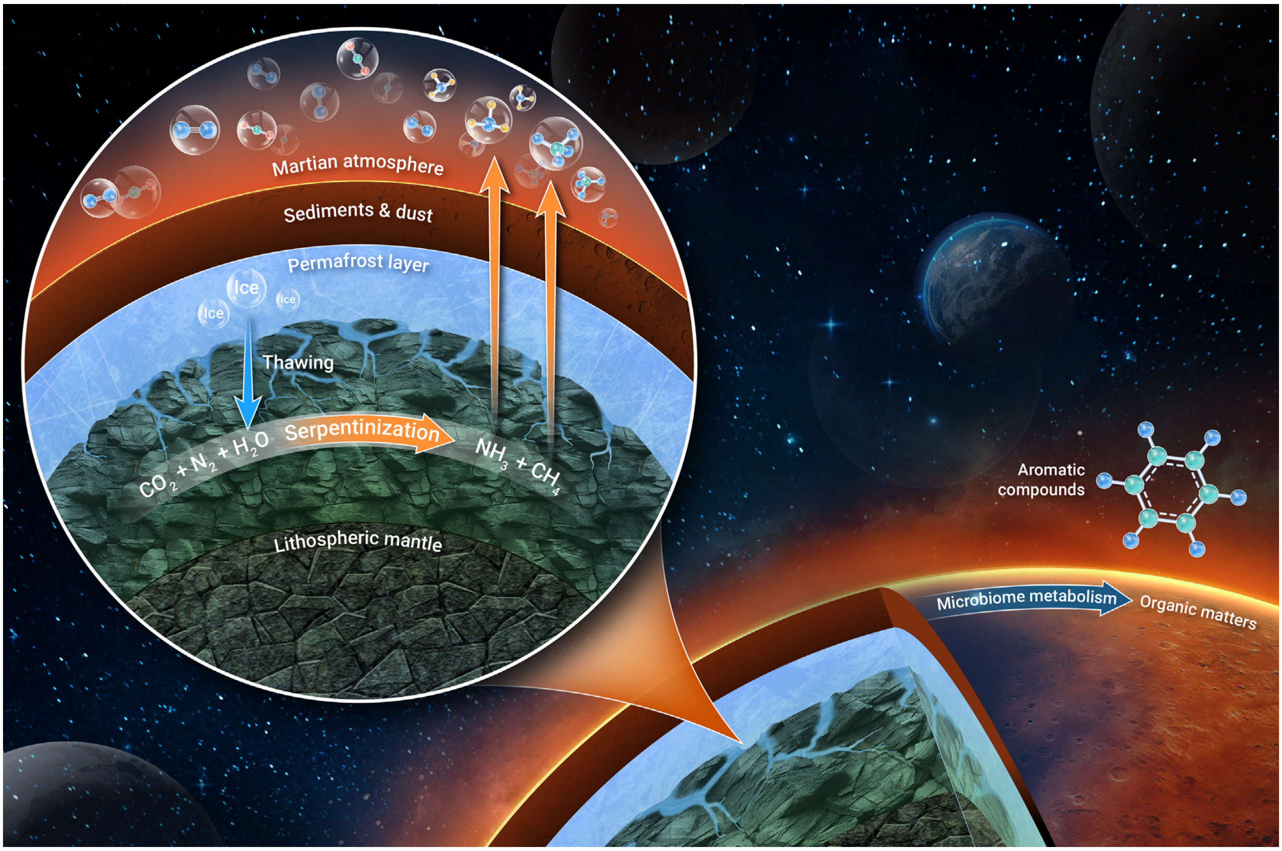

Figure 1. Schematic figure of the ecosystem model on the Martian subsurface Beneath the Martian surface, a permafrost layer may be composed mainly of ice. Due to geotherm, flowing water reacts with rocks beneath the permafrost. The water-rock reactions, especially serpentinization, produce CH_4 and NH_3, which profoundly impact the Martian subsurface system. Serpentinization reactions provide nutrients for the microbiome, allowing them to yield complex organic matters such as aromatic compounds.

exist under the permafrost layer and be available as a fluid to react with (ultra) mafic rocks, forming serpentine, CH_4, and NH_3. Such warm and wet domains underneath the permafrost layer on Mars are habitable for microbiomes and may support an ecosystem in the presence of methane-utilizing bacteria, forming complex organic matter (Figure 1).

Due to the current low contents of CO_2 and N_2 in the Martian atmosphere, the amount of organic matter on the surface is scarce and thus is intensively used, leaving behind chemically stable residual organic matter, such as aromatic compounds.

The evolution of life on planets is directly correlated with the activities of flowing water. The earliest life on Earth emerged at ~3.8 Ga, consistent with the activity of surface fluids since that period. The activity of fluid water on the Martian surface decreased in the Hesperian period (~3.7 to ~3.1 Ga) and swiftly transitioned to desert conditions. Correspondingly, organic matter on the Martian surface was likely predominantly produced during the Noachian period. The intensity of surface water activities could potentially serve as an indicator of microbial metabolism. The end of a habitable planet is desiccation of its flowing water resources.[2]

In contrast to Earth, the main components of the Martian atmosphere are dominated by CO_2 (95.1 vol %) and N_2 (2.59 vol %), similar to the likely proto-atmospheres of Venus and Earth. Considering the escape of CO_2 and N_2 to space during geological history, previous authors have suggested that the Martian atmosphere may have lost 50–90 wt % of its CO_2 and ~90 wt % of N_2. Nevertheless, the amount of CH_4, NH_3, and amino acids synthesized through serpentinization on the Martian surface is several orders of magnitude less than that on early Earth, which makes it difficult to form a thick prebiotic amino acid soup.

Water-rock interaction on Mars may have produced methane, ammonia, and even amino acids, making it a fertile environment for microbiomes to thrive in the early solar system, which has implications for the origin of life on Earth.

REFERENCES

1. Sharma, S., Roppel, R.D., Murphy, A.E., et al. (2023). Diverse organic-mineral associations in Jezero crater, Mars. Nature ***619***(7971): 724–732. https://doi.org/10.1038/s41586-023-06143-z.
2. Ansari, A.H. (2023). Detection of organic matter on Mars, results from various Mars missions, challenges, and future strategy: A review. Front. Astron. Space Sci. ***10***: 1075052. https://doi.org/10.3389/fspas.2023.1075052.
3. Shang, X., Huang, R., and Sun, W. (2023). Formation of ammonia through serpentinization in the Hadean Eon. Sci. Bull. ***68***(11): 1109–1112. https://doi.org/10.1016/j.scib.2023.04.038.
4. Zheng, Y.C. (2020). Mars Exploration in 2020. Innovation ***1***(2): 100036. https://doi.org/10.1016/j.xinn.2020.100036.
5. Navarro-González, R., Vargas, E., de la Rosa, J., et al. (2010). Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars. J. Geophys. Res. Planets ***115***(E12): 1–11. https://doi.org/10.1029/2010je003599.

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DECLARATION OF INTERESTS

The authors declare no competing interests.