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PRESS RELEASE

THE GEOCHEMISTRY OF THE EARLY EARTH MAY HAVE SHAPED THE CHEMISTRY THAT PRECEDED LIFE

Researchers at the Centre for Astrobiology (CAB), CSIC-INTA) have shown that the composition and abundance of minerals can influence HCN chemistry in aqueous environments, thereby modulating the balance between molecular diversity and selectivity, two key factors in understanding how the first protobiological systems evolved towards life.

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Hydrogen cyanide (HCN) polymerisation reactions have long been regarded as one of the main pathways leading to the formation of some of the organic compounds that preceded the origin of life. However, this study demonstrates that the composition of the reaction mixtures produced by these processes depends largely on the geochemical environment in which they occur. The researchers found that some minerals, such as certain silicates and alumina, have little effect on the reaction pathways, whereas iron- and copper-bearing minerals, together with carbonates, significantly alter the diversity and selectivity of the organic molecules formed. They also observed that increasing mineral abundance tends to reduce molecular diversity, highlighting that both the identity and concentration of mineral substrates play a decisive role in the evolution of chemical complexity. “Our results show that minerals did not simply act as passive surfaces or catalysts for prebiotic chemistry; rather, they could have directed reaction pathways and, consequently, shaped the chemical evolution of the early Earth,” explains Antonio López-García, researcher at the Centre for Astrobiology and first author of the study. Molecular diversity broadens the range of possible chemical outcomes, while selectivity favours reaction pathways capable of generating increasingly functional compounds. The study shows that this delicate balance depends not only on HCN chemistry itself, but also on the composition and abundance of the minerals present in the surrounding environment.

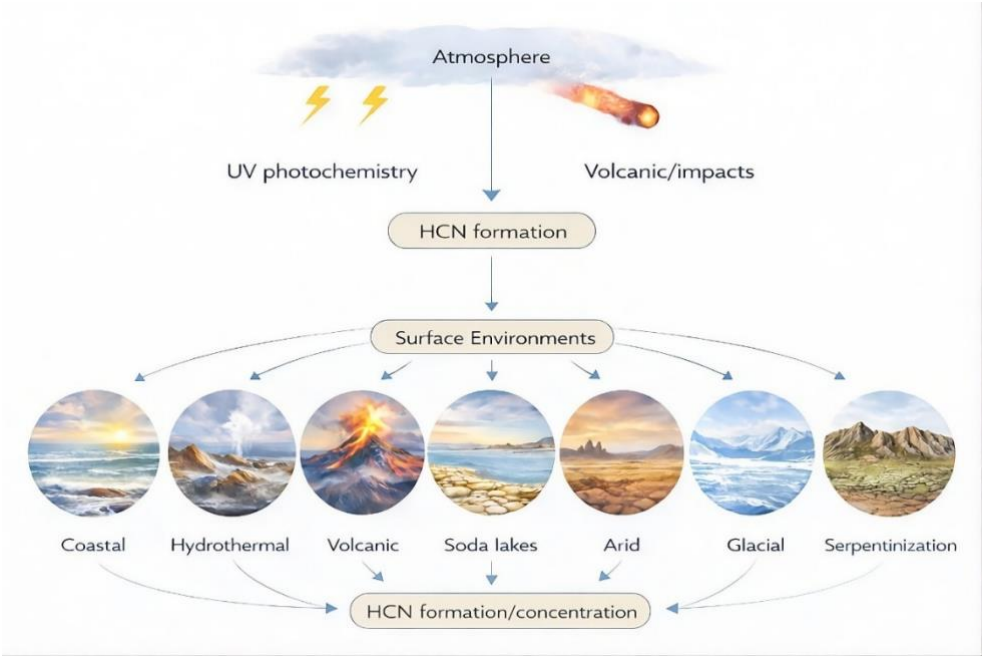
Geochemistry modulates chemical evolution

To reach these conclusions, the research team simulated prebiotic planetary environments in the laboratory using aqueous aerosols. These microenvironments, consisting of tiny water droplets, can promote chemical reactivity that differs from that occurring in conventional aqueous solutions by concentrating reactants and generating highly reactive air–water–mineral interfaces. Under these conditions, alkaline cyanide solutions were allowed to react in the presence of eighteen different minerals at varying concentrations. The resulting complex reaction mixtures were subsequently analysed using infrared spectroscopy, liquid chromatography, gas chromatography–mass spectrometry, and multivariate statistical methods, enabling the researchers to compare the overall behaviour of hundreds of chemical signals without focusing on individual compounds. The analyses revealed that both mineral composition and mineral loading

modify cyanide polymerisation pathways, reshaping chemical complexity in ways that are specific to each geological environment. “By combining complementary analytical techniques with multivariate statistical tools, we have been able to investigate HCN chemistry as a model of a complex prebiotic system, revealing patterns that would have remained hidden had we focused solely on identifying individual molecules,” says Marta Ruiz Bermejo, researcher at the Centre for Astrobiology and corresponding author of the study.

New insights into planetary habitability

The findings have important implications for Astrobiology, showing that the chemical evolution preceding the origin of life was likely conditioned by the geochemical context of each planetary environment. The study also highlights the role of aqueous aerosols as natural microreactors capable of concentrating molecules and promoting reaction pathways that differ from those occurring in large bodies of water. As a result, regions with different mineral compositions and abundances may have followed distinct chemical trajectories, producing molecular inventories with different capacities to evolve into increasingly complex systems. This work provides a new framework for understanding how geology may have influenced the habitability of the early Earth and other bodies in the Solar System, such as Mars. Furthermore, by examining the evolution of the chemical system as a whole, rather than focusing on specific molecules, the study offers a fresh perspective on the processes that drove the increase in chemical complexity. “Understanding how geochemistry modulates the balance between molecular diversity and selectivity will help us identify which planetary environments provided, or may still provide, the most favourable conditions for inert matter to evolve into increasingly complex and organised chemical systems and, ultimately, towards the origin of life,” conclude the authors.



Prebiotic planetary environments simulated in this study

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About CAB

The Centro de Astrobiología (CAB) is a joint research center of INTA and CSIC. Created in 1999, it was the first center in the world dedicated specifically to astrobiological research and the first non-US center associated with the NASA Astrobiology Institute (NAI), currently the NASA Astrobiology Program. It is a multidisciplinary center whose main objective is to study the origin, presence, and influence of life in the universe through a transdisciplinary approach. In 2017, the CAB was awarded by the Ministry of Science and Innovation as a "María de Maeztu" Unit of Excellence.

The CAB has led the development of the REMS, TWINS y MEDA instruments, operational on Mars since August 2012, November 2018, and February 2021, respectively; as well as the science of the RLS and RAX Raman instruments, which will be sent to Mars at the end of this decade as part of the ExoMars mission and to one of its moons in the MMX mission, respectively. In addition, it is developing the SOLID instrument for the search for life in planetary exploration. The CAB also co-leads, together with three other European institutions, the development of the PLATO space telescope, and participates in various missions and instruments of great astrobiological relevance, such as MMX, CARMENES, CHEOPS, BepiColombo, DART, Hera, the MIRI and NIRSpec in JWST, and the HARMONI in ESO's ELT (Extremely Large Telescope).

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