Patterns on the Rocks. C. Jenewein[1], J. M. García-Ruiz[1,2], and the ExoMars Science Working Team (ESWT)[3] [1]Consejo Superior de Investigaciones Científicas (CSIC), chris.jene@gmail.com, [2]Donostia International Physics Center (DIPC), juanma.garciaruiz@dipc.org, [3]European Space Agency (ESA).

Unveiling the origins of life and identifying its most early forms are two aspects of scientific research that are very closely related. The formation of the very fundamental bricks of life, so-called prebiotic molecules, and the compartmentalization into vesicles have been considered two different events that are both critical to the formation of life. It is still believed, that these events have occurred far apart in time. However, our recent research suggests that they might occur concomitantly on any methane, nitrogen, and water-bearing rocky solar body.

The view of the first eon of Earth – the Hadean – has changed drastically over the last decade. Currently, available information suggests that water already condensed shortly after solidification of the first ultramafic crust resulting in a serpentinization reaction that created a highly alkaline, methane-bearing, reducing atmosphere. [1–3] For this reason, we have revisited the famous Miller-Urey experiments from 1959 in our lab, which had been neglected by the scientific community in recent decades due to the previously believed absence of such an environment. [4] In this research, we revealed the significance of minerals, especially silica and silicate when it comes to the formation of a wide range of prebiotic molecules like amino acids and nucleobases in the so-called "primordial soup". [5] Understanding the formation processes and the conditions under which these molecules form is crucial for the identification of molecular biosignatures. Contrary to its water-soluble and liquid components, the solid organic matter that is forming in the Miller-type experiments has been described as "resistant to conventional analytic chemistry" by Carl Sagan who referred to this matter as "tholins". [6] Today, we know that they primarily consist of HCN-derived polymers but surprisingly, their morphology and morphogenesis have gained little attention from scientists so far. In our most recent work, we have therefore focused our research on investigating the solid organic matter that is forming simultaneously to the plethora of prebiotic molecules in the Miller experiment and its role with respect to morphological biosignatures.

Our results show that the solid organic matter forming in the primordial soup can self-organize into vesicles and biomorphic structures of fascinating morphologies. We found cocci- and caterpillar-like structures that form under the purely abiotic conditions of a primitive world, solely composed of methane, nitrogen, carbon dioxide, and a basic, silicate-rich water body. We further could show that these structures are vesicular, as they have a hollow core, which can hold gaseous and liquid contents. This is remarkable as vesicles can act as microreactors for synthesizing a wide variety of highly complex molecules in the very early stages of the life of a planet. In addition, this discovery will ultimately change our understanding of biosignatures in a broader sense as we could demonstrate that a purely abiotic formation pathway in a plausible geochemical environment can lead to microscale vesicles and biomorphic structures along with molecular bricks of life (**Figure 1A**).

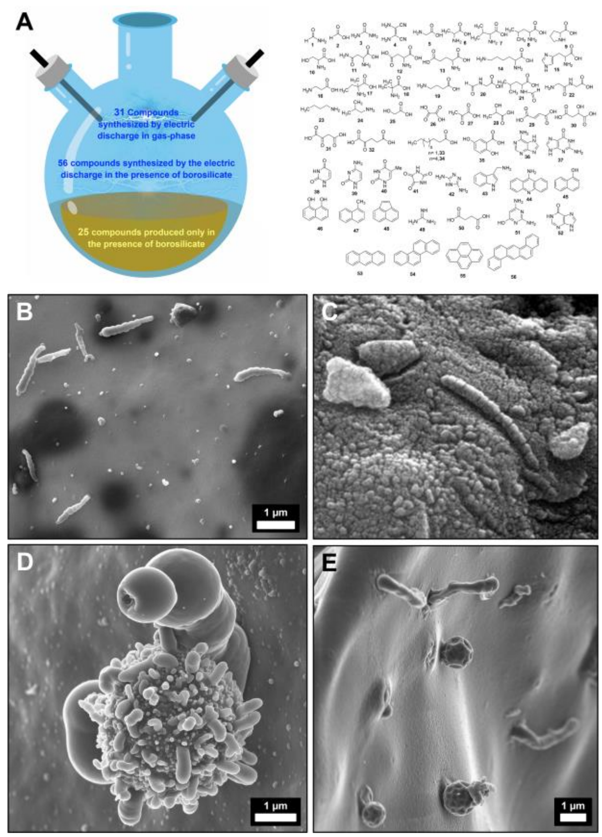

Figure 1: (**A**) shows a schematic illustration of the prebiotic organic molecules found in the Miller experiment in the presence of borosilicate. The FE-SEM image in (**B**) displays caterpillar-like organic biomorphs formed on the organic film inside the Miller reactor. Their morphological similarities to the "worm" found in the Martian meteorite ALH 84001 are displayed in image (**C**), Source: NASA. Micrographs in (**D**) and (**E**) show different biomorphs found growing inside the Miller reactor. Images in (**A**) have been reproduced from Ref [5] under the permission of the Creative Commons CC BY license.

Structures like the one found on the Martian meteorite Allan Hills 84001 have remarkable similarities to the abiotically formed organic biomorphs that we found in our experiments, thus further challenging claims of the biological origin of such structures (**Figures 1B and C**). The plethora of yet uncategorized morphological and chemical specimens that emerge in this abiotic environment (**Figure 1D and E**) appears to be just a glimpse into what is possible over the timeframe of several millions of years.

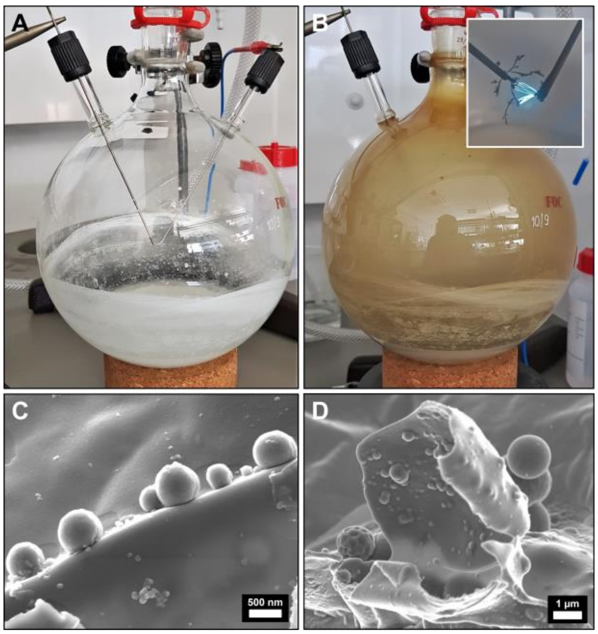

Figure 2: Photographs of a Miller-type reactor containing Mars-analog minerals before (**A**) and after (**B**) 14 days of sparking. FE-SEM micrographs in (**C**) and (**D**) show spherical particles of different sizes and morphology that have formed on the solid organic film inside the reactor.

Although these experiments were performed in the presence of borosilicate, we anticipate that other silicate-bearing minerals, such as olivine and pyroxenes, forming the mafic and ultramafic rocks of a primeval crust would further catalyze the synthesis of prebiotic organic compounds upon interaction with water and energy activated by lightning, radiation, or temperature. As members of the ExoMars Science Working Team (ESWT) our current research is directly dedicated to the primary objective of the ExoMars mission: the search for life and its remnants. [7] The same principles we use to recreate Earth's Hadean atmospheric conditions in our experimental setup can be applied to recreate a Martian environment (**Figure 2**). These experiments provide plausible reference samples rich in molecular and morphological diversity for the rover instrument teams like MOMA and MicrOmega to be analyzed. Our current scientific task is to investigate and expand the research on prebiotic chemistry and prebiotic organic biomorphs by further exploring the role of atmospheric compositions and the effect of different mineral surfaces on Mars in the yielding and molecular diversity of the synthesized compounds alongside the emerging organic biomorphs. With this data, we will create new and complement existing databases that the ESWT will utilize to interpret and classify the data obtained from the red planet. This work is crucial not only for the ExoMars mission but also for future missions like the Mars Sample Return (MSR) on a fundamental basis, as we are working towards an updated definition of what can be considered “evidence” for life and what cannot.

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