Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.27749

Concomitant formation of protocells and prebiotic compounds in the primordial soup

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Recent research challenges the traditional view that the formation of life's fundamental molecules and vesicle compartmentalization occurred as separate, sequential events. Our study suggests that on any rocky body containing methane, nitrogen, and water, these processes can occur simultaneously.[1] Analyses of asteroid Bennu samples indicate that such conditions were widespread in the early solar system, supporting revised interpretations of the Hadean eon linking water condensation, serpentinization, and a methane-rich atmosphere.[2,3] Revisiting the Miller-Urey experiments, we demonstrate that silica plays a crucial role in synthesizing diverse prebiotic compounds, including lipids, amino acids, and nucleobases.[4]

Our findings show that the solid organic matter formed in these experiments can self-organize into vesicular and biomorphic structures reminiscent of primitive microorganisms.[1] Focused Ion Beam (FIB) cross-sectioning confirms their vesicular nature, with hollow cores capable of compartmentalization. Chemical analyses reveal they consist of HCN polymers, key precursors to complex biopolymers.[5]

Investigating the morphological and chemical properties of the solid organic film (SOF), we identified a crucial interplay between liquid water and silica surfaces in its formation and the emergence of protocell-like structures. Drier regions lack protocells but exhibit thicker organic layers, whereas hydrated areas encapsulate water droplets, fostering predominantly spherical protocells (Figure 1). When the organic HCN-polymer layer forms at a water-air interface, biomorphic protocells more frequently adopt caterpillar- or polyp-like morphologies. FIB cross-sections suggest that precursor flow through the porous SOF, combined with the semi-permeability of protocell walls, plays a key role in their formation.

These protocells may function as microreactors, enhancing chemical complexity and facilitating polypeptide synthesis during early planetary evolution. Furthermore, our findings broaden biosignature criteria by demonstrating that abiotic processes under plausible geochemical conditions can generate microscale protocells and biomorphic structures similar to those observed in the Martian meteorite Allan Hills 84001 (Figure 2). This suggests that early planetary environments could have simultaneously supported both molecular synthesis and compartmentalization, a critical step toward life's emergence.

[1] Jenewein (2025), *Proc.Natl.Acad.Sci.*, **122** (2), e2413816122. [2] García-Ruiz (2020), *Phys. Life Rev.*, **34**, 62-82. [3] McCoy (2025), *Nature* **637**, 1072-1077. [4] Criado-Reyes (2021), *Sci. Rep.*, **11**, 21009. [5] Ruiz-Bermejo (2013), *Life*, **3** (3), 421-448.

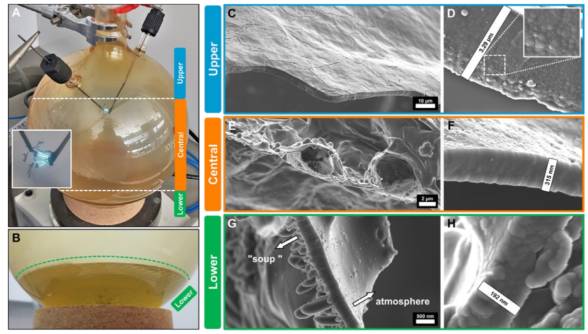

Figure 1. Photograph of the Miller-type reactor (**A, B**) and FE-SEM micrographs of its insoluble compounds. Upper (**C, D**), central (**E, F**), and lower (**G, H**) sections including a cross-section (**D, F, H**).

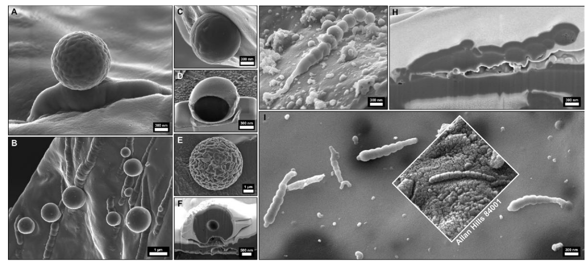

Figure 2. FE-SEM micrographs of the insoluble compounds located on the SOF. Protocells (**A-F**) as well as biomorphic structures (**G-I**) including a cross-section (**H**) and a comparison the structure found on meteorite Allan Hills 84001 (**inlet I**).