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Potential misassumptions on the clay hypothesis in origin of life: a geochemical perspective

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1 Introduction

The origin of life on Earth is an unsolved mystery that has engaged many of the best minds in the Earth and biological sciences. Since the Miller-Urey experiment (Miller, 1953) showed the formation of organic molecules required for life, scientists have tried to simulate the molecular precursors of life and to explain how they assembled into replicating forms. There are several competing hypotheses about how this may have occurred (Ferris, 1999). All these hypotheses suggest conditions or material suitable as template to allow formation of rudimentary DNA or RNA, as well as vesicles, membranes and protocells. Here I focus on the clay-template hypothesis proposed by Cairns-Smith in 1966 (Cairns-Smith, 1966), which suggests that the polymerized crystal structures of (alumino)silicates that form clay minerals provide ideal surfaces on which large organic molecules could have been assembled. I argue that disproportionation of amorphous silicon monoxide under hydrogen-rich conditions may have allowed abiogenesis.

2 Mineral composition during origin of life

Different silicate minerals (e.g., achondrite, olivine, feldspar, pyroxenes) (McCord and Gaffey, 1974) or crystalline clay minerals such as smectites (Baird et al., 1977) exist on Earth as well as on Mars, Moon, meteorites, asteroids and comets. The initial mineral evolution on Earth was driven by volcanism, degassing, fractional crystallization, and associated large-scale fluid-rock interactions (Hazen et al., 2008). Deploying the idea of the clay-template hypothesis (Kloprogge and Hartman, 2022), one could assume that prebiotic molecules assembled (i) in interstellar space, (ii) after arriving on Earth, or (iii) during water-mediated weathering of magmatic minerals on the early Earth which results in the formation of secondary minerals. Despite the attractiveness of the clay-template hypothesis, no research has been able to explain the process needed to assemble the precursors of life on crystalline clays.

Today, amorphous clay minerals in soils on Earth show a larger chemical activity, and play a more important role in sorbing organic and inorganic compounds than crystalline clays (Cairns-Smith, 1982), by ligand exchange, cation bridging, van der Waals force, and hydrogen bonding (Shang, 2023). Some of the amorphous compounds present on today's Earth have been identified in Martian soils as well. Such amorphous compounds offer a loosely coordinated 3-D structure which provides a more flexible template, compared to the 2-D structure of crystalline clays, allowing for more complex polymerization of organic molecules that can act as pre-cursors of life.

It is well known that silica gels, a form of amorphous silica connected to water, exhibit ideal properties for binding DNA, which is the reason why this material is commonly used for DNA extraction (Vogelstein and Gillespie, 1979; Chase and Hills, 1991). Such amorphous silicas are prone to adsorb amino acids and potentially force the formation of nucleic acids, the backbone of RNA and DNA structures. Amorphous silica polymers enhance amino acid polymerization and other prebiotic organic reactions like vesicle, membrane, and protocell formation (Cho et al., 2024; Samrout et al., 2024; Jenewein et al., 2025) that would have been necessary to the genesis of replicating biomolecules. Hence, amorphous silica may serve as a catalyst for the origin of life.

Chemical and physical conditions on early Earth were likely far different from the present and may have favored stability of amorphous silica phases. For example, hydrogen may have been present in the early Earth crust as meteorites were found to contain large share of hydrogen (Barrett et al., 2025) and due to hydrogen formation by low temperature water-rock reactions (Mayhew et al., 2013), limiting oxidation. Early Earth may have had a much higher hydrogen content compared to present conditions as light elements like hydrogen are lost from the Earth due to meteor impact (Biersteker and Schlichting, 2019) and if not bound to other elements, could escape to outer space because Earth gravitation is not able to prevent losses (Hunten and Donahue, 1976). It can be assumed that hydrogen loss would have favored a shift toward more oxidizing conditions even before the strong shift associated with photosynthesis. Another example for the different conditions of early Earth compared to present Earth is the presence of silicon monoxide (SiO) in interstellar space (Gibb et al., 2007), which is the most common oxide of silicon in the universe (Cherchneff, 2013). Hence, such material may have also been present in early Earth during the time of origin of life and the presence of hydrogen may have prevented immediate oxidation to amorphous SiO_2.

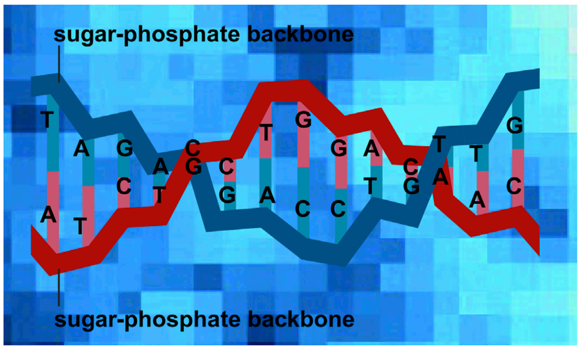

FIGURE 1
Small-scale pattern (~0.4 nm) of elemental Si and SiO_2 from SiO disproportionation, adapted from Hirata et al. (2016), which is on the same scale as the distance between nucleotides of DNA (~0.34 nm). One should note that the number for SiO disproportionation, ~0.4 nm, is based on the resolution limit of the analytical method used and may in fact be lower. Different blue shades of squares in the background indicate different Si species from amorphous elemental Si (light blue) to amorphous SiO_2 (dark blue). The red and blue lines represent DNA backbones.

3 Importance of disproportion of amorphous silicon monoxide

Disproportion of amorphous silicon monoxide to elemental silicon and silicon dioxide (Hirata et al., 2016) would have been favored by strong reducing conditions on early Earth, potentially offering conditions to support abiogenesis. The lower the temperature, the slower the disproportionation process (Mamiya et al., 2001). The disproportion of amorphous silicon monoxide into Si and SiO_2 will result in distances between elemental Si and a neighboring SiO_2 unit at molecular level of about ~0.4 nm (Hirata et al., 2016) which is comparable in scale to the distance of nucleotides of DNA (~0.34 nm) (Alberts et al., 2014) (Figure 1).

At a scale of about 0.4 nm the formation of a protective SiO_2 layer of a few atoms thickness, preventing further oxidation, is negligible. Because of the missing protections from a SiO_2-layer the single Si atoms distributed at the surfaces of the amorphous solids may be oxidized to SiO_2 even under low temperature conditions (Greenwood and Earnshaw, 2012). However, under hydrogen rich conditions this direct oxidation of SiO to SiO_2 may be restricted. A potential process may have started by the absorption of amino acids already in meteorites (Cronin and Pizzarello, 1983). The amino acids adsorbed to the amorphous material (in the immediate vicinity of a Si atom) may cause oxidation of the Si to SiO_2, as the formation of SiO_2 is thermodynamically favored. During oxidation of Si the amino acid groups will be transformed into amines or N-containing heterocycles, the latter offering a base structure for the formation of nucleic acid. Note: variations in the spatial arrangement of the Si atoms (or Si-Si dimers) and the SiO_2 units across the surface of the amorphous material may allow formation of an innumerable number of different amines or heterocyclic acid structures (Hohl et al., 2003; Hirata et al., 2016).

Life seems to have originated only once in Earth history. There are no intermediates or leftovers from the ancient origin of life (like rudimentary DNA or RNA trapped in minerals) found in current Earth environments. Consequently, the process must have occurred under conditions different from present Earth conditions. I suggest that amorphous silicon monoxide was both available (SiO rich meteorite input) and chemically favored because of the presence of free hydrogen. If any amorphous phase formed from SiO was involved in the origin of life, no leftovers would occur. This is because oxidation of Si to SiO_2 and restructuring of the Si template due to structural rearrangement by crystallization of the amorphous material to crystalline minerals would have destroyed all organic residues. Additionally, if amorphous silicon monoxide was involved in the origin of life, such abiogenesis could have happened during a short period in Earth history, as the amorphous silicon monoxide will have been disproportionated and oxidized to silicon dioxide eventually. With amorphous silicon dioxide (eventually forming after SiO disproportionation) supporting vesicle, membrane and protocell formation (Cho et al., 2024; Jenewein et al., 2025), necessary environmental conditions to support the survival of replicating biomolecules might have ensured Abiogenesis.

Author contributions

JS: Visualization, Writing – original draft, Writing – review and editing, Conceptualization.

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