Mechanical Forces before Chemical Energy at the Origins of Life?

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Abstract: Mechanical forces are prevalent in living cells. This may be because mechanical forces and mechanical energy preceded chemical energy at life’s origins. Mechanical energy is more readily available in non-living systems than the various other forms of energy used by living systems. Two possible prebiotic environments that might have provided mechanical forces are hot springs that experience wet/dry cycles and mica sheets as they move, open and shut, as heat pumps or in response to water movements.

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1. Introduction

Mechanical forces are prominent in living systems, at all size scales, from the molecular to the cellular and beyond [1-17]. Much of the cells’ chemical energy, such as ATP, is used to generate these forces. Perhaps these mechanical forces are remnants of mechanical forces that brought life into being, before chemical energy was readily available.

Mechanical forces shift reaction pathways [18]. Force lowers the transition states for reactions by tilting the energy landscape. Forces also give different reaction products than reactions without force [19].

Forces at life’s origins would resemble synthetic mechanochemistry, because there would be no enzymes to carry out the (bio)chemical reactions. How feasible is synthetic mechanochemistry, in practice? Synthetic organic mechanochemistry has been used to produce many organic molecules, including pyrimidines [20], peptides, nucleosides, optically active products, oxidations, reductions, condensations, nucleophilic reactions, and cascade reactions [21]. The industrial appeal of synthetic organic mechanochemistry is that it reduces the use of solvents.

Many forces pushed molecules around before ‘biochemical’ energy was available. These forces include entropic forces [22], hydration, dehydration, and surface forces. All these forces could generate mechanical energy (the product of force and distance), without chemical energy, at life’s origins. The motions and forces of enzymes need energy...
transduction from an energy source such as ATP. Most energy sources used now by living systems were not readily available at life’s origins.

2. Materials and Methods

Muscovite mica was obtained from New York Mica Co., New York, New York. Biotite mica was obtained from Makhan Lal Sangai, Jharkhand, India. Micas were scanned at 600 dpi and 1200 dpi, respectively, with an HP Officejet 4635.

3. Results and Discussion

Two Embodiments of Mechanical Forces at Life’s Origins. Wet/dry cycles and moving mica sheets are two sources of forces available for powering the many types of chemical reactions that occurred as life was coming into being. The primary type of reactions discussed here are the polymerization of monomers into polymers. Biopolymers such as peptides and nucleic acids form when closely spaced monomers join, by losing a water molecule.

a. Wet/Dry Cycles

Biomolecules such as amino acids polymerize when dry but hydrolyze when wet [23]. As polymers dry, polymerization rates increase, because diffusion distances are shorter. As polymers continue drying, polymerization rates decrease, because crowding decreases diffusion rates [24].

Clays have been used for many of these polymerization experiments, catalyzing or supporting the formation of both peptides and oligonucleotides (e.g., [25]). Clays are layered silicate minerals that swell when wet and shrink when dry. Montmorillonite clays are best for these polymerizations. The anionic silicate layers of Montmorillonite clays are held together by hydrated sodium (Na) ions. The hydration of the Na ions causes shrinking and swelling in response to changes in hydration.

In most nucleotide polymerization experiments, the nucleotides are chemically activated, which is not an ideal model for the origins of life. A better model for life’s origins is the polymerization of the unactivated mononucleotides AMP and UMP. This polymerization occurs during wetting and drying in the presence of lipids [26]. Lipids protect the oligonucleotides from the hydrolysis that occurs during drying without lipids. This lipid-assisted origin of life is proposed for an ancient Australian rock formation that may contain evidence of the earliest life on earth [27].

A feasible prebiotic way of forming peptides by wetting and drying begins with the formation of depsipeptides, which have both amide (peptide) bonds and ester bonds. The ester bonds form and break more easily than the peptide bonds. Initially, mostly ester bonds form. With cyclic wetting and drying, ester residues are placed by amino acid residues, leading to a hetero-polymer that is increasingly rich in amino acids [28].
b. Moving Mica Sheets

Mica is old – old enough to be the mineral from which life emerged [29]. Mica’s mineral sheets move, open and shut, in response to heating and cooling and water flow (Fig. 1). The movements of the mica sheets squeeze and stretch the molecules with enough force to make and break covalent bonds between them [30]. These forces might be capable of forming monomers and polymers of prebiotic molecules, as diagrammed for the reaction of alanine + di-alanine to form tri-alanine in Fig. 2. Longer DNA polymers bind more strongly to the mica sheets than shorter DNA polymers, which are more likely to be washed away, as observed by atomic force microscopy (AFM) [31, 32].

Figure 1. (A) Diagram of forces between biotite mica sheets, stretching and compressing polymers, due to: (Upper panels) water flow at the edges of the biotite sheets, and (Lower panels) heat pumping in a biotite bubble (lower). (B) Biotite bubble imaged by imaged by HRTEM (high-resolution transmission electron microscopy) The thickness of a single biotite sheet is 1 nm (10 Angstroms) [45]. (C) Top view of a bubble in Muscovite mica (upper arrow) and of sheet separation at the edges of the mica sheet (bottom arrow).
Figure 2. Energy diagram of the way that mechanochemistry from moving mica sheets might polymerize molecules, such as Alanine (A), shown here. (Top) tri-alanine, A-A-A, forming, reversibly from alanine and di-alanine (A-A). (Bottom) Force vs distance curve showing Attractive and Repulsive regimes as molecules are pushed closer together, to the bonding distance. Modified from [39].

Biotite may be the best mica for life’s origins (Fig. 3). Biotite is a black mica, rich in iron (Fe) and magnesium (Mg) [33]. The iron is predominately Fe(II), capable of reducing organic molecules. Mg is a major inorganic divalent cation in living systems. The mineral sheets of biotite and other micas has the same layered silicate structure as montmorillonite clay, but mica’s mineral sheets have fewer defects than the tiny sheets in clays, resulting in large mineral sheets that stack into ‘mica books’.

Figure 3. Biotite mica. (Left) Biotite mica ‘book’ of stacked sheets. (Right) Thin layer of biotite mica sheets peeled from a ‘book’ with transparent tape.

Mica sheets have several similarities with life, as would be expected for a place where life originated [30, 34]: Potassium ions hold mica sheets together and are the predominant inorganic cation in all living cells. Mica sheets and nucleic acid polymers are anionic, with
exchangeable inorganic cations. The anionic sites on the surfaces of mica sheets have a periodicity of 0.5 nm, which is also the spacing of phosphate groups in single stranded nucleic acids and sugar residues in carbohydrates. Both mica sheets and enzymes have open and shut motions that do work on the molecules between them. As the title of a recent article says, ‘Enzymes at work are enzymes in motion’ [35].

Wetting and drying occurs between mica sheets but much more slowly than in open pools or on clay. These slow changes in water levels are likely to be good for forming biopolymers without hydrolyzing them too fast.

Sugars, especially ribose, are a major biomolecule in living systems. A plausible prebiotic reaction for forming sugars is the formose reaction, in which formaldehyde polymerizes into sugars [36]. In a test tube, the end products become increasingly larger sugars, branched sugars, and eventually a tarry mess. In the confined spaces between mica sheets, simpler sugars are likely to predominate.

Mica sheets might shelter emerging life without the need for membranes. Membranes are fragile. They leak, acquire and lose molecules, swell, and rupture. In living cells, nucleoli and other membraneless organelles contain RNA and protein. Smaller than membraneless organelles, ribosomes have some of the most ancient proteins and RNA. Ribosomes were present in the Last Universal Common Ancestor of life (LUCA) [37]. When life was coming into being, in the pre-LUCA stages, ribosomes and their precursors may have been the first ‘membraneless organelles’ [38].

4. Conclusion

Molecules in cells are crowded. Protein molecules in cells are so crowded that there is typically only 10 nm between protein molecules [22]. Crowding speeds up the rates of reactions that are diffusion limited [24]. Crowding may even be the origin of homochirality [39]. Given the molecular crowding in living cells, molecular crowding at life’s origins is a desirable scenario for hypotheses about the origins of life. Molecules in wet/dry cycles can become crowded during the drying phase. Molecules in narrow spaces between mica sheets will typically be crowded, by the mica sheets above and below, in addition to crowding by other molecules.

Confinement chemistry would occur both between mica’s sheets and during drying cycles in lipid-containing prebiotic systems. Chemistry in confined spaces produces fewer different molecules and simpler molecules [40, 41]. Confined spaces also help proteins fold [42, 43]. Chaperone proteins perform this function in living cells, where molecular crowding often inhibits newly synthesized proteins from folding correctly [44].

Mechanical forces in living systems provide energy in a form that is common in non-living systems. Wind, rain and waves do mechanical work on rocks, sand and water at all size scales from the molecular to the global. Mechanical work can be done without the chemical energy, ion gradients, or proton gradients, which provide energy for most of the
mechanical forces in living systems. Ion gradients and proton gradients need an energy source to create the gradients, and they need a continuous supply of energy to maintain the gradients. Electrical energy is found in both living and non-living systems, but the electrical energy in non-living systems is intermittent and highly localized, while the electrical energy in living systems needs other energy sources to maintain it, and specialized structures to control it. Mechanical energy is a readily available energy source that may have brought life into being, and it is now found throughout living systems.

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References


