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# The Ribofilm as a Concept for Life's Origins

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**Recent phylogenetic data indicating that the first archaea were methane-producing galvanizes cross-disciplinary evidence supporting the hypothesis that life arose via thermodynamically directed events at hydrothermal vents. The new developments lead us to propose the concept of a ribofilm in which RNA's origin-of-life role is more akin to a slowly changing platform than a spontaneous self-replicator.**

## Converging Evidence for Methanogenic Origins at Hydrothermal Vents

There are lots of ways to investigate early evolution, one of them involves the construction of phylogenetic trees from genome data. Such trees naturally tend to change over time as new methods and lineages are included. Presently, trees are changing at a rapid pace. One exciting change in the tree of life concerns the root of the archaea. Using existing genome data, Raymann et al. (2015) pieced together the roughly 30–40 genes (37 in their case) that are universally conserved across virtually all genomes and that are sufficiently conserved in all species sampled to generate alignments for phylogenetic inference. Their focus was on the question: where is the root in the archaeal tree? They find that the archaeal root sits within the methanogens.

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A methanogenic origin of archaea brings phylogeny into agreement with other independent lines of evidence about the nature of the earliest archaea. First, isotope evidence attests to the antiquity of biological methane production in rocks 3.5 billion years of age (Ueno et al., 2006), making it the oldest biological process known in the isotope record. A methanogenic root of archaea thus provides a congruent link between trees and isotope data from the geochemical record. That link also makes sense from a microbiological perspective, as microbiologists have long considered methanogenesis to be one of the most ancient forms of physiology (Liu et al., 2012). It also fits with the distribution of tetrahydromethanopterin ($H_4MPT$) biosynthesis genes across all archaeal lineages. (Archaea use $H_4MPT$ as their main C1 cofactor in central metabolism whereas bacteria use tetrahydrofolate.) $H_4MPT$ is essential for methanogenesis because of its redox potential. That nonmethanogenic archaea have retained $H_4MPT$ in metabolism points to the early divergence of bacteria and archaea (Sousa and Martin 2014), and among archaea it is likely a relic of methanogenic origins.

Second, and more exciting in many ways, a methanogenic root for the archaea means that the first archaea were, well, methanogens. That has several implications, one of which is that it bears out a key prediction generated by the theory that life arose at hydrothermal vents. Since their discovery, hydrothermal vents have been seen by biologists as likely sites for life's origin, because of their highly reactive chemical environments and far from equilibrium nature (Baross and Hoffman, 1985). Alkaline hydrothermal vents were proposed as a particularly likely site for life's origin (Russell and Hall, 1997), because their chemical conditions have much in common with life itself: modest temperatures on the order of 70°C and rich in $H_2$ from the geological process of serpentinization, which is conducive to the synthesis of reduced carbon compounds from $CO_2$ (McCollom and Seewald, 2013; Schrenk et al., 2013). Also, alkaline hydrothermal vents generate natural pH gradients of the same polarity and magnitude used by modern cells: more alkaline on the inside by about 3 pH units (Sojo et al., 2014). In a laboratory scale simulation of alkaline hydrothermal vents, Roldan et al. (2015) recently generated formate, methanol, acetate, and pyruvate from $CO_2$. That is exciting because it shows that hydrothermal vent conditions can generate biologically relevant organic compounds that are furthermore central to the main energy releasing reactions of carbon and energy metabolism as it occurs in methanogens. Progress in understanding the chemistry at real vents and at simulated ones forges stronger links than ever before between methanogenic metabolism and geochemical processes—all the more reason that methanogens should belong at the base of the archaeal tree, where the paradigm-shifting findings of Raymann et al. (2015) put them. Does this help us better understand the seemingly insurmountable evolutionary transition from rocks, water, and $CO_2$ to growing cells at life's origin? Possibly.

## Slow and Stable Origins: The Concept of a Ribofilm

Life arose in a fairly narrow window of time between the appearance of liquid water on Earth 4.2 billion years ago and the isotope evidence for first life 3.8 billion years ago. How long did the origin of life take? The late Christian de Duve had a good answer: Life is much more likely to arise in 10 thousand years than in 10 billion, because if it takes 10 billion, it is not going to happen anyway. Clearly, nobody knows exactly how long it took for life to arise. Yet there are concepts. Probably since Sol Spiegelman and Manfred Eigen did their famous experiments on Qβ replicase, showing exponential growth of molecules and selection for the fastest replicators, there has been a widespread notion out there that the origin of life was somehow a fast process, initially involving exponential replication among molecules (not cells) right from the outset. This is where the heart of the RNA world concept resides. An enticing idea, but it might be wrong.

If one thinks that a limiting step at life's origin was RNA replication (assuming that there were abundant bases as starting material), then PCR-like cascades come to mind, which are indeed fast and which can take place through simple thermophoresis in simulated hydrothermal environments (Baaske et al., 2007). But for that to happen, there has to be a steady supply of specifically and spontaneously synthesized ribonucleoside triphosphates without contamination by products that would lead to chain termination. Specific synthesis of nucleoside triphosphates is not among the most plausible of spontaneous geochemical reactions on the early Earth.

Thermodynamic aspects are more telling. From the thermodynamic standpoint, amino acids are far more likely to accumulate in any quantity at a hydrothermal vent than ribonucleotides (Amend and McCollom, 2009), and, at least in cellular metabolism, amino acids are one of the ingredients needed to synthesize bases. In addition, efficient carbonyl sulfide-dependent peptide bond formations have been reported (Leman et al., 2004), a mechanism far simpler than that manifest at the 3′ ends of activated tRNA molecules on ribosome. So it is not out of the question that short abiotic peptides might have accumulated at a vent setting. Hydrolysis precludes peptide accumulation, critics might interject. But locally, low-water activities might have been possible through phase separation and accumulation of hydrophobics within the vent. Much of what modern enzymes do for catalysis is to exclude water from the active site; hydrophobic layers not dissimilar to the ubiquitous "tar" encountered in prebiotic chemistry experiments along the insides of a vent might have had a useful function after all.

In addition to the indispensable catalysis provided by transition metals at a vent, small organic compounds could have provided a small amount of catalysis themselves, so that more organics could have accumulated. That is only possible, however, if organic synthesis is favored by thermodynamics, which is the case in serpentinizing systems, where the spontaneous reduction of $CO_2$ can drive it forward (McCollom and Seewald, 2013; Schrenk et al., 2013). This is how autocatalytic networks function, and surprisingly little catalysis is needed on order for autocatalytic networks to emerge (Hordijk and Steel, 2012). What is the point?

This point is this. Accumulation of organics along the inner surfaces of a hydrothermal vent could lead via minimal catalysis to accumulation of more organics and an interplay between kinetically controlled reactions (the fastest formed products accumulate, meaning catalysts direct synthesis) and thermodynamically controlled reactions (the most stable products accumulate) in a continuously far from equilibrium system. Assuming any stability against hydrolysis—an assumption germane to all theories for the origin of life—the products of the first spontaneous organic syntheses would have been obeying the laws of thermodynamics and seeking stable conformations.

The precursor to life might thus have looked more like a stable biofilm than a PCR-reaction. In other words, the transition from non-living state to the catalytic and self-organizing living state might have entailed chemical intermediate states that resemble modern cells (or precellular molecular agglomerations) that do not divide or grow, but that just turn over their carbon and nitrogen on timescales of hundreds or thousands of years (Hoehler and Jørgensen, 2013), while catalyzing exergonic reactions that tend to lead to the accumulation of more precursors and the maintenance of stable conformations.

Clearly, RNA has to come into play at some point in biochemical evolution, because it bears the genetic code, the ubiquity of which is still the best evidence we have for life's single origin. But rather than RNA replicating wildly in runaway reactions, maybe its first role was more similar to what it does today: fold stably and promote condensations. This line of thinking leads to a more biologically oriented view of the transition to life, one that departs from a standard RNA world of lone replicators to the concept of a ribofilm having some biological activities, embedded along an accumulating hydrophobic layer harboring small, spontaneously synthesized peptides and abiotically synthesized hydrocarbons. This notion of a ribofilm puts a premium on spontaneous, thermodynamically controlled reactions early, the products of which are stable and lead to kinetically controlled reactions as organic catalysts gradually became more complex. But in order for those reactions to go forward at all, there has to be disequilibrium and a thermodynamic push toward reduced carbon compounds. This is what serpentinization at methane-emitting vents does; we can even see it still in operation at vents today, where methane arises through spontaneous geochemical reactions (McCollom and Seewald, 2013; Schrenk et al., 2013). A phylogenetic anchor pointing to the most ancient archaea having been methane producers links modern life to early Earth in a natural and exciting manner.

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