A Candidate Self-Propagating System Enriched by Chemical Ecosystem Selection

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Abstract

The surface metabolism theory posits that adaptive evolution initiated when autocatalytic chemical systems became spatially localized on mineral surfaces. We searched for such surface-limited metabolisms (SLiMes) using a chemical ecosystem selection paradigm. This involves creating a prebiotic microcosm containing mineral grains and a "soup," rich in food and potential sources of chemical energy, and then serially transferring a subset of the grains to a new microcosm containing fresh soup and new grains. This repeated dilution should enrich for chemical systems that can self-propagate more rapidly than the rate of serial dilution, and such enrichment should be detectable based on changes in microcosm chemistry over the course of multiple transfers. We deployed chemical ecosystem selection on several different soups and minerals and identified a combination that appears to be conducive to the enrichment of a SLiMe. In these conditions, chemical changes were observed over the first 12-18 transfers, most notably a loss of both orthophosphate and organics (as detected by optical density) from the solution. This loss from the solution correlated with the appearance of fractal structures on the surface of the grains. The putative SLiMes show clear evidence of self-propagation ability and manifest basic ecological dynamics. Ongoing work is evaluating the systems' evolutionary capacity.

Introduction

The surface metabolism model, first presented 30 years ago by Wächtershäuser, suggests that the first self-propagating systems were autocatalytic sets of simple organic compounds adsorbed onto mineral surfaces (Wächtershäuser, 1988). Once seeded, these surface-limited metabolisms (SLiMes) could use fluxes of food and energy to generate all of their components, resulting in lateral growth as they collectively propagated over the surface (Baum, 2015). Furthermore, because rare chemical reactions can alter or expand an autocatalytic network, SLiMes could be evolvable (Vasas et al., 2012; Baum, 2018). In the context of a plausible prebiotic environment such as the seafloor, the turnover of mineral surface could select for variants that are more stable, more competitive, and/or better at colonizing newly exposed mineral (Baum, 2019). We used chemical ecosystem selection (Baum & Vetsigian, 2017), a procedure which enriches SLiMes based on their ability to repeatedly colonize new mineral surfaces, to identify a putative SLiMe that emerges repeatedly when incubating synthetic prebiotic soups with pyrite.

Approach

Chemical ecosystem selection involves incubating simulated prebiotic soups with mineral grains and mimicking the active turnover of the mineral surface expected to occur in natural environments. We used a rich chemical soup, reasoning that the more diverse the inputs the higher the likelihood of an autocatalytic systems being present (Kauffman, 1986; Mossel and Steel, 2005; Virgo, et al., 2013). We included minerals to provide a surface, which is needed to spatially segregate cooperating species and might also provide useful catalytic functions. Most of the experiments reported here transferred 10% of either the grains, or the grains and soup every 2-3 days (future experiments will examine the effect of liquid transfer only). The serial dilution protocol means that self-propagating systems will only become enriched over transfers if they are initially rare but can move from grain to grain at a rate greater than 10X each 2-3 days. Furthermore, if multiple systems are present or arise over time (e.g., through addition of new side-reactions), our procedure should enrich for variant SLiMes that propagate faster. To seek evidence of systematic changes in the chemistry of the systems over multiple transfers, we monitored several chemical proxy traits of the solutions following each incubation. In addition to looking for changes over transfers, we also look for heritable differences among lineages (a lineage being a chain of "parent" and "offspring" vials), and compare experimental lineages with control lineages that are generated in parallel with a certain set of experimental vials, but have only undergone one prior round of transfer. We have deployed the protocol on some dozen different combinations of mineral substrate, organic soup, energy source, and atmospheric gases and have identified at least one set of conditions that consistently provides evidence of SLiMe formation.

Results

We have found that incubating a synthetic, enriched prebiotic soup with natural pyrite grains maintained under low-oxygen conditions produced significant and repeatable evidence of a self-propagating system. Over the first 10+ transfers, chemical proxy traits (free orthophosphate and optical density at UV-Vis wavelengths) show systematic changes suggesting autocatalysis (=self-propagation). During this period of change, lineages differ heritably and we frequently find dramatic and significant differences between experimental and control lineages. This evidence of self-propagation is seen whether we transfer just mineral grains or a grain/soup slurry.

Coincident with the reductions in phosphate and organics from the solution, we observe an increase in the abundance of branched fractal structures on the surface of the pyrite (Fig. 1). These structures are observed never to touch or over-grow one another, suggesting a diffusion-limited growth process We hypothesize that these structures correspond to SLiMes, which nucleate rarely, but once nucleated are able to transfer readily to other grains. Fractal structures are only formed when organics are present but can form when phosphate is replaced by sulfate. We are conducting additional experiments to further characterize the putative SLiMes and their chemical composition.

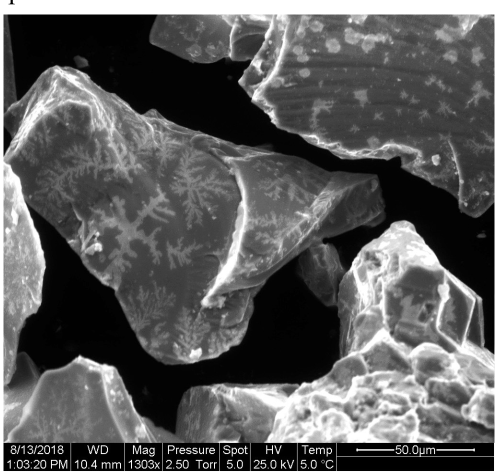

Figure 1: Environmental scanning electron microscopy image of pyrite grains from a lineage exposed to 18 rounds of serial transfer.

We observed that once a proxy trait (e.g., phosphate) reaches a certain critical value, the lineages suddenly return to their initial value. After a few further transfers, lineages begin declining again, resulting in a multigenerational oscillation. We interpret this phenomenon as an ecological boom-and-bust cycle, in which SLiMes reach carrying capacity at which point they deplete their food within the incubation period, resulting in dissolution of all structures. We are testing this hypothesis using experiments in which we dilute populations to prevent them reaching carrying capacity. This experiment will also allow us to see if the rate of self-propagation increases over generations, which would suggest a capacity for adaptive evolution.

Significance

Our discovery that SLiMes appear to be able to arise spontaneously in plausible prebiotic environments provides circumstantial support for the surface-metabolism model. If we find evidence that the systems are evolvable, our data will support a model in which selection is initiated in SLiMes prior to the formation of compartments. It will be interesting to see how chemically similar these putative SLiMes are to extant life and how alike the systems are that are enriched in different iterations. Moreover, the chemical ecosystem selection framework can be adapted to explore a nearly infinite number of combinations of chemical soups, mineral grains, and environmental factors, which would permit a broad search for conditions conducive to the spontaneous emergence of systems capable of self-propagation and open-ended evolution.

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