Cracking how life arose on Earth may help clarify where else it might exist

July 30 2013

Elbert Branscomb is an affiliate faculty member at the Institute for Genomic Biology at the University of Illinois at Urbana-Champaign. Credit: Kathryn Coulter

Does life exist elsewhere or is our planet unique, making us truly alone in the universe? Much of the work carried out by NASA, together with other research agencies around the world, is aimed at trying to come to grips with this great and ancient question.

"Of course, one of the most powerful ways to address this question, and a worthy goal in its own right, is to try to understand how life came to be on this planet," said Elbert Branscomb, an affiliate faculty member at the Institute for Genomic Biology (IGB) at the University of Illinois at Urbana-Champaign. "The answer should help us discover what is truly necessary to spark the fateful transition from the lifeless to the living, and thereby, under what conditions and with what likelihood it might happen elsewhere."

While many ideas about this fundamental question exist, the real challenge is to move beyond speculation to experimentally testable theories. A novel and potentially testable origin-of-life theory—first advanced more than 25 years ago by Michael Russell, a research scientist in Planetary Chemistry and Astrobiology at the NASA Jet Propulsion Laboratory—was further developed in a recent paper published in *Philosophical Transactions of the Royal Society B* (*PTRSL-B*), the world's first science journal, by Russell, Wolfgang Nitschke, a team leader at the National Center for Scientific Research in Marseille, France, and Branscomb.

Russell's hypothesis proposes that the transition to life was brought about by a peculiar geophysical and geochemical process called serpentinization—a process that played out on and just beneath the surface of our very young planet's ocean floor in the "Hadean" epoch more than 4 billion years ago.

One attractive aspect of the Russell hypothesis is that it provides potential explanations for several seemingly arbitrary and puzzling aspects of how all life on Earth works, including, most notably, how it taps into and exploits sources of energy. This process, quite oddly, involves constantly filling up and depleting a kind of chemical reservoir that is created by pushing a lot more protons onto one side of a membrane than the other—just like pumping water uphill to fill a lake behind a dam.

Then, mimicking how hydroelectric turbines are driven by water flowing downhill, these protons are only allowed to flow back "downhill" through the membrane by passing through a turbine-like molecular "generator," which creates, instead of high-voltage electricity, a chemical fuel called ATP, the cell's "gasoline." All cells then "burn" ATP in order to power their vital processes. The cells of air-breathing organisms, like us, "burn" ATP by ultimately converting oxygen to CO_2.

Furthermore, while every bacterial cell has its own proton reservoir system, our bigger cells contain and cultivate herds of "ex-bacteria" (called mitochondria) that maintain their own reservoir, ATP-producing turbines, etc.—a trick of "agricultural domestication" at the cellular level that makes it not only possible for multi-cellular organisms to exist but to be huge, fast, and dangerous.

This "reservoir-mediated energy business" is not a minor undertaking of life, Branscomb notes. Every day our bodies produce and consume their weight in ATP molecules. In seconds, each newly made ATP molecule is used. In minutes, the body's entire ATP energy reserve is consumed and regenerated."That's why you can't stand to be without oxygen for more than a few minutes," Branscomb said. "We live on a thin, desperate edge to keep our metabolic motors running full blast. Yet in spite of this desperation, the process isn't carried out by using our energy sources directly, but by using the indirect, proton reservoir method. It's an arrestingly strange way of doing business that has made many scientists question why it is this way."The amazing answer, Russell's model suggests, is because that's how life got launched. "Before there was anything lifelike to take advantage of it, the geochemical process of serpentinization produced "for free" (along with much else of critical importance) two of the major components of this energy system: cell-like compartments surrounded by membranes and proton concentration differences on each side of the membranes," Russell said.

Thus, according to Russell's hypothesis, first life didn't have to make any of this stuff for itself. It was all a free gift of geochemistry on a wet, rocky, and tectonically-active planet.

"It's only later when life set out to take its act on the road that it had to figure out how to make its own membranes, pump protons uphill across these new membranes, tap into other sources of energy to do the pumping, etc.," Branscomb said. "But once hooked on the free stuff, the trans-membrane proton gradient in particular, life never broke the habit. And here we are, every living thing, still frantically pumping protons as if just staying alive depends on it—which it does."

Also notably, the Russell serpentinization hypothesis is founded directly on modern understandings regarding the physical nature of early Earth. In particular, at the time life arose, the world was almost entirely covered in a great, deep, and weakly-acidic ocean, the atmosphere was relatively oxidized and rich in CO_2, and tectonic processes constantly replenished and destroyed the crusts of the ocean floor, as they still do today. And it is the exposure of newly made ocean crust to the ocean that gives rise to the geochemical magic of serpentinization.

As areas of new ocean crust cool, the still-stressed rock becomes brittle and develops cracks. Seawater gravitates down the cracks where it is heated and reacts chemically with rock minerals to form a highly-alkaline solution rich in hydrogen (H_2) and methane (CH_4), and containing molybdenum, a metal required by all life. This transformed water, or effluent, is then driven back to the surface, at a temperature of about 100 degrees centigrade, where, in Hadean times, it reacted with cooler, mildly acidic ocean water to create precipitates that form massive chimney-like towers similar to chemical gardens.

These highly-structured precipitate chimneys are comprised of a myriad of micro-compartments bounded by semi-permeable "mineral membranes." Across these membranes, a pH (i.e. proton) gradient arises between the extremely alkaline (~pH 11) emerging serpentine effluents and the surrounding, relatively acidic (~pH 5.5) ocean.

Magically, this pH gradient is almost exactly the same as the gradient that all living cells constantly recreate with the same strength and the same direction: acidic on the outside and alkaline on the inside.

"It is at least highly suggestive that every living thing is constantly and indeed furiously recreating something equivalent to this ancient 'ocean effluent' membrane-based proton gradient that serpentinization handed life to start with on the rocky floor of the ancient Hadean ocean," Branscomb said. "It was, in part, by exploiting that naturally-given, geochemical proton gradient that the engines required to produce the molecular 'starter kit' of life got going. So suddenly it's obvious why we pump protons and use this silly method—we became dependent on this 'free lunch' energy system when life was born, developed a lot of fancy machinery for using it, and have never severed that umbilicus since."

After Russell proposed this theory, scientists discovered a real-world example of an alkaline hot spring in the North Atlantic Ocean, famously called the Lost City. This geochemical edifice provides strong and detailed evidence in its structure and chemical properties for Russell's model that origin-of-life expert Nick Lane, a senior lecturer at University College London, has called the only credible theory to date.

One of the most important, and exciting, aspects of Russell's hypothesis is that the key ideas can, in principle, be tested. This just-released paper and its companion paper by Nitschke and Russell in *PTRSL-B* have advanced Russell's hypothesis and brought it substantially closer to experimental testing. To this end, Russell and his collaborators are currently making experimental model systems that recreate the serpentinization process, including the theory's mineralogical membranes and chemical gradients.

Branscomb, a member of the IGB's Biocomplexity research theme led by Swanlund Professor of Physics Nigel Goldenfeld, was funded in part by a recently awarded, five-year grant totaling $8 million from the NASA Astrobiology Institute. The grant funds the University of Illinois's Institute for Universal Biology, a member of the NASA Astrobiology Institute, which includes many members of the Biocomplexity theme who are studying the origin and evolution of life. Find out more about Illinois's Institute for Universal Biology and the IGB's Biocomplexity theme.

"We have a sample of only one planet known to harbor life," Goldenfeld said. "Thus it is critical that we be creative in extracting the most information from Earthly life as possible, if we are to ever understand the existence, likelihood, and nature of life elsewhere in the Universe. Russell, Nischke, and Branscomb's work lays an intriguing foundation for that endeavor, by cleverly bringing together concepts from thermodynamics, geochemistry and biology to advance a major new hypothesis for life's origins."

Provided by University of Illinois at Urbana-Champaign

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