The setting for the origin of life: a geological-geochemical perspective

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There are many different scientific aspects involved in the challenge of understanding the origin of life (OoL). These include organic geochemistry – how to make RNA and DNA molecules from the simple organic building blocks delivered from space in the form of amino acids and some other compounds. Other aspects involve the study of inorganic geochemistry – how elements are made available to promote organic molecule complexification, under what conditions will lipid membranes form and how to bring together the different components that make a functioning cell.

In this review, I investigate the challenge of understanding the OoL from a geological-geochemical perspective; specifically, the best environment to promote complexity. I am a geologist/geochemist and have researched a wide range of environments on Earth that host the oldest evidence of life on our planet, including the habitats where ancient life grabbed a foothold. Recently, a group of colleagues and I have been using this deep-time information to guide us on where life may have started on Earth and where to search elsewhere in the solar system for evidence of a second genesis.

Currently, there is increasing evidence-based support for an OoL on land, rather than in the deep oceans, as previously widely favoured. Evidence in support of a terrestrial setting comes from a number of the scientific
research fields mentioned above, but here, I want to investigate the potential that terrestrial hot springs have for developing processes that promote complex chemistry, based on our knowledge both of the ancient – and modern – geological record.

Charles Darwin was the first to suggest an OoL on land in his now famous letter, written 147 years ago to his friend Joseph Hooker, speculating on whether life got started “...in some warm little pond...”. Indeed, OoL on land models persisted into the late 1970s and were only replaced by the discovery of black smokers on mid-ocean ridges (MORs), and their abundant vent fauna that thrived under completely dark conditions in a deep-marine setting based on a microbial community that gained their metabolic energy from the chemistry of the vent systems. This sparked a radical re-evaluation of our understanding of life on Earth, spawned by the identification of Archaea as the third branch on the tree of life. The visual impact of the deep-sea communities, combined with our increased awareness of the importance of a deep, non-phototrophic biosphere, led to models for the OoL at hot (400°C), acidic, deep-sea black smoker hydrothermal vents with sulphide minerals. More recently, however, the attention has shifted to cooler, alkaline, white vents in off-axis sites, with carbonate minerals.

However, there are a number of insurmountable problems with either of these deep-sea sites, as indeed there are for any permanently wet setting, relating to developing organic molecule complexity and concentrating the required ions for prebiotic chemistry leading to OoL. In oceanic settings, there is the well-known problem that organic molecule polymerization (the process whereby simple organic molecules are made more complex) is limited under hydrous conditions as all of the major polymerization reactions require dehydration and because organic polymers break down in the presence of water.

Another major issue with OoL in the oceans relates to the fact that they are a uniform, extremely dilute reservoir with no capacity to concentrate either ions or organic molecular components. Reactions can occur at hydrothermal vents that can provide some element enrichment and the possibility for limited geochemical complexification, but this is extremely limited and any products from such reactions will be dispersed from their reaction site below ground, up into the seawater and diluted. The potential for geochemical complexity in these systems is restricted to water–rock interactions.

Currently, there is a developing paradigm shift back to an OoL on land. This is based partly on the recognition of the problems with a marine (or other, permanently wet) environment as noted above, but also on the recognition of the many benefits that a terrestrial hot spring setting provide.

Principal benefits of hot springs are:
1) The potential for wetting-drying cycles that promote

Figure 1. Panorama across a water-coated sinter terrace linking Champagne Pool (pH = 5.5, T = 75°C, actively precipitating gold-silver) in the background with an unnamed, highly acidic, sulphur-rich pool (pH = 2, T = 98°C) in the left foreground. The orange colour is cyanobacterial mat; yellow is native sulphur.
polymerization, through recharge and draining of hot spring pools and through geyser eruption.
2) They contain fresh water, with low total salts, and K+/Na+ ratios that match the cytoplasm of cells in all three branches of life.
3) The ability to concentrate the organic building blocks for life delivered from space, and to then concentrate polymers formed under 1), above.
4) Hot springs typically occur in fields with tens to hundreds of pools, each of which has a distinct set of features (Eh, pH, chemistry, ionic concentration, etc.), including pools that range from highly acidic, through neutral, to alkaline (see Figure 1).
5) Hot springs are known to concentrate prebiotically important ions, including boron (e.g. Puga geothermal field, India), hydrogen, sulphur or iron (e.g. Chocolate Pots spring, Yellowstone National Park, USA), and even precious metals (e.g. Champagne Pool, New Zealand).
6) Pools within hot spring fields are often in close proximity and have the capacity to mix components (‘share information’), through geyser-related splashing, physical mixing (connecting streams, internal currents), overspilling from one pool to the next, changes in the subterranean plumbing network, wind, steam, etc.
7) Hot springs enable not only water–rock interactions, but also rock–air and water–air interactions that promote exchange between the atmosphere and the land/water surface.
8) Circulation of hot water through the underlying rocks and the formation of steam promotes mineral reactions and hydrothermal alteration, producing complex mineral chemistry, including the widespread formation of clays that can be important for complexing organic molecules.
9) Acidic pools have the ability to spontaneously create lipid membranes, a key component to cell development.

Using a biological analogy, such diversity and potential for mixing results in innovation pools and peaks of fitness. Most importantly, different components required for the OoL (e.g. cell membranes, polymers, ionic concentrations, etc.) could arise in different pools (or fumaroles, or subterranean plumbing networks or in altered wallrocks) and then be brought together through any one of the many mixing mechanisms (Figure 2).

But what about on early Earth? Could such conditions have occurred then?

One of the most exciting developments relating to an OoL on land is the recent discovery of an inhabited hot spring setting amongst the oldest recorded evidence of life on our planet. Our group found the spring in the 3.5 billion-year-old sedimentary rocks of the Dresser Formation from the Pilbara region of northwestern Australia. Evidence for life in this unit had been known for almost 40 years, yet had always been inferred to have thrived in a solely marine setting. The new discovery of geyserite and other types of hot spring deposits in these

Figure 2. Schematic diagram showing how hot spring pools with different physical characteristics (pH, Eh, temperature; represented by different colours) that can mix and match their contents (‘information’) by overspill, splashing, wind, steam, subterranean networks, etc., may act as innovation pools for different components of the origin of life and lead to peak(s) of greater complexity (‘fitness’).
rocks, together with evidence for their inhabitation by diverse communities of microbes, shows that some of the most ancient life on Earth thrived in hot springs, on land.

Significantly, the setting of the ancient, inhabited Pilbara hot springs shows that the geochemistry of this system reveals many similarities to modern hot springs, including the generation of clays and other mineral compositions as a result of hydrothermal alteration (Figure 3), and concentrations of prebiotically important ions including hydrogen, sulphur and – critically – boron.

These findings, together with recent models for the occurrence of a stable, thick crust in the volcanically active and already ocean-bearing Hadean Era – the time when life must have arisen on Earth – suggest that hot springs could have formed and remained active over the long periods necessary for the chemical reactions required for the OoL. Indeed, if – as Carl Sagan suggested – life required a trillion reactions to get started, a back of the envelope calculation of the reactions and interactions in a hot spring field suggests that life may have started within only 10 million years!

So, is life unique to Earth, or could life have started elsewhere? Well, if terrestrial hot springs were indeed the site for the OoL on Earth, and exposed land surfaces are a key to OoL, then one of the most important discoveries in astrobiology has been that of hot spring-generated opaline silica deposits on a volcanically active, ‘warm and wet’ early Mars, showing that the conditions for OoL were present on another planet within our solar system.

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Figure 3. Outcrop of well-preserved pillow shapes in 3.5 billion-year-old submarine basaltic rocks of the Dresser Formation (Pilbara, northwestern Australia) that have been altered by steam-heated acid-sulphate hydrothermal alteration to an assemblage dominated by white kaolinite and illite, after clay. Note the concave bases and convex tops of the pillows indicating the palaeofluid during eruption was at the top right of the photo.

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