How life evolved: 10 steps to the first cells

We may never be able to prove beyond any doubt how life first evolved. But of the many explanations proposed, one stands out – the idea that life evolved in hydrothermal vents deep under the sea. Not in the superhot black smokers, but more placid affairs known as alkaline hydrothermal vents. This theory can explain life’s strangest feature, and there is growing evidence to support it.

Earlier this year, for instance, lab experiments confirmed that conditions in some of the numerous pores within the vents can lead to high concentrations of large molecules. This makes the vents an ideal setting for the “RNA world” widely thought to have preceded the first cells. If life did evolve in alkaline hydrothermal vents, it might have happened something like this:

1. Water percolated down into newly formed rock under the seafloor, where it reacted with minerals such as olivine, producing a warm alkaline fluid rich in hydrogen, sulphides and other chemicals – a process called serpentinisation. This hot fluid welled up at alkaline hydrothermal vents like those at the Lost City, a vent system discovered near the Mid-Atlantic Ridge in 2000.

2. Unlike today’s seas, the early ocean was acidic and rich in dissolved iron. When upwelling hydrothermal fluids reacted with this primordial seawater, they produced carbonate rocks riddled with tiny pores and a “foam” of iron-sulphur bubbles.

3. Inside the iron-sulphur bubbles, hydrogen reacted with carbon dioxide, forming simple organic molecules such as methane, formate and acetate. Some of these reactions were catalyzed by the iron-sulphur minerals. Similar iron-sulphur catalysts are still found at the heart of many proteins today.

4. The electrochemical gradient between the alkaline vent fluid and the acidic seawater leads to the spontaneous formation of acetyl phosphate and pyrophosphate, which act just like adenosine triphosphate or ATP, the chemical that powers living cells.
These molecules drove the formation of amino acids – the building blocks of proteins – and nucleotides, the building blocks for RNA and DNA.

5. Thermal currents and diffusion within the vent pores concentrated larger molecules like nucleotides, driving the formation of RNA and DNA – and providing an ideal setting for their evolution into the world of DNA and proteins. Evolution got under way, with sets of molecules capable of producing more of themselves starting to dominate.

6. Fatty molecules coated the iron-sulphur froth and spontaneously formed cell-like bubbles. Some of these bubbles would have enclosed self-replicating sets of molecules – the first organic cells. The earliest protocells may have been elusive entities, though, often dissolving and reforming as they circulated within the vents.

7. The evolution of an enzyme called pyrophosphatase, which catalyses the production of pyrophosphate, allowed the protocells to extract more energy from the gradient between the alkaline vent fluid and the acidic ocean. This ancient enzyme is still found in many bacteria and archaea, the first two branches on the tree of life.

8. Some protocells started using ATP as well as acetyl phosphate and pyrophosphate. The production of ATP using energy from the electrochemical gradient is perfected with the evolution of the enzyme ATP synthase, found within all life today.

9. Protocells further from the main vent axis, where the natural electrochemical gradient is weaker, started to generate their own gradient by pumping protons across their membranes, using the energy released when carbon dioxide reacts with hydrogen. This reaction yields only a small amount of energy, not enough to make ATP. By repeating the reaction and storing the energy in the form of an electrochemical gradient, however, protocells “saved up” enough energy for ATP production.

10. Once protocells could generate their own electrochemical gradient, they were no longer tied to the vents. Cells left the vents on two separate occasions, with one exodus giving rise to bacteria and the other to archaea.