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The epic hunt for the place on Earth where life started

Darwin's warm little pond, the deep ocean and icy shores – all have been suggested as the birthplace of life. Now one location could have it all

By **Penny Sarchet**

NEARLY 4 billion years ago, the first life appeared on our planet. It would have looked unlike any life as we know it today, more basic even than bacterial cells – barely more than a few genetic molecules packaged up in some kind of a sac. Working out how this popped into existence is one of our greatest intellectual endeavours. And at the root of the problem is an epic hunt for the perfect location.

Researchers studying the origins of life each have their favourite spot. Some sites offer the right molecular ingredients, others provide ready-made little containers to hold these early reactions. But is it possible that one special place had the perfect combination of all the conditions essential for the chemistry of life? And does a similar place still exist today, on Earth or elsewhere in the universe?

Charles Darwin kicked off the quest. In a letter he wrote to the botanist Joseph Dalton Hooker in 1871, he described a hypothetical warm little pond, rich in chemicals and salts, with sources of light, heat and electricity. He imagined that in such an environment, proteins might spontaneously form, ready to turn into something more complex. In the 1950s, chemists Stanley Miller and Harold Urey managed to create Darwin's pond in the lab. They mixed water with gases they thought would have been present on early Earth, and zapped them with simulated lightning. This produced amino acids, the building blocks of all proteins.

Basic supplies

Their experiment is one of the most famous of the last century, but we now know that what they created, protein components in water, is not enough to constitute life.

To truly get going, life would have needed three quite special features: a genetic code that would carry the blueprint for making cells, a chemical system – or metabolism – to generate the energy to power the cells, and a sac or membrane to hold it all together. In all organisms alive today, the trio is built from the same atoms: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur. So at the most basic level, life's crucible must have offered a ready supply of these atoms and the right conditions for them to come together and form all three of life's essential features.

While biochemists were pondering these matters, deep-sea explorers made a surprising discovery in the Pacific. In 1979, the US submersible Alvin was diving at a volcanic ridge 2 kilometres beneath the surface when it discovered black smokers, underwater vents spewing superheated water at 350°C. These were host to a whole ecosystem unlike any that had been seen before. The find was fortuitous: at a time when biologists were trying to imagine what life not-as-we-know-it might look like, here were living, thriving examples. "There were some very alien, ancient-looking fauna living around [black smokers]," says Philipp Holliger at the MRC Laboratory of Molecular Biology in Cambridge, UK.

Coincidentally, only two years later the Voyager 2 space probe was sparking interest in the possibility of extraterrestrial life and its origins by sending back photos of Jupiter's icy moon Europa (see "Could space be the place?"). "People thought it would have a subsurface ocean with vents," says Holliger. Their speculation fuelled excitement that deep hydrothermal vents could have kick-started life elsewhere as well as on Earth.

That idea is still fixed in the public imagination, even though researchers have long since left it behind. "There are relatively few people defending black smokers as the place that life started," says Nick Lane at University College London. The problem is that they are low in hydrogen and too hot for nascent molecules to stay intact for long. In particular, RNA – a molecule that many evolutionary biologists think served as life's genetic material before DNA – degrades rapidly at high temperatures.

"There were some very alien fauna living in these locations"

Then came the discovery, in 2000, of cooler submarine vents in the mid-Atlantic. The site, christened the Lost City, was a collection of alkaline hydrothermal vents. Here, seawater reacts with the minerals of the sea floor to produce rocks that are riddled with tiny pores, as well as a warm fluid that is rich in hydrogen. Lane thinks the rocky pores would have been ideal for the reactions of early life. In particular, the electrochemical gradient between the alkaline vent fluid and the acidic seawater back then could have led to the spontaneous formation of acetyl phosphate and pyrophosphate, two molecules that act just like ATP, the chemical that powers living cells today.

The rest of the essentials could have followed, says Lane. Acetyl phosphate and pryophosphate could have provided the energy to synthesise the first organic molecules from dissolved carbon dioxide and hydrogen gas. From these, the building blocks of proteins and RNA might have been made. If lipids had been made too, they may have coated the inside of the pores to form the first cell membranes.

The top candidates for life's crucible

Life could have got started in a range of environments, from the bottom of the oceans to deserts. Each has its pros and cons

Alkaline ocean vent – Around 65°C

Large columns of rock on the sea floor, riddled with tiny pores, where alkaline water bubbles into the ocean

Where on earth today: Lost City in the mid-Atlantic

Arguments in favour: Lots of hydrogen; a chemical set-up similar to modern metabolisms; geothermal energy to drive reactions

Arguments against: Too salty for membranes; too wet for large biomolecules

Hot freshwater pool – Around 90°C

Small pools on warm volcanic land, repeatedly replenished by geysers or hot springs in between dry spells

Where on earth today: Bumpass Hell in California

Arguments in favour: Wet and dry cycles help large biomolecules form; membranes form naturally if fatty acids are present

Arguments against: Unclear how metabolism could have got started

Geothermal field – Around 150°C

Hot, geothermally active rocky landscapes with cooler water vapour enriched with minerals

Where on earth today: Mutnovsky field in Kamchatka, Russia

Arguments in favour: Vapour rich in essential elements; water droplets could help RNA to form

Arguments against: Unclear how metabolism could have got started

Image credits (top to bottom): Courtesy of University of Washington; Prisma by Dukas Presseagentur GmbH/Alamy; robertharding/Alamy

Alkaline ocean vents are great in the way they offer a ready-made metabolism to run life's first reactions, but they have a problem: they are too wet, says David Deamer at the University of California in Santa Cruz.

Proteins, genetic material and lipids are polymers, chains made from their respective building blocks. Way back when things were just getting started and biomolecules were painfully rare, something had to stop the building blocks being too diluted – unable to bump into each other and form chains. The answer, says Deamer, is a place with wet and dry cycles to bring things together: “If you have cycles, you can have natural experiments going on again and again, thousands of times until something interesting happens.”

There’s another argument in favour of life starting on land, in an environment that dried up periodically. Dehydration plays a key role in making organic molecules. Every time a building block is added to a growing chain, a molecule of water is released. Enzymes control the process in modern cells. Without enzymes to help, a dryer environment would have encouraged such reactions in life’s early stages.

Deamer imagines volcanic islands with freshwater pools that are sprayed by hot springs or geysers in between drying out. These pools would also have been good places to form the first fatty membranes – much better than deep-sea vents. In the ocean, dissolved calcium and magnesium ions could have stopped the fatty acids coming together to make a continuous membrane. But in fresh water, lipids easily coalesce in the same way as oily drops clump together when you mix oil and water.

Desert origins

Deamer’s team has been taking samples from hot springs in Yellowstone National Park and at Bumpass Hell in Mount Lassen National Park, California, and putting them through wet-dry cycles. In unpublished work, they have found that if they dry out these samples and then rehydrate them, RNA-like molecules can become encapsulated within fatty membranes, resembling genetic material within rudimentary proto-cells.

In a slight twist to the hot pools scenario, Armen Mulkidjanian at Osnabrück University, Germany, prefers an even drier environment, in the form of geothermal fields – hot rocks that release water vapour heated by geological activity inside Earth. His team argues that the chemistry here is similar to what goes on inside our own cells. “Geothermal vapour is enriched in elements important for life,” says Mulkidjanian. As the vapour condenses, some experiments suggest that the tiny droplets that form can create ideal conditions for components of RNA to materialise.

However, to make RNA, you first need to make the sugar ribose – the R in RNA. The atoms for that would probably have been available in the atmosphere, but tend to form something other than ribose unless given a helping hand. Borate minerals could have done the job, according to Steven Benner at the Foundation for Applied Molecular Evolution in Florida. They guide reactions towards producing more ribose. Better still, they stop the ribose from falling apart.

More candidates for life's crucible…

Desert – Around 80°C

Arid land with sporadic rains that bring minerals and compounds from the mountains and atmosphere

Where on earth today: Death Valley, California

Arguments in favour: Borate from the rocks helps RNA components to form

Arguments against: Unclear how metabolism could have got started

Ice – Around 0°C

Frozen water riddled with narrow fissures and channels, filled with concentrated brine

Where on earth today: Freshwater at high altitudes or in cold climates

Arguments in favour: Long strands of genetic material can assemble and build further strands in a nearly self-sustaining system

Arguments against: Unclear how metabolism could have got started

Impact crater – Around 2000°C*

Iron-rich rocks heated by successive meteorite impacts

Where on earth today: Meteor Crater in Arizona

Arguments in favour: Right conditions for genetic material, proteins and membranes to form

Arguments against: Implies a cyanide-based metabolism, unlike anything on Earth today

**Upon meteorite impact, then much cooler*

Image credits (top to bottom): Larry Geddis/Alamy; Naturfoto-Online/Alamy; National Map

Benner thinks this makes deserts an appealing candidate for life's cradle. The rocks there are rich in borates and occasional rains would have leached them out. "If you have been to Death Valley, you have seen an example of what we have in mind," he says.

One thing all these environments have in common is heat. This makes sense, in that warmer temperatures can help power chemical reactions. So it comes as a bit of a surprise that some researchers think life could have begun on ice. "When water freezes, everything dissolved in it gets dehydrated and concentrated into brine," says Holliger. The brines get trapped inside narrow cracks in the ice, where polymer chains can form, and the cool temperatures help stabilise biomolecules long enough for them to keep growing.

Researchers have experimented with making long RNA strands by freezing a solution of its building blocks together with metal ions. These ions are common in the environment and help catalyse the reactions.

Holliger and his colleagues have also found that repeated freeze-thaw cycles help build enzymes made of RNA. That's key because the enzymes can themselves make more RNA strands – precisely the kind of set-up you might expect for early life. "I think ice is an interesting medium to facilitate that important transition towards a system that can propagate itself," says Holliger.

The one that had it all?

Hypothetically, one place could have offered everything necessary for life to get started

Terrestrial hydrothermal crater lake Around 165°C

A hot lake within a meteorite crater – possibly with ice around the edge

Where on earth today: Lonar crater, India

Arguments in favour: Conditions are right for three components of early life – genetic material, proteins and membranes

Arguments against: Implies a metabolism unlike anything on Earth today… although if an alkaline vent happened to be nearby then maybe – just maybe – this could have been the place that had it all

Image credit: Dinodia Photos / Alamy Stock Photo

All these land and freshwater scenarios have a catch. Unlike Lane's alkaline vents, they don't offer an easy explanation for how metabolism evolved. And they all lack a convincing hypothesis for how all three pillars of early life – genetic material, metabolism and membranes – came together.

"Everyone pretty much agreed 50-odd years ago that you couldn't get everything in one go," says John Sutherland at the MRC Laboratory of Molecular Biology. Most researchers fall into one of two camps, depending on whether they focus on genetics or metabolism when looking for the origins of life. Sutherland's team is seeking a scenario that creates everything in one place, at one time. "We deliberately set out to look for chemistry that would make [all] the various bits and pieces," he says.

That led them to meteorite impacts, which would have been common 4 billion years ago. These rocks from outer space could have brought hydrogen cyanide with them, a convenient source of three of the essential elements of organic molecules: carbon, nitrogen and hydrogen. Sutherland's experiments show that if accumulations of hydrogen cyanide became superheated – say by another meteor impact – in the presence of water and UV light, they could have formed a whole suite of precursor molecules for RNA, proteins and lipids. There's a snag though: "No life uses cyanide as a source of either carbon or nitrogen," says Lane.

"It comes as a surprise that some think life could have begun on ice"

So was life's cradle wet, dry or frozen? "I don't think these are mutually exclusive," says Holliger. For example, Sutherland's meteor-impact chemistry needs at least one wet-dry cycle and hydrogen sulphide, both of which could have been provided by hydrothermal activity at hot freshwater pools, the kind of environment Deamer thinks is good for membranes. One place where all of this could have come together is a hydrothermal lake inside a meteorite crater. "We know that when a big meteorite hits, it causes fissuring of the crust," says Sutherland. If water pools in the crater, it can percolate down through the cracks and go deep enough inside Earth to be heated and bubble up again.

"Hydrothermal crater lakes would have been abundant on the proto-continents of the young Earth," says Sankar Chatterjee at Texas Tech University. Why stop there? Throw in ice around the edge (like you see at Yellowstone in the winter) and a nearby terrestrial alkaline hydrothermal vent (similar to those at the bottom of the ocean but on land) and you might get Holliger's self-sustaining RNA enzymes, and Lane's ready-made metabolism. Everything you need wrapped up in one place.

Could space be the place?

Panspermia is the idea that life on planets such as Earth was seeded from space, but how likely is it? "I think it shouldn't be ruled out, but it's not worth considering it until we've more extensively explored likely possibilities on Earth," says John Sutherland at the MRC Laboratory of Molecular Biology in Cambridge, UK.

If life arrived from elsewhere, it would have had to make it through the atmosphere without burning up, and then adapt to our planet. A more probable scenario is that some of the building blocks arrived by interstellar transport and were assembled after delivery. Some meteorites contain fatty molecules that can coalesce into membranes, an essential component of all cells. And the building blocks of proteins have been found around comets. Despite this, there is still some argument over whether these components could have arrived intact in large enough amounts.

The chemistry of life may have started independently on Earth and elsewhere in the universe, in which case the quest to pin down its origins at home could help us find it in the great beyond. For every possible cradle of life on Earth, there could be an equivalent in space. The Gale crater on Mars, which is being explored by NASA's Curiosity rover, used to have a lake, and there are signs of alkaline hydrothermal vents on Enceladus and Europa, icy moons of Saturn and Jupiter respectively. And that's just within our own solar system.

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