ÁRON SÜVEG/ANZENBERGER/EYEVINE

Home and dry

Water was probably the last thing the first life needed, says Colin Barras

"SOME warm little pond." Charles Darwin's speculative description of life's cradle, in a letter written to the botanist Joseph Hooker in 1871, still chimes today. Seed a watery environment with the right ingredients, Darwin mused, then cosset it with a little light, heat or electricity, and a purely chemical miracle of creation might occur.

Hard and fast evidence of how and where on Earth inanimate matter became animate is hard to come by. Other backdrops for life's first steps have gained in popularity since Darwin's time – around submarine hydrothermal vents, in ice or on Earth's radioactive first beaches,

Did life's cradle look like Death Valley?

for example. If pressed, though, most of us would still plump for the primordial soup.

In the intervening years, we have devised more detailed recipes showing how the early Earth might have cooked up simple organic molecules, and how these might have reacted further to form the more complex building blocks of life: things like amino acids, DNA and RNA. Besides the right chemical ingredients, the process needs warmth, sunlight, perhaps a little lightning and, most importantly, H_2O. Water is, after all, the essential solvent that underpins carbon-based life.

For Steven Benner, that is all a fairy tale. "We tend to think that water's properties are ideal for life, but the opposite is true," he says. "Water is corrosive." Benner is a chemist at the Foundation for Applied Molecular Evolution in Florida and for three decades he has been doing pioneering work in synthetic biology, which aims to recreate life's chemistry in the test tube. And he is no lone voice. As water's deleterious effects have become more apparent, many researchers are asking: is it time to dry out life's recipe?

Around 70 per cent of our planet's surface is ocean, and water makes up 60 per cent of our body weight. Few living things can survive for long without water: it is a perfect medium in which organic molecules can dissolve and react to sustain the core processes of life on Earth.

But this perfect solution is also a problem. Life's molecules don't just dissolve in water; the electron-rich oxygen of its molecules attacks them, and they begin to fall apart. "In your body right now, the DNA in your cells is losing an amino group many times a second because of the action of water," says Benner. Living things keep their molecules intact only through clever chemical strategies that perpetually repair the breakages.

Tricky when wet

The first life on Earth wouldn't have had time to develop those strategies. According to the widely accepted "RNA world" theory, RNA was the first self-replicating molecule, and a precursor to today's DNA-based life (see "Dawn of the living", page 10). Like DNA, RNA is built up from nucleotides, complex organic molecules that are themselves formed from two simpler components, a nucleobase and a sugar called ribose. Decades of research have shown that making nucleotides in water is a very tricky business. Individual steps can be made to work, but they don't all gel together. "We are still at the stage of scraping out the product of step seven, and carefully spooning it into the flask to begin step eight," says Benner. Fail to spoon in just the right amounts of various molecules at the right time, and the end result is a gunky mess.

In 2004, Benner made a breakthrough. He showed that borates – minerals containing varying proportions of boron and oxygen – could act as scaffolds for the construction of ribose, making that part of the chemistry a much more hands-off, naturally plausible process. The problem of attaching the ribose to the nucleobases remained, however, until in 2012 Benner made a simple and bold suggestion: to make life, just remove water. By replacing it with an organic solvent richer in carbon and poorer in oxygen such as formamide (CH_3NO), the right components would, in theory at least, stick together spontaneously to make RNA. This idea was bolstered by seminal work in 2015 showing that a simple set of chemical reactions can yield all the important building blocks of life, but only when the conditions are dry or nearly dry for some stages of the reaction.

Formamide would have been created when hydrogen cyanide in Earth's early atmosphere mixed with water. Its boiling point is higher than that of water, so in a hot environment the formamide would have become more ›

WORLDS WITHOUT WATER

Evidence that drinkable water once flowed on Mars, as found by NASA's Opportunity rover, is still lapped up as suggesting the planet could have harboured life. But with the realisation that water may have hindered early life on Earth (see main story), should we be looking elsewhere?

In fact, astrobiologists at NASA and elsewhere have long discarded the assumption that life needs aqueous chemistry. Earth and Mars aside, the solar system body thought most likely to harbour life is Titan, Saturn's largest moon. The Cassini probe, in orbit around Saturn since 2004, has shown Titan's dense atmosphere veils rough terrain but also smooth seas filled not with water, but the hydrocarbons methane and ethane. "Titan is an excellent place to explore for non-aqueous experiments in chemical self-assembly," says Jonathan Lunine, a planetary scientist at Cornell University in Ithaca, New York.

Lab experiments confirm that amino acids, the basis of proteins, could be generated on the surface of Titan, although temperatures are so frigid - as low as -180 °C - that life there would probably not be able to operate on Earth-like chemical principles. Covalent bonds of the sort that underpin our carbon chemistry would not form and break quickly enough, but weaker van der Waals bonds would be more stable and could play a more prominent part.

Whether life's origins were wet, dry or something else altogether, the different sorts of chemistry that might support life mean we should keep an open mind when considering the 2000-odd planets that missions such as NASA's Kepler space telescope have now found orbiting other stars, very few of which look like Earth. "We cannot limit ourselves to what we know in exploring the unknown," says Lunine. "We cannot simply search for the keys to life's origins underneath the narrow beam of the aqueous street lamp."

"The search for life beyond our planet has traditionally followed the mantra 'follow the water'"

concentrated as the water evaporated away. Borates are scattered across Earth's surface today, where they result mainly from the erosion of igneous rocks. Looking at Earth now, Benner has found one environment that combines both sweltering conditions and the presence of borates. It aptly sums up how unexpected life's earliest requirements might have been. Its cradle, says Benner, might have looked a lot like California's Death Valley.

Benner's chemistry arguably provides the first one-pot recipe for life that can bubble away without human intervention. Armen Mulkidjanian, a chemist at the University of Osnabrück in Germany, is a fan. But he points to a problem with cooking it up in a primeval Death Valley. "The world's borate minerals are all found in relatively young rocks," he says. There is no evidence that surface concentrations of borates were sufficient for the chemistry to work until about 3 billion years ago, he says – around a billion years after life supposedly got started.

So where then? Mulkidjanian sees inspiration in the geothermal fields of Kamchatka in eastern Russia. These are spots where fluids have flowed through Earth's crust and come to the surface as vapours, bringing with them nutrients accumulated from rocks along the way. Borates are often found in these geothermal fumes, as are the chemical components of formamide. One further chemical convergence emboldens Mulkidjanian in thinking that a similar environment could have cradled life: the geothermal fields of Kamchatka are just about the only place on Earth where the balance of sodium and potassium ions matches that inside living cells.

Mulkidjanian's twist on Benner's tale has gained supporters. "What's nice is that geothermal fields provide a constant set of conditions for the origin of life, since the chemistry is coming from Earth's stable interior and not its exterior," says Ernesto Di Mauro at the Sapienza University of Rome, Italy. "If you frame Benner's proposal in these geothermal fields, you have a scenario that doesn't have many weak points."

But not so fast. These scenarios require Earth to have supplied dry environments like a Death Valley or a Kamchatkan geothermal field 4 billion years ago. Until recently, the consensus would have been that this was no problem: Earth was then exiting an interval dubbed the Hadean because of its hot and hellish conditions. But in the past decade, geologists have cooled on the idea of a hot young Earth. Their main evidence comes from tiny crystals, each less than a millimetre across, of a mineral called zircon. These are tough, easily outlasting the rocks they formed in, which have been obliterated by subsequent tectonic activity.

A close look indicates that the crystals were made in cool, soggy conditions, implying that Earth's early history was wet, with land accounting for perhaps just 5 or 10 per cent of its surface. Joseph Kirschvink, a planetary scientist at the California Institute of Technology in Pasadena, goes so far as to speculate there was no dry land at all. That leads him to a seemingly way-out conclusion: if the first life needed to be dry, it cannot possibly have started on Earth.

Premature requiem

The search for life beyond our planet has also traditionally followed the mantra "follow the water" – although recent discoveries in and out of the solar system are causing that assumption to be revisited (see "Worlds without water", above). Kirschvink has been an enthusiastic supporter of the idea that Earth's life possibly began on Mars, ever since the infamous announcement in 1996 that fossilised "microbes" had been discovered in a 4.1-billion-year-old Martian meteorite called ALH 84001. The consensus now is that these are just rock features that look like cells – but we should not discount the Martian option just on that basis, according to

"If life needed a dry place to get started, Mars had the right conditions at the right time"

Kirschvink. "The requiem for life on Mars was very premature," he says.

And if life needed a dry place to get started, Mars had the right conditions at the right time. Although it once had an ocean basin around its north pole, its southern highlands were almost definitely never submerged. "The RNA world would have done very well there," says Kirschvink. He thinks that later on, probably after the RNA world had given rise to the DNA-based cellular life we are familiar with today, an asteroid hit the Martian surface, throwing chunks of rock and ice containing these cells beyond the planet's atmosphere. Perhaps as little as nine months later, some of them made it to Earth.

In 2013, at the Goldschmidt geochemistry conference in Florence, Italy, Benner agreed that there is logic to Kirschvink's arguments. "The evidence seems to be building that we are actually all Martians; that life started on Mars and came to Earth on a rock," he said, generating a wave of media interest.

Just weeks before the conference, James Stephenson, now at the NASA Ames Research Center, California, and his colleagues had provided further succour for the theory, with confirmation that Mars is rich in a key ingredient for Benner's pathway. They published an analysis of a 1.3 billion-year-old Martian meteorite called MIL 090030 that showed it was riddled with boron. "I was honestly surprised that people hadn't really looked at boron in Mars samples before," says Stephenson. He hopes to collaborate with Benner soon to develop the idea further.

Mulkidjanian agrees that conditions on early Mars may have been suitable for the origin of life, and wryly points to evidence that the planet may even have had geothermal fields similar to those in Kamchatka, his favoured sort of cradle for life.

But he questions whether dry life arriving on a wet Earth on a Martian meteorite could have assimilated well. Genomic studies show that life on our planet traces back to a collection of cells that survived by sharing the products of their genes, creating a single-celled organism referred to as the last universal common ancestor (See "Meet your maker", page 6). "If you dropped a primitive Martian cell into Earth's oceans, it is highly unlikely that it would have proliferated alone," he says. Rather, it would take a whole microbial ecosystem arriving, intact, from Mars.

MICHAEL MELFORD/NATIONAL GEOGRAPHIC CREATIVE

Geothermal chemistry might have fitted the first life perfectly

Back to Darwin

This hints at a wider problem. No matter where and on what planet the delicate early forms of life originated, water's corrosive nature would have caused them to struggle when first introduced to a wet environment. All indications are that this happened very early: life has thrived in the oceans for billions of years. "There is a paradox," admits Benner. "You have to get out of water to solve the water problem, but then you've got to get back into the water." The only real solution, he says, is to gradually moisten a dry cradle and allow the variety of molecules to either cope or perish through natural selection.

Or we tweak our story still further. Nicholas Hud, a chemist at the Georgia Institute of Technology in Atlanta, points out that most researchers accept that DNA somehow evolved from RNA, so we should at least consider the possibility that RNA evolved from a different molecule that was stable in water. "When I look at RNA, I see a molecule that is perfect at what it does, but that's hard to make," he says – perhaps a telltale sign that natural selection helped shape RNA. "Which is more probable? Life began on Mars, was transported to Earth and picked up where it left off, or life began on Earth, but with a molecule different from RNA?"

Hud's thinking could remove the need for Kirschvink's Martian scenarios and Benner's chemistry, but would demand a rethink of the underlying assumption that life's chemical origin lies with RNA. It would seem fitting, though, that the ultimate solution to the water problem, even before life as we know it got started, could lie in the principles of natural selection. Stories about the origins of life begin and end with Darwin. ■