PAINTING BY D. PARKINS

Nascence man

Like an alchemist of yore, Mike Russell is taking basic elements and trying to transform them — not into gold, but into the stirrings of life, **John Whitfield** reports.

You could call the two linked aluminium containers in Mike Russell's lab the biological equivalent of a particle accelerator. But rather than simulating the birth of the Universe, he hopes that this apparatus will recreate the first moments of life on Earth, and give experimental support to his ideas about how geology begat biology. Alternatively, you could call it a machine for making 4-billion-year-old waste.

One of the containers holds a liquid that mimics the oceans of the early Earth. The water is rich in carbon dioxide and iron, has a pH of 5.5 and is held at room temperature. The other container is heated to 130 °C, and its water is laden with hydrogen and sulphide. With a pH of 11, this second fluid is meant to stand in for the hot waters that spewed out of ocean-bottom springs early in the planet's history. The liquids mix in a chrome steel pressure barrel containing a catalyst of iron and nickel sulphide.

It is here that Russell (illustrated above) hopes to reproduce life's first steps, by reacting the carbon dioxide in the 'ocean' water with the hydrogen in the 'spring' water to make the simple organic molecules methane and acetate. Step by step, he thinks, the chemistry of life accreted around this reaction, until eventually, like caravels from the court of Henry the Navigator, the first cells carried it around the world.

As a candidate for the spark of life, this reaction has a lot going for it. It releases chemical energy and can fix carbon — that is, convert carbon dioxide into organic compounds — two of life's most characteristic properties. It uses ingredients that are abundant and it fits with what we know about the early Earth. Moreover, it is still used today, albeit with a good deal more sophistication, by the microbes called methanogens and acetogens, which produce methane and acetate as waste.

Russell has spent nearly three decades developing this hypothesis. Now, working at the Jet Propulsion Laboratory (JPL) in Pasadena, California, he's gearing up to test it, hoping to score a victory for the school of origin-of-life researchers known by the label 'metabolism first' in its long struggle with the more popular school called 'replicator first'. The latter holds that life began with a molecule — perhaps RNA or a simpler precursor — that was able to duplicate itself. Russell, however, thinks that the key breakthrough was the set of metabolic reactions that underpins biochemistry. The thermodynamic and chemical properties of the early Earth, he says, made these reactions a statistical inevitability.

Despite the rivalry, however, there is widespread recognition that Russell brings a much-needed dose of geological reality to research into the origin of life. "What I respect most about Mike's work is his keen insight into the early Earth's geochemical environment," says Robert Hazen, a geochemist and origin-of-life researcher at the Carnegie Institution for Science in Washington DC. "The origin of life is the story of the emergence of complexity, and you can't have the emergence of complexity unless you have a complex environment. Mike, as much as anybody out there, has recognized this fact and incorporated it into his models. That's his strongest contribution."

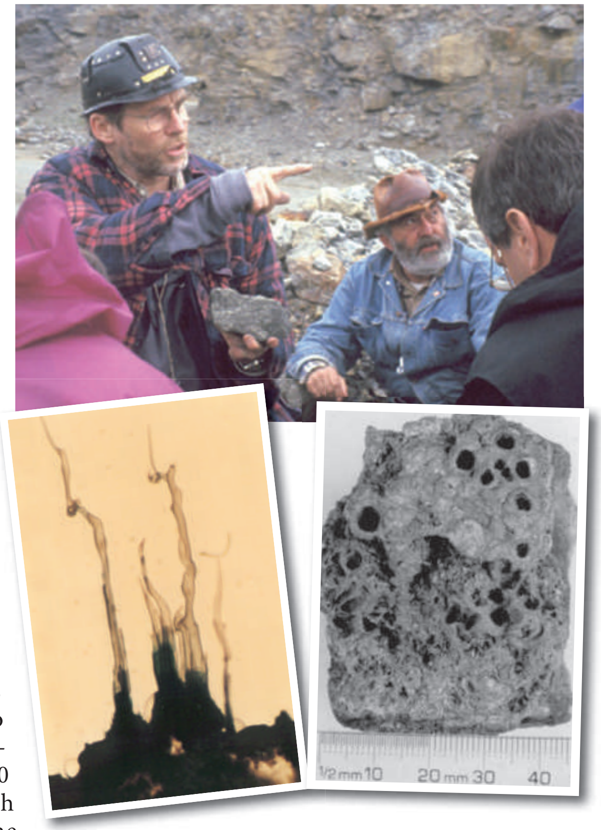
From aspirin to volcanoes

Studying the origin of life is not a great way to build a scientific career, so the people who work on the topic tend to have built up their reputations in other disciplines. But even by these standards, Russell's route to the JPL has been circuitous. When he left high school in 1958, he got a job making aspirin at a chemical plant in Ilford, a small town on London's northeast edge. But he continued to study at evening classes, and the Quaker-run company gave him days off to attend college.

Five years later, having left the factory and taken a degree in geology and chemistry, he found himself on the Solomon Islands in the Pacific Ocean, as a volunteer geologist with the UK Mission to the United Nations. In his first week, his boss pointed out the office window to a smouldering volcano on a nearby island. "He said: 'The chief has just radioed. He thinks it's going to explode.' I had no idea what to do," Russell recalls. Charged with deciding whether to evacuate the island's 3,000 inhabitants, Russell gave himself a crash course in volcanology, measured the ground temperature around the island's smoking volcanic vents, and decided, correctly as it turned out, that on this occasion the chief was mistaken.

While he was on the Solomons, Russell worked with the Australian geologist Richard Stanton from the University of New England in New South Wales. On Stanton's advice, he became an ore geologist, going to Canada to work in mineral exploration, before moving into academia in the late 1960s. Stanton also recruited Russell to his then-unorthodox idea that mineral deposits were the legacy of ancient submarine hot springs. When such hydrothermal vents were found on the Pacific floor in 1977, Stanton was proved right. Many valuable mineral deposits are indeed the remains of ancient vent sites, showing various similarities to the 'black smokers' that pour out water heated to 400 °C and are loaded with dissolved zinc, copper, iron and other elements.

By then, Russell was working at the University of Strathclyde, UK, and doing fieldwork in the Republic of Ireland at the mineral deposits in Silvermines, County Tipperary. There, he and his students found rocks riddled with small tubes of iron sulphide. They looked like miniature versions of the hydrothermal chimneys formed by minerals precipitating out of vent water.



G. EARLS

M. RUSSELL

J. H. E. CARTWRIGHT *ET AL.* J. COLLOID INTERFACE SCI. 256, 351-359 (2002)

Mineral deposits Mike Russell (in a helmet) found at Silvermines in Ireland (above, right) looked like chimneys near ocean hot springs. Chemical gardens (above, left) helped to inform his ideas.

A child's discovery

Russell began trying to work out what sort of environment would give birth to these structures. His suggestion that the tubes were formed in vents[1] met with a cool reception, he says, because the chimneys at black smokers were much bigger — 10 centimetres across, whereas those he saw in Ireland were less than 1 millimetre. Revelation came courtesy of Russell's 11-year-old son, Andrew. Russell had introduced Andrew to chemical gardens, toys in which pretty structures grow from a seed crystal added to a mineral solution. In a fit of destructiveness, however, Andrew had locked himself in the bathroom and started pulling the gardens apart. "Suddenly he yelled out 'Hey Dad, these things are hollow'," says Russell.

"I realized our little chimneys at Silvermines were actually chemical gardens," he says. That, he decided, must mean that black smokers were not the only kind of vent. There had to be cooler, gentler springs that would produce more delicate structures. More-or-less simultaneous with this thought came the idea that such a place was a good candidate for life's nursery. Some researchers had already suggested that hydrothermal vents had provided life's primordial source of energy and chemicals, but others protested that the extreme heat of a black smoker would break any large organic molecule into pieces. At the kind of vent Russell had in mind, however, the temperature would not have got much above 100 °C, which is much more amenable to organic chemistry.

The final clue emerged during a visit to Yugoslavia in the mid 1980s, which revealed even greater diversity in ancient hot springs. The water in modern black smokers is acidic, thanks to dissolved sulphur compounds creating sulphuric acid. When life emerged in Hadean times some 4 billion years ago, the ocean, too, would have been acidic, thanks to the large amounts of carbon dioxide in the atmosphere that would have dissolved in the waters. But in the Dinaric Alps, Russell saw deposits of the magnesium-bearing mineral magnesite that had formed in the ancient ocean floor and precipitated out of alkaline springs[2]. At the time, however, no active alkaline vents were known, only black smokers.

Between the late 1980s and the mid 90s, Russell and his colleagues stitched all their evidence into a portrait of the 'Goldilocks' spot, where the mineral chemistry was just right for what happens in cells today. "We recognized that some types of mineralization had a lot in common with the chemical processes of life," says geologist Allan Hall of the University of Glasgow, UK, and one of Russell's principal collaborators at the time.

Their theory of how life got going starts inside the tiny mineral chimneys. This protected environment would allow chemicals to become concentrated — a key problem facing anyone trying to explain how biochemistry can begin without cells. When these chimneys formed, they would have been gels rather than rocks, with membranes that would have allowed small molecules to pass through, much as cell membranes do. And the team found they could produce such a mineral gel in the lab[3]. The gel's membranes contained mineral sulphides of iron and nickel that would have catalysed organic reactions — just as these metal sulphides do inside modern enzymes.

Across the membranes, gradients would have developed. Inside the vent, the water would have been hot, alkaline and rich in hydrogen, thanks to reactions between water and iron minerals in the crust, a process called serpentinization. Outside in the ocean, the water would have been cold and acidic. The vast majority of modern cells power much of their chemistry by creating similar gradients across their membranes. But they use a large variety of proteins to do it. Life's diverse ways to harness a ubiquitous energy source — the proton gradient — makes Russell think that the proteins are a secondary adaptation, and that life latched onto inorganic proton gradients before it could make its own.

Left to their own devices, hydrogen and carbon dioxide form methane only slowly, because the reaction's initial steps, from carbon dioxide to formaldehyde, require an input of energy. In the ancient vents, the energy of the proton gradient accelerated this reaction, says Russell. He draws an analogy with geological convection, the churning currents of ductile rock that speed up the release of heat from Earth's interior to the surface. "Metabolism is to geochemistry as convection is to geophysics," he says.

Russell initially thought that the key reaction in the origin of life was a redox reaction involving iron, so called because the iron is said to be reduced and the hydrogen oxidized. In 1998, however, he saw a paper in *Nature* arguing that eukaryotes arose when a hydrogen-requiring archaeal cell engulfed a hydrogen-producing bacterium[4]. Piqued by the mutual interest in hydrogen redox reactions as a biological energy source, Russell explained his ideas to one of the authors, William Martin. Martin, now at Heinrich Heine University in Dusseldorf, Germany, loved Russell's ideas. "I looked at it," says Martin, "and I said 'Well, this is easy — the origin of life is basically solved.'"

Martin had one problem. He thought that, if you want to say anything about how life came to be, then modern organisms must harbour the descendent of the first biochemical reaction, and in modern organisms the key to success is reducing carbon dioxide, not iron. "Is it reasonable to assume that what was possible for the very first cell has since been forgotten, and nobody is left who can do it?"

He steered Russell away from pursuing a hypothetical, forgotten reaction and towards what's called the Wood–Ljungdahl pathway, also known as the acetyl coenzyme A (CoA) pathway after the energy-rich molecule that forms its end product in modern acetogens and methanogens. Martin favours this explanation because it is the only one of the five known biochemical pathways for fixing carbon that turns a net profit in ATP, the universal chemical fuel of life. In this scenario, relatively cool spots within the vent favour the formation of acetate, an intermediate in the pathway, whereas in hotter spots, the reaction goes all the way to methane — possibly creating the divide between acetogens and methanogens, and between the groups that eventually became the Bacteria and Archaea.

UNIV. WASHINGTON

NOAA

The carbonate structures at the Lost City hydrothermal field in the Atlantic Ocean have a delicate structure when first formed (inset).

Another advantage of the Wood–Ljungdahl pathway is that its products and intermediates plug into other metabolic pathways. Some of those make amino acids and nucleic acids, through reactions with ammonia — which Russell is including in his simulated vent water — and phosphate, which is present in his simulated ocean. When nucleic acids and amino acids first formed on Earth, their initial job, say Russell and Martin, would have been to catalyse reactions involving carbon dioxide and hydrogen[5].

In a metabolism-first world, before genetic molecules had a decisive role in evolution, selection would have favoured not the best replicator, but the reaction that sucked in fuel the quickest, denying energy to other chemical processes. And what would become the network of cellular chemistry could have grown by adding links that increased energy consumption. Even though there were no organisms, a set of reactions would store information in its components and processes. And that network could be said to replicate by drawing in more molecules and more energy into itself, a process sometimes called chemical evolution.

What's needed at this point is some evidence that will help to distinguish between the various hypotheses, says Robert Shapiro, a chemist at New York University. "Basically, one has to provide a setup and demonstrate self-sustaining and evolving chemical cycles." Thanks to NASA's astrobiology programme, which has provided increased visibility to origin-of-life research, Russell is now in a position to attempt that as a researcher at the agency's JPL.

Giant chemical garden

Russell already has a natural model to copy. In 2000, the type of vent he had predicted — alkaline and not too hot — was discovered[6]. The Lost City hydrothermal field lies in the Atlantic Ocean, 15 kilometres from the mid-ocean ridge. The vents pump out water that has been drawn down into cracks in the ocean floor and heated to about 200 °C. As the fluids return to the cold ocean, calcium carbonate precipitates out of the water, building 60-metre towers like gargantuan chemical gardens. And last year, oceanographers reported finding abiotically produced organic compounds, including methane, in the water flowing from the vent[7].

Russell thinks that his reactor might produce amino acids and peptides, but first he wants to test whether sulphide minerals standing in for the ocean crust will dissolve in the alkaline hydrothermal solution. That would be the initial step toward the formation of the iron-sulphide chimneys that he believes provided a home for life's first metabolizing system.

It's a high-risk strategy, says Hazen, because the early Earth would have had many sources of organic molecules, and many places where they could have become concentrated. He likens Russell's approach of testing just one detailed possibility to starting a game of twenty questions by asking "is it Winston Churchill?" rather than "is it a man?". It is glorious if you're right, but it doesn't narrow things down much if you're wrong. "Mike Russell has a hunch, and there's nothing wrong with that," he says. "Maybe it'll be like winning the lotto and his hunch will be right, or maybe it wasn't Winston Churchill after all, and that leaves the other 6 billion people on Earth to go through."

A competing possibility is that one of the other four carbon-fixing pathways is a better candidate for the primordial biochemical reaction. Metabolism in acetogens and methanogens uses specialized enzymes, comments Eric Smith, a theoretical physicist and origin-of-life researcher at the Santa Fe Institute in New Mexico, and it is much more sensitive than other biological carbon-fixation pathways to changes in the isotope of carbon used. "That says that you're using a very carefully refined enzymatic reaction to do something difficult," he says. Instead, he and his colleagues believe that the initial biochemical pathway was the reductive citric-acid cycle. This pathway reverses the normal respiratory cycle seen in every oxygen-using cell, and some microbes still use it to fix carbon. It builds acetate, which has two carbons, up into citrate, which has six, and then breaks the citrate into acetate and oxaloacetate. This cycling can provide positive feedback that functions like reproduction, drawing more and more carbon into itself — an advantage that the one-way Wood–Ljungdahl pathway lacks.

Indoor hot springs

Smith thinks that the metabolism-first viewpoint is making headway, especially with the focus on hydrothermal vents. "The disagreements are really small compared with the basic orientation that we have in common," he says. He also thinks that the next move needs to be experimental; his colleagues are working to reproduce the reactions in the citric-acid cycle in vent-like laboratory conditions. Once someone gets their preferred pathway to work in the lab, "everyone can quiet down and say 'this is something we can agree on.'"

Others, however, think that the whole metabolism-first theory is misconceived. The idea has two great flaws, says Steven Benner of the Foundation for Applied Molecular Evolution in Gainesville, Florida. In any system of organic reactions, some will make products other than those that might lead to life. "Organic chemistry has an intrinsic propensity to make tar," he says. "That tends to divert molecules out of any cycle." And any such set of reactions is unlikely to evolve greater complexity in a Darwinian fashion; instead it will just dissipate energy. What's more, he argues that acetyl CoA would not survive long at the temperature and alkalinity of Russell and Martin's favoured vent.

T. DAGAN

William Martin thinks that origin-of life research is 'unfalsifiable conjecture'.

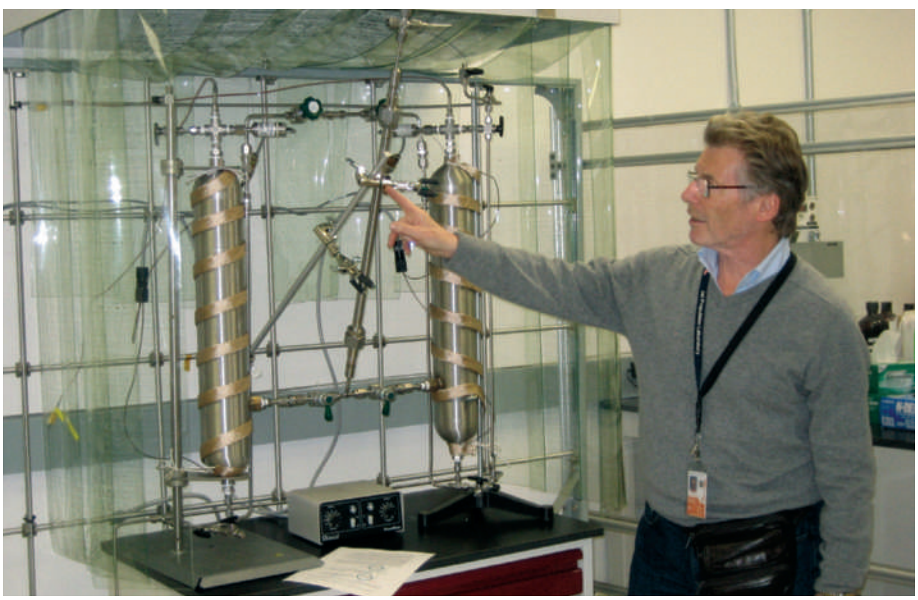
Benner aligns himself with the other main school of thought, which says that life started with a gene-like molecule that could catalyse its own replication. He has done many studies on how RNA could have first been made, although he also acknowledges the formidable difficulty of creating an RNA molecule large enough to behave like both a gene and an enzyme in abiotic conditions. The RNA camp did get a boost last week with a study suggesting it would be chemically easier to produce this molecule than was previously believed[8].

In the end, there is no agreement on how to solve the problem of life's origin. Martin thinks that research on the topic is "unfalsifiable conjecture" — the best we can hope for is a convincing story. "Even if you were to make a reactor in the laboratory, and put hydrogen and carbon dioxide and nitrogen in one end, and out pops something like *Escherichia coli* at the other end, you still couldn't prove that we and our ancestors arose that way. You'd just have a narrative that made it more plausible."

Russell thinks that if his reactor produces just about anything from tar to *E. coli* it will have been worthwhile — he quotes Thomas Edison's remark that he did not build 1,000 failed prototype light bulbs; rather he discovered 1,000 ways that the light bulb wouldn't work (see page 312 for one that did). Similarly, Russell hopes to help move the field forwards by sorting out what was possible and what was improbable around those warm vents, some 4 billion years ago. That's the most he can do, he says. "It's just a step at a time." ■

John Whitfield is a freelance science writer based in London and author of *In the Beat of a Heart: Life, Energy, and the Unity of Nature*.

NASA



Mike Russell is attempting to recreate the origins of life in his lab.

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See News Feature, page 312.

Infrared scan reveals colourful past of the Parthenon

BRITISH MUSEUM

Conservation scientists at the British Museum in London have found the first evidence of coloured pigments on sculptures from the Acropolis in Athens. The figures formed part of the decoration on the Parthenon temple, and were taken from Greece by Lord Elgin in the early 1800s.

Ancient Greeks and Romans normally painted their sculptures, and traces of the pigments tend to survive on the objects to this day. But no hints of paint had been found on the Parthenon sculptures despite detailed studies — including an analysis in the 1830s by English physicist Michael Faraday.

The researchers revealed the presence of a pigment known as Egyptian blue on the belt of the goddess Iris (pictured). They used a portable detector to beam red light onto the surface and capture the infrared light emitted by the luminescent pigment particles (inset).

For a longer version of this story, see http://tinyurl.com/m24ylw

Editor to quit over hoax open-access paper

The editor-in-chief of an open-access journal is to resign after claiming that its publisher, Bentham Science Publishing, accepted a hoax article without his knowledge.

Bambang Parmanto, an information scientist at the University of Pittsburgh, Pennsylvania, and editor-in-chief of *The Open Information Science Journal*, said he had not seen the computer-generated manuscript, accepted by Bentham on 3 June.

The fake paper was submitted by Philip Davis, a graduate student in communication sciences at Cornell University in Ithaca, New York, and Kent Anderson, an executive director at *The New England Journal of Medicine*. Davis says he wanted to test if the publisher would "accept a completely nonsensical manuscript if the authors were willing to pay". He retracted the paper after being notified that it had been accepted, and that he should pay US$800 to Bentham's subscription department.

Mahmood Alam, director of publications at Bentham Science Publishing, told *Nature* that "submission of fake manuscripts is a totally unethical activity and must be condemned", adding that "a rigorous peer-review process takes place for all articles that are submitted to us for publication".

For a longer version of this story, see http://tinyurl.com/lrx6m6

FDA gains the power to regulate tobacco products

L. JACK/CONTOUR

Obama in his youth.

The US Food and Drug Administration (FDA) will get the power to regulate tobacco for the first time in its 103-year history under legislation passed by Congress last week. President Barack Obama, himself a sometime smoker (see picture), has promised to sign the bill into law.

Passed by substantial majorities in both the House and the Senate, the Family Smoking Prevention and Tobacco Control Act requires that new tobacco products win pre-market approval from the FDA.

The bill bars the FDA from banning nicotine, but it gives the agency standard-setting authority that could lower nicotine levels in tobacco products. It constrains advertising, requires large warning labels on packaging and levies user fees paid by the industry to help finance FDA regulation. The fees will total $235 million in 2010.

Japan's lunar orbiter ends mission with crash landing

The Japanese space agency's KAGUYA lunar orbiter ended its 21-month mission with a planned crash into the Moon on 10 June.

Formally known as SELENE (Selenological and Engineering Explorer), the mission was launched in September 2007. The orbiter gathered detailed geological information about the Moon, mapping its gravitational field and taking high-definition video images.

As *Nature* went to press, NASA's Lunar Reconnaissance Orbiter was scheduled to launch on 18 June. Together with India's Chandrayaan-1 spacecraft, which launched in October 2008, it will attempt to spot water ice at the Moon's poles (see *Nature* 459, 758–759; 2009).

Artefact raiders charged after undercover operation

A two-year federal investigation of widespread Native American grave robbing and artefact theft in the Four Corners region of the United States culminated in charges against 24 people last week.

The arrested individuals, from Utah, Colorado and New Mexico, were arraigned in the federal court on 10 and 11 June for multiple felony indictments for trade in 256 artefacts with a total value of more than US$335,000. Purloined items included pottery, baskets, sandals and necklaces taken from excavations on federal lands.

An undercover agent purchased the looted artefacts from, among others, a high-school teacher and an honoured archaeological-tourism promoter. One man — James Redd, a physician from Blanding, Utah — committed suicide on 11 June, authorities say, the day after he and his wife were charged with artefact theft.

US revives FutureGen 'clean' coal plant

The US Department of Energy (DOE) has announced plans to revive FutureGen, a commercial-scale coal-fired power plant in Mattoon, Illinois, that would capture carbon dioxide emissions and sequester them underground.

Under George W. Bush's administration, the DOE pulled the plug on the flagship 'clean' coal technology programme in January 2008, citing a dispute with industry partners over the US$1.8-billion price tag (see *Nature* 451, 612–613; 2008).

Energy secretary Steven Chu revived FutureGen on 12 June, announcing an agreement to restart the negotiations, update the cost estimate and begin preliminary design activities. The DOE and FutureGen industry partners hope to make a final decision on whether to go ahead with the project early in 2010.

Corrections

The News Feature 'Sucking it up' (*Nature* **458,** 1094–1097; 2009) incorrectly stated that Global Thermostat is waiting for venture-capital funding to build a prototype for the capture of CO_2 from the air. It already has sufficient funding in place.

The News story 'Funding struggle for mercury monitoring' (*Nature* **459,** 620–621; 2009) erroneously located Changbai Mountain in Taiwan. It is in northeastern China.

In the News Feature 'Nascence man' (*Nature* **459,** 316–319; 2009), the picture of the Lost City on page 318 should have been credited to D. S. Kelley.