In search of a second evolutionary experiment

Don Cowan & Monica Grady

The UK Astrobiology Forum defines astrobiology as the 'formation, evolution and adaptation of life in a planetary and stellar context'. Don Cowan and Monica Grady describe current thinking on extra-terrestrial life.

Exobiology (life on other planets, now generally termed 'astrobiology') is a subject of intense interest and speculation, particularly in the public domain, with some of the most fundamental questions of science – how did life evolve, what other forms might life take and 'are we alone'? Such questions have long stimulated scientific minds, not to mention those of science-fiction writers, the media and the film industry. But despite our preoccupation with the subject, we still have little understanding of the answers. For example, the molecular and energetic processes linking prebiotic chemicals and the first simple replicating cell are subject to a number of hypotheses, but little experimental verification. Such studies are limited by two fundamental problems: we have access to only a single evolutionary experiment, i.e. our own, and the starting conditions were fixed $4{\cdot}56 \times 10^9$ years ago, leaving little if any physical evidence of the process. An ability to access and investigate a second evolutionary experiment, as we might find on a neighbouring planet, would be a major breakthrough in our understanding of the development of molecular processes and structures in our own evolution. Are there, for example, thermodynamic imperatives in the molecular basis of living systems, and will alternative evolutionary pathways have employed similar structures and processes in evolving key systems such as energy capture, compartmentalization and information storage?

Mars, Viking and meteorites

Following the unsuccessful attempts in the late 1970s by the Viking missions to identify life on the Martian surface, interest in astrobiology waned, at least amongst the scientific community. However, analyses of Martian meteorites have added impetus to the resurgence of interest in astrobiology. A collection of 17 now exists, many of which have been collected from glacial surfaces in Antarctica (Fig. 1). The Martian origin of these meteorites has been deduced partly from their young crystallization ages (implying planetary, rather than asteroidal origin) and also from the presence of gas inside that has the same elemental and isotopic composition as Mars' atmosphere (as measured by the Viking landers in 1976). The observation that at least one of the Martian meteorites, EETA79001, contained indigenous, i.e. Martian, organic material associated with carbonate minerals sparked discussion on the possibility of the meteorites containing evidence for extraterrestrial life.

The debate was reactivated in 1996 with the announcement that possible evidence of past life had been discovered in the Martian meteorite ALH 84001. A team of scientists, led by David McKay of NASA's Johnson Space Centre in Houston, described nanometre-sized features within carbonate patches in ALH 84001 and claimed to have found evidence for a primitive 'fossilized Martian biota'. Identification of the features remains controversial, since much of the evidence is circumstantial and relies on the coincidence between a number of otherwise unrelated characteristics of the meteorite (the occurrence of carbonates, organic compounds and magnetite associated with the carbonates). The most compelling 'observation', though not the most compelling scientific evidence, was NASA's electron microscopic image of a putative microfossil (Fig. 2). The features, however, are smaller by about two orders of magnitude than most common micro-organisms known on Earth. Subsequent investigation has revealed that nanobacteria might be more prevalent than previously anticipated and nanometre-sized organisms have been isolated from terrestrial sedimentary rocks. Even so, many doubts still arise as to the validity of interpreting morphological data as fossil nanobacteria, especially given that the environment and mode of formation of the host of the features in ALH 84001, the carbonates, are not fully understood. Current thinking is that the carbonates were produced at the surface of Mars

FAR LEFT:
Fig. 1. Antarctic glaciers – collection points for meteorites.
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LEFT:
Fig. 2. Putative 'microfossils' in martian meteorites as revealed by electron microscopy.
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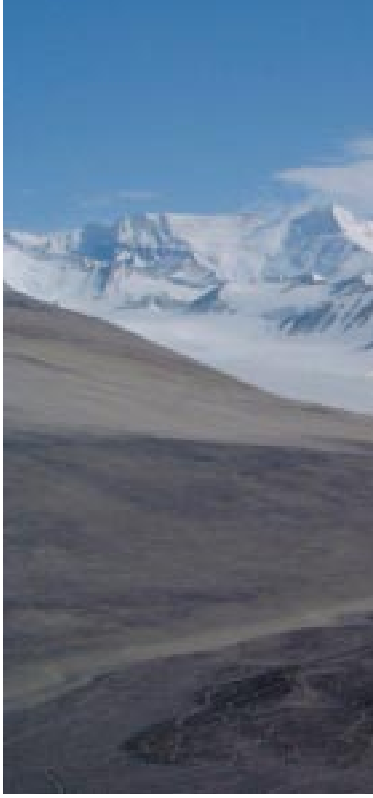
in a region of restricted water flow, such as an evaporating pool of brine. This hypothesis satisfactorily accounts for the chemical and isotopic characteristics of the carbonates and is also a mechanism compatible with an environment in which micro-organisms might survive.

The debate over interpretation of the features continues, with definitive clarification probably dependent on recovery of new Martian meteorite samples, or the acquisition of appropriate material directly from a planetary source. Fortunately, there is an active programme of meteorite collection in Antarctic and other deserts, although a very small proportion of meteorites collected are of Martian origin. NASA 'sample return' missions to Mars and elsewhere are scheduled for 2008 and beyond. So, with this material available, what technologies could be best applied in the search for evidence of life? The answers differ, depending on whether the target is evidence of fossil or extant life. Numerous chemical signatures are accepted as fossil biomarkers, including polyaromatic hydrocarbons, hopanes, terpenoids, etc. Here we focus on methods applicable to the detection of extant life or life processes, such as might be applied to new meteorite samples or incorporated in a planetary lander package. One major caveat must be borne in mind when considering measurement of organic materials on planetary surfaces: to date, no organics have yet been detected, let alone have isotopic, chiral or molecular systematics been determined.

● Panspermia?

Several groups of meteorites contain abundant carbon, up to several weight percent in the types classified as carbonaceous chondrites, in which it mainly occurs as organic material. There is currently no general belief that this organic matter is biogenic in origin – it is understood to be built up from simple carbon-bearing molecules, first in the interstellar medium, subsequently through processing on asteroidal parents. Comets are also rich in organic molecules and bombardment by comets and asteroids is a favoured possible mechanism by which the Earth was seeded with the starting materials necessary for life to arise. The addition to the Earth of a late-stage veneer of organic material by bombardment is very different from the transfer of biological material within the Solar System via cometary or asteroidal transport. Thus far, there is no evidence for viable biological material in meteorites, but the possibilities of its retention in meteoritic samples cannot be completely discounted. The hypothesis, promoted under the popular title of 'panspermia', has attracted considerable public and scientific notoriety, not least because of some of the more dramatic predictions of its consequences. If the three phases of 'panspermic' transfer (ejection, interplanetary transport and collision) are considered, the survival of living micro-organisms is at least hypothetically possible. Ejecta from major asteroid impacts are exposed to temperatures of a few thousand degrees for periods of only seconds before being exposed to the near-absolute-zero temperatures of space. The low thermal conductivity of most rock types would effectively protect all but the outer layer of the ejected body from significant heating. Survival of biological material during interplanetary (or interstellar) transport is an issue of molecular (in)stability, particularly with respect to the deleterious effects of chemical degradation and intrinsic and cosmic radiation damage. Biological material is also exposed to extremely low temperatures and total desiccation, over very long periods. While molecular stability over such extended periods might seem unlikely, recent reports of viable bacterial spores being recovered from ancient salt deposits and 1·25 million-year-old Antarctic ice cores suggest a lower (but not an upper) limit of microbial survival.

Finally, before a meteorite arrives at the Earth's surface, it must undergo the energetic processes of entry through the atmospheric layers and impact. Entry heating, caused by friction, melts the outermost layer of the meteoroid; the molten rock is carried away, back along the entry trajectory. Continued passage through the atmosphere melts successive outer surfaces, but the rapid removal of melt from the meteoroid prevents the inner regions from becoming hot. Eventually, friction decelerates the meteoroid such that its speed is no longer sufficient to cause melting and the surface cools. Thus meteorites are cool when they land and any organic material in the interior will be intact and unaltered by entry heating. Although there is no evidence of biogenic material in meteorites, recognition of meteorites from the Moon and Mars has re-opened the possibility of interplanetary cross-contamination by material ejected from planetary surfaces by impact.



RIGHT:
Fig. 3. The 'Dry Valleys' of Antarctica.
COURTESY D. COWAN

What is 'life'?

Any analytical method designed to identify 'life', whether applied to meteorites or Martian 'soil' samples, must take account of the possible differences in the molecular answers to fundamental questions in an alternative evolution. For example, the selection of ATP as a biomarker, appropriate on Earth because of the central function of this molecule as an energy carrier, ignores the possibility that an alternative nucleotide, a different phosphate derivative, or a different molecular structure altogether may act as a core energy transducer in an alternative evolution. Exactly how 'life' should be defined has been a matter of scientific and philosophical debate over a period of centuries. Definitions such as 'an energy-consuming, self-replicating system' suffer from the limitation that they can be successfully applied to obviously non-biological entities, such as fire!

One of the apparently fundamental properties of biological systems on Earth is symmetry. At least at the level of higher organisms, symmetry in at least one plane seems to be an evolutionary theme. While less obvious at the microbial level, structural symmetry is still evident, as seen in bacterial coccoid, bacilloid and spirilloid cellular morphologies. The impact of the ALH 84001 'microfossil' on the public and scientific consciousness may have been due largely to our instinctive association of life with symmetry. However, any assay system designed to detect symmetry in the context of 'life' must be capable of excluding those non-biological forms, such as crystals, which exhibit a symmetrical form.

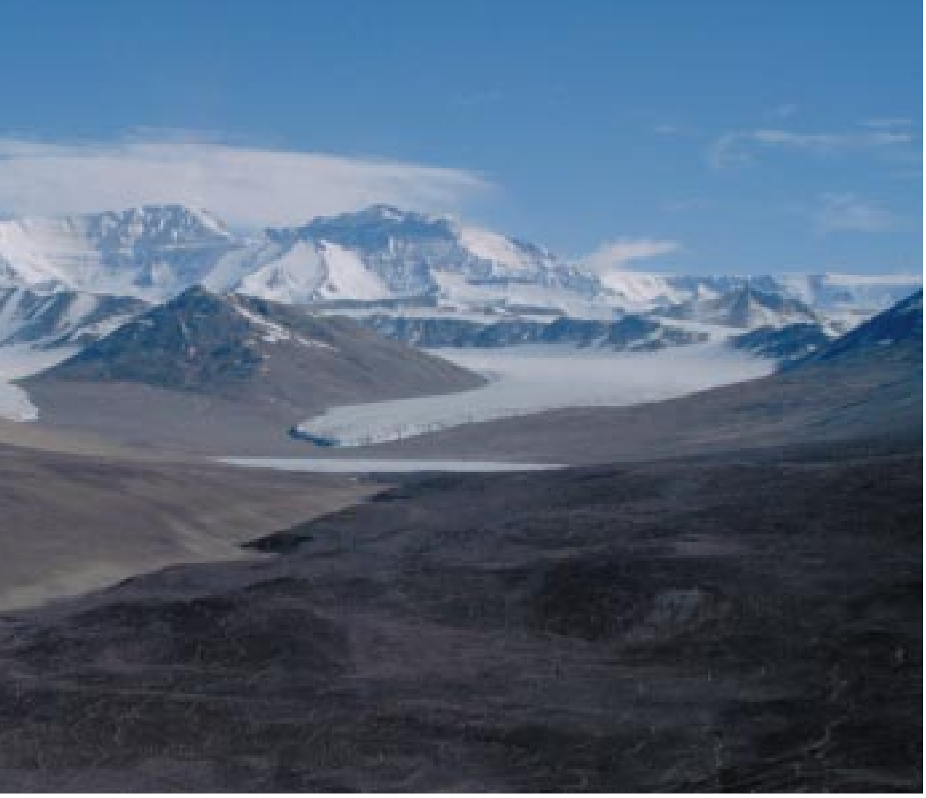
Conversely, molecular asymmetry has been proposed as a useful biomarker. The selective use of chiral building blocks (i.e. D-sugars and L-amino acids) in biological systems potentially provides a mechanism for either remote or *in situ* identification of a putative biology. As always, such analyses incorporate an assumption of universality, although there are good theoretical grounds for suggesting that biological systems will tend to employ one, but not both, chiral forms of the monomeric precursors of important polymers. For example, a catalytic system capable of using both chiral forms of a molecule must either possess low specificity or must be duplicated for each form, both alternatives being of low global thermodynamic efficiency.

Biomarkers

The selection of any molecular biomarker incorporates the assumptions discussed above. However, this apart, a huge range of biomarker options exist. Table 1 shows some of the 'appropriate' targets and assay systems. Each has strengths and weaknesses, depending on the site of assay. For example, for remote planetary investigations (i.e. unmanned landers) miniaturization, sample handling and power requirements are major constraints for the development of spectroscopic technologies. Similar constraints apply to assays requiring liquid handling (such as enzyme or polynucleotide assays). However, leading-edge developments in many technological areas (such as polymer imprint detection systems) may dramatically change the feasibility of such analyses. Many of these limitations are automatically removed in the event of 'sample return' and ultra-high stringency handling facilities designed to avoid bi-directional contamination are in the planning stages both in the US and in Europe.

Table 1. Biomarkers, targets and assay systems

Biomarker	Target	Assay system	Advantages	Limitations
Metabolic activity	CO_2 release from glucose	Radiolabelling	Facile experiment, very high sensitivity	Non-biological catalysis Heterotrophic metabolism
	CO_2 fixation	Radiolabelling	Suggests autotrophic metabolism	Non-biological processes
Catalytic activity	Enzyme function	Various	Multi-enzyme array assays are feasible	High specificity of many enzymes
Biochemical intermediate	ATP	Bioluminescence	Universality?	Liquid handling required
Biological polymers	Nucleic acids	Spectroscopic	High sensitivity	High background
		Catalytic (e.g. PCR)	A positive result would be unequivocal	Liquid handling, extremely specific, very subject to contamination
	Lipid	Spectroscopic	Diagnostic signals for some lipid derivatives (e.g. using Raman spectroscopy)	Easily applicable only to aromatic molecules
	Protein	Spectroscopic	Diagnostic signals at many wavelengths	



● Isotope techniques

Possibly one of the most diagnostic of techniques for the identification of biological processes is the detection of isotopic fractionation between components within a system. Abiotic systems, where fractionations are based on well understood chemical and physical reactions, tend towards equilibrium. In contrast, biological systems tend to be out of equilibrium. The carbon cycle on Earth encompasses components within the atmosphere (CO_2, CO), biosphere (organic compounds), hydrosphere (carbonate and bicarbonate anions) and lithosphere (carbonate and calcium-silicate rocks). Measurement of the isotopic composition of carbon from different components has enabled modelling of the extent of biomass turnover through sediment recycling during tectonic processes. Measurement of the end-member compositions of analogous materials on Mars is intended to enable the construction of an equivalent carbon cycle; detection of biological signatures within such a framework is then entirely possible.

● Astrobiology today

In anticipation of the arrival of samples from the Martian or Europan sub-surface, what are the world's astrobiologists doing at present? Contrary to the opinion that '*astrobiology is the one subject where scientists have nothing to work on*', there are numerous avenues for research and technological development. These include (to name but a few) the modelling of Earth's early molecular evolutionary pathway, the development of new spectroscopic technologies for identification of biological molecules and the study of organisms inhabiting the most extreme biotopes on this planet as a means of understanding the range of environments which might be targeted on other planets. With respect to the latter, the world's deep-sea hydrothermal vents have yielded hyperthermophilic chemoautotrophs which may best reflect the earliest forms of life on this planet. Similarly, the deep subterranean biosphere and the cold deserts and ice-covered lakes of Antarctica (Fig. 3) are the best available analogues of possible microbiological habitats on Mars and Europa. Such sites are vital in the development and testing of chemistries and technologies which will eventually be applied to the discovery of life on other planets.

There is a resurgence of interest in the many facets of astrobiology in the UK. The recently established UK Astrobiology Network (http://ast.star.rl.ac.uk/astrobiology/panel/) has a remit to promote collaborative astrobiology research in the UK and has been assured by the UK Research Councils that research grant applications in this field will receive a fair hearing. There are now active centres of astrobiological research in the Universities of Bradford, Portsmouth, Kent, the Open University, University College London, the British Antarctic Survey and the Natural History Museum.

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