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Planetary environments and the conditions of life

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Life arose on Earth within a billion years (1 Ga) after planetary accretion and core formation. The geological record, which begins 3.8 Ga BP, indicates environmental conditions much like today's, except for the absence of oxygen. By 3.5 Ga BP microbial ecosystems were already colonizing shallow marine hydrothermal environments along shorelines of volcanic islands. Although similar environments could have existed more than 3.8 Ga BP, they may not have been the spawning grounds of life. Geophysical models of the first 600 Ma of Earth history following accretion and core formation point to a period of great environmental disequilibrium. In such an environment the passage of energy from Earth's interior and from the Sun through gas–liquid–solid domains and their boundaries with each other generated a dynamically interacting, complex hierarchy of self-organized structures, ranging from bubbles at the sea–air interface to tectonic plates. Nested within this hierarchy were the precursors of living systems. The ability of a planet to produce such a hierarchy is speculated to be a prerequisite for the origin and sustenance of life. Application of this criterion to Mars, which apparently experienced no plate tectonism, argues against the origin of martian life. Because only further geological and biogeochemical exploration of the planet can place these qualitative speculations on firm ground, the search for evidence of extinct life on Mars continues to be of highest scientific priority.

1. INTRODUCTION

Present understanding of biology and the natural history of life on Earth leads to the conclusion that living systems originate on planets and that biological evolution is subject to the vicissitudes of planetary and Solar System evolution. What planetary properties, and how planetary processes, made possible the conditions conducive to the origin of life may be seen in broad outline, but detailed understanding of the geochemical circumstances and molecular mechanisms is lacking. My purpose here is neither to advance any particular scenario for the origin of life nor to put a quantitative face on the problem, but rather, first, to place it squarely in the context of planetary evolution, to identify some bounds on the present state of knowledge concerning the process; then, to draw attention to some qualitative considerations concerning the relation between biological and planetary evolution on Earth, and finally to consider the prospects for past and present life on Mars. In the following discussion, the term 'prebiotic' will be used to signify the time before the origin of life, as distinct from the term 'probiotic', which refers to events and processes involved directly in the development of biological from chemical systems.

2. THE ANCIENT GEOBIOLOGICAL SETTING

The 3.8 Ga old metasediments of Isua, Greenland, provide the earliest record of Earth's environment from which an earlier geologic history can be inferred. They show the occurrence of sediments rich in volcanogenic debris laid in water, carbonate minerals and reduced graphitic carbon, and basalts with melting temperatures approaching 1600 °C. These in turn signify surface temperatures below 100 °C, extensive bodies of liquid water; carbon dioxide, water vapour and presumably nitrogen in the atmosphere; higher heat flow and more active volcanism than at present; and the beginnings of continental growth, weathering, a hydrologic cycle and a carbon geochemical cycle, perhaps driven by a form of tectonism ancestral to modern plate tectonics (Ernst 1983). The record is mute regarding additional compositional details of the atmosphere and sea except that both were essentially anoxic, and that the composition of seawater was influenced by more extensive exchange with the crust and mantle than today. For the most part, with the exclusion of atmospheric oxygen and oxidized atmospheric species derived from it, the record is consistent with the existence 3.8 Ga BP of a habitable environment resembling some that occur today.

The 3.3–3.5 Ga old sediments from South Africa and Western Australia contain the earliest compelling evidence of life in the form of stromatolites (Walter 1983) and microfossils (Schopf & Walter 1983). Stromatolites are 'organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of the growth and metabolic activity of microorganisms' (Walter 1983). Analogies between ancient and present-day stromatolitic microbial communities suggest that the early ecosystems included both heterotrophic organisms (those that used organic matter as source of cellular carbon) and autotrophic organisms (those that used carbon dioxide as carbon source), and that some of the latter were phototactic and possibly photoautotrophic (capable of using sunlight directly as their energy source). Apparently, sunlight and the free energy of organic and inorganic compounds were used as energy sources by these organisms.

Sedimentological studies done by Byerly *et al.* (1986) and Lowe *et al.* (personal communication) indicate that stromatolites grew in narrow, shallow water zones along shorelines of volcanic islands where they were subject to periodic agitation by waves or currents and occasional rapid burial by lava flows. Localization of stromatolitic or microbial mat growth may have been influenced by hot springs or hypersaline conditions. Black cherts, some of them microfossiliferous, were apparently deposited during relatively quiescent periods between cycles of volcanic eruptions. The overall impression is of a shallow, marine, hydrothermal environment dominated by episodic island volcanism. It is highly probable that similar environments existed much earlier than even 3.8 Ga ago. Hydrothermal and volcanic environments have been suggested as the loci for the origin of life by a number of workers (e.g. Fox & Dose 1972; Sylvester-Bradley 1976; Corliss *et al.* 1981). It is especially noteworthy that the contemporary microorganisms with the most ancient lineages based on molecular phylogenies are anaerobic thermophilic sulphur-metabolizing archaebacteria. These organisms were isolated from hot springs and hydrothermal vents where they thrive at temperatures up to 105 °C (Achenbach-Richter *et al.* 1987). Whether life actually arose in such environments remains uncertain.

Indeed, aside from the appeal of a uniformitarian perspective there is no compelling reason why the environment in which life arose had to resemble that recorded in the Isua rocks; it could have been very different. In the latter case, the lack of a useful record or the inability to extrapolate far enough back in time from the existing record means that first principles must be applied to the development of theoretical models for the early geophysical development of the planet. In principle, the theoretical approach should yield a model which, when extrapolated forward in time, converges with that inferred by extrapolation backward from the geological record.

3. The geophysical model

The recent decades of planetary science have yielded a modern model for Earth's early geophysical history. According to this model, the planet was essentially fully formed by impact accretion within about 100 million years of the formation of the Solar System. By the time Earth had grown to 10% of its present size, the deposition and burial at depth of kinetic energy from impacting planetesimals would have raised temperatures high enough to melt free iron and permit subsolidus convection of silicates. Thus accretion and differentiation into core and mantle were essentially contemporaneous processes, and both structures were convecting vigorously to dissipate the enormous amount of energy associated with these early phenomena (see, for example, Stevenson 1983). Outgassing, possibly impact-induced (Jakosky & Ahrens 1979), occurred early, and was likely to have produced a massive steam atmosphere and a global magma ocean (Walker *et al.* 1978; Matsui & Abe 1986). Climate model calculations by Zahnle *et al.* (1988) substantiate the surface temperature estimated at about 1200 °C by Matsui & Abe (1987) for a 100 bar† steam atmosphere. The survival of any organic matter or the formation of bodies of liquid water during this early period would appear to be exceedingly unlikely.

As the accretion rate and concomitant energy deposition decreased sharply, mantle convection slowed, and a rapid transient cooling ensued. Accordingly, the following scenario of overlapping events probably occurred between about 4.4–3.8 Ga ago (see, for example Ernst 1983). The putative magma ocean began to crystallize; lighter crustal material that floated to the surface continued to be overturned and rehomogenized into the mantle; the steamy atmosphere condensed to form liquid water; thin solid lithospheric plates developed which became covered with a veneer of crustal material, which in turn was overlain by oceans; and deposition of immature sediments began. This period of time would also have been punctuated with occasional impacts by asteroidal or cometary objects, each causing transient perturbations of the environmental conditions on regional to global scales depending on the size of the projectile. Possibly life would not have arisen before the last major impact that caused large increases in global surface temperature.

Over this period of about 600 Ga the structure of the planet became increasingly complex. Accretion afforded the core and mantle; the atmosphere outgassed and an ocean formed; the mantle segregated into mesosphere, aesthenosphere and lithosphere; the crust was sorted into continental and oceanic realms; and sediments of both clastic and chemical types developed. The emergence of this complexity was largely driven by internal energy, that is from the thermal régime established early on, predominantly by the deposition of accretionary energy within the planet, then by the decay of radionuclides. Within the large geophysical domains at Earth's surface, the onset of plate tectonism, weathering, erosion and sedimentation resulted in further diversification into regional, local and micro environments, among which life arose.

Influences other than the internal restructuring of the planet were also at work. As the input of accretionary energy fell off rapidly, solar radiation became the dominant source of energy. Then as now the energy received from the Sun would have been about 10000 times the thermal energy delivered from the interior. Stellar evolution theory asserts, however, that the Sun was only 70 to 80% as luminous 4 billion years ago as it is today. To prevent the oceans from

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† 1 bar = 10^5 Pa.

freezing, therefore, the atmosphere must have been better able to retain the incoming solar radiation. Recent theoretical climate models (see, for example, Kasting 1987) suggest that the early atmosphere could have had from 100 times the present atmospheric level (0.003 bar) to as much as 10–20 bars of carbon dioxide, thus giving rise to greenhouse effects which would have kept the surface temperature in a range from close to the present value of 15 °C to near the boiling point of water.

A massive carbon dioxide atmosphere in the first several hundred million years of Earth history has been hypothesized to result from the smaller amount if not total absence of continental land mass (Walker 1986). Today, carbon dioxide is removed primarily by silicate weathering on continents. Early on, removal of the carbon dioxide component of a massive early atmosphere would have been restricted to the slower process of submarine weathering. According to Walker (1986), as much as one sixth of the Earth's present reservoir of carbonate could have resided in the ocean–atmosphere system. Clearly the pH of the sea and its chemistry would have been strongly influenced. Whether life could have arisen in such an atmospheric environment is as unknown as whether this massive atmosphere actually existed and dissipated over time. This hypothesis serves to show how chemical models of the prebiotic environment, the context within which molecular models for the origin of life are developed (see §4), may be subject to change as new developments in planetological and climatological theory emerge.

Clearly planetary evolutionary processes occurring on global or regional scales provided the geophysical driving forces for setting, maintaining and altering the physical and chemical conditions of the planet's various environments wherein probiotic evolution might have been realized. When or where life originated within this gross model of geophysical evolution remains unknown. Probiotic evolution, which could have occurred in ubiquitous or rare environments, or both, comprised the chain of reactions among inorganic and organic molecular systems which led ultimately to living systems. The initial stages of probiotic evolution are usually, but not exclusively or necessarily, associated with the synthesis and transformations of organic compounds.

4. THE PROBIOTIC EVOLUTION MODEL

Sources of free energy provided the driving force to synthesize and assemble from the materials of the prebiotic environment the structures with functions that are attributable to primitive life. Among the essential functions were the abilities to: (*a*) capture, store and use energy from the environment; (*b*) autocatalyse the synthesis of new structures capable of function; (*c*) maintain a micro-environment distinct from that of the surroundings; (*d*) self-replicate. Functions (*a*) and (*b*) together make up a primitive metabolic system, (*d*) a genetic system and (*c*) the compartment within which the metabolic and genetic systems are coupled and preserved from dissipation in the environment.

Although it is not possible to specify a universally accepted sequence of transformations constituting the path of probiotic evolutionary development, it is usually assumed to have occurred in stages beginning with simplicity and leading to complexity. According to one conventional theory, first came simple monomers (e.g. amino acids, nucleotides) relatively dispersed and associated with many inorganic complexes. From the monomers were formed oligomers of higher molecular mass and polymers (e.g. oligonucleotides and peptides) with rudimentary catalytic properties. Next the oligomers and polymers, along with a limited number of organic molecules and inorganic complexes, were enclosed within a primitive membrane (e.g. lipid bilayer), which limited matter and energy exchange with the environment. Further development within the membrane-bound environment afforded many polymeric subunits (i.e. enzymes and nucleic acids) functioning cooperatively to achieve the functional complexities of metabolism and self-replication.

It has been within the context of this sequential development that a multitude of so-called prebiotic simulation experiments have been done. Considerable progress has been made in demonstrating how the synthesis of monomers and oligomers could have been accomplished under certain conditions (see below). Understanding how the metabolic and self-replication functions were acquired in the prebiotic environment poses the primary challenge.

Could gains in functional complexity have been realized and preserved without a genetic system for replication? When considered independent of the genetic apparatus, metabolism reduced to its essence may be regarded as a process by which the dissipation of free energy in a restricted environment results in synthesis and eventual degradation of a physical–chemical structure. Accordingly, a process that is capable of repeatedly synthesizing new structures is metabolic. In this view simple metabolic systems could exist without replication, and they are in essence self-organizing systems (see §5).

Possibly, the path of probiotic evolution did not involve only sequential steps. Instead, from the very beginning some chemical systems could have existed as metastable structures in what might be called 'protometabolic' systems. There is necessarily some vagueness here in what is meant by the term 'protometabolic' system. It could have been a network of chemical reactions constrained in space and time by concentration gradients or it could have been a microscopic or macroscopic structure produced as the result of such a network of reactions, or some combination of these two concepts. For example, one part of a system might have been able to take up energy from the Sun and act as a transducer of that energy so that another part of the system could synthesize an organic compound by reducing carbon dioxide (see, for example, Hartman 1984).

The lifetimes of these metastable systems would be limited by the dissipation of energy and materials fluxes which produced them (or their components) or by their intrinsic physical–chemical stability in the environment. The nature, distributions and abundances of such systems would likely have been subject to many fluctuations due to variations in the efficiencies of production and destruction mechanisms as regulated by local environmental conditions. The formation of coupled metastable systems might bear some distant analogy to the intimate associations between prokaryotic organisms that resulted in the symbiotic origin of chloroplasts (photosynthetic organelle) and mitochondria (oxygen respiring organelle) within eukaryotic (nucleated) organisms (Margulis 1981).

Indeed the 700 million years of Earth history following planetary accretion, the period of greatest environmental change, was the time during which sampling of a large number of variants in metastable structures could have occurred. Accordingly, the existence of a multiplicity of complex structures embodying aspects of metabolic function and possibly even distinctly different metabolic strategies, but not genetic function, should be considered a distinct possibility throughout this time.

Eventually, however, there would have been a need for coherent system evolution, and this seems possible only after a capability was acquired for self replication through a genetic apparatus. At this point probiotic evolution ended and biological evolution began. How the mechanism of self-replication arose on the primitive Earth stands as the central problem for the origin of life. Recently, however, the exciting discovery that ribonucleic acids can function as catalysts as well as carriers of genetic information suggests that metabolic and genetic functions could be embodied in a single type of molecule (Pace & Marsh 1985; Orgel 1986).

Returning now to the earliest stages in probiotic evolution, it is important to recognize that the very nature of probiotic structures is not known with certainty, their composition may have been inorganic, organic, or a combination thereof. Two factors have focused most research attention on organic structures. First, all contemporary life forms are virtually entirely composed of a restricted but universal set of organic compounds. Second, the Miller–Urey experiment and its many successors convincingly demonstrated the ease with which biochemically relevant organic compounds could have been synthesized in Earth's prebiotic atmosphere, which at the time of the experiment was perceived as a strongly reduced or methane-containing gas mixture. As a consequence, considerable weight was given to the view that the first organisms were organic and heterotrophic, that is, capable of utilizing organic compounds already in the environment as their source of energy and the elements for their biosynthesis. This viewpoint has resulted in considerable progress toward the synthesis of organic structures, e.g., peptides, microspheres, coacervates and nucleic acids, under putative prebiotic conditions.

In contrast, the geochemistry of Earth's oldest sediments from Greenland's Isua Formation, evolutionary models of the atmospheres of Venus and Mars as well as of Earth, and new ideas about the energetics of planetary accretion and the timing of core formation lend strength to the alternative view that carbon in Earth's early atmosphere occurred as carbon dioxide and that the prebiotic atmosphere was in a more or less neutral redox state much like today's absent oxygen and oxidizing species derived from it (see, for example, Chang *et al.* 1983). Experiments simulating the synthesis of organic compounds in such an atmosphere are much less fruitful in terms of both abundance and molecular diversity of products. In the synthesis context, the role of minerals becomes more important, leading along some lines of argument to support of the hypothesis of crystal genes and a mineralic rather than an organic chemical nature for the first living systems (Cairns-Smith 1982).

In addition, the fossil records of life embodied in the stromatolites and microfossils of the 3.5 billion year old sediments of Western Australia and South Africa, as well as in the molecular phylogeny of contemporary organisms, hold open the possibility that the universal organic ancestor of all such recorded life could have been either a heterotroph or an autotrophic organism. Whether this organic universal ancestor was also the archetypal organism remains an open question. If it was not, then the question concerning the organic or mineralic or mineral–organic makeup of the first life forms must also remain open. Thus, for biology, a gap in the evolutionary record exists comparable in magnitude to the gap in the planetary record. For biology, unlike the case for planets, there are no readily accessible examples of other systems from which insights into origins and constraints on origins can be drawn from comparative study, a point to which we shall return later. None the less, it may be possible to arrive at some general notions about the biological potential of planets based on some very general properties of living systems and the environments that sustain them.

5. Toward a biogeophysical synthesis

Living systems comprise a subset of self-organizing structures far from equilibrium with their environment and open with respect to exchange of energy and matter (Nicolis & Prigogine 1977). They differ in essence from such non-living systems in that they undergo darwinian evolution through genetic self-replication, mutation, and natural selection. Conditions far from equilibrium prevail at the interfaces between phase domains and are maintained there by the flux of matter and energy through the boundary regions and by the gradients in physical and chemical properties that are established therein. On the prebiotic Earth a multitude of types of self-organizing systems must have existed, as they do today, differing in physical and chemical composition, size, distribution, abundance and lifetime against dissipation. Then, as today, such systems must have encompassed a range of structures from those as small and ephemeral as bubbles at the sea–air interface to ones as large and persistent as the tectonic plates. In the sense used in §4 these may be taken as 'metabolic' systems. The ability of a planet to produce and sustain a complex hierarchy of such systems over geologic time may be a prerequisite for the origin and sustenance of life.

The hierarchy appears to be a consequence of two main factors: first, the occurrence of phase boundaries between gas, liquid and solid domains over dimensional scales ranging from the microscopic, as in aerosols, to the macroscopic, as at the interface between sea and crust at mid-ocean ridges; and second permeation of these boundary regions by fluxes of energy which themselves vary extensively in quality (e.g. wavelength) and intensity. In this context one of the critical roles played by liquid water is to provide both a domain and a multitude of boundary regions within which self-organizing structures could develop. Another is to moderate otherwise destructive flows of energy through it. In this view, liquid water is essential for the origin of life for reasons other than to serve eventually as a medium for biochemistry.

Discussions of energy in the context of the origin of life have usually been couched in terms of how much of what sort of energy would have been available for converting inorganic constituents of the primitive atmosphere into organic compounds. Perhaps another useful perspective can be gained by considering the totality of its interaction with an environment over time. Just as thermal energy from the interior maintains the self-organized structures of the solid earth domain and disequilibria at its boundaries with other domains, so is solar energy the driving force for the structures and dynamic motions occurring in the atmosphere and ocean system (see, for example, Shukla 1985) from the thin film of the sea–air interface to deep ocean currents. Both sources of energy drive the exchange of matter between subsystems within domains, as well as between domains themselves. The time-scales for exchange range from 10^{-5} a for formation and dissolution of bubbles at the sea surface to 10^{8} a for sea-floor renewal. Perhaps some source of energy was more important at a particular stage in probiotic evolution than at another; or some sources were involved directly (sunlight) and others indirectly (radioactive decay). But all were needed, acting together, before origin of a genetic system, to generate the dynamically interacting complex hierarchy of self-organized structures, nested within which were the precursors of living systems. Life on Earth continues to be imbedded in such a hierarchy, and the failure to produce one or sustain one in the history (or future) of a planet may impose strong constraints on the origin and evolution of life.

Thus conditions far from equilibrium where self-organizing structures could form certainly occurred throughout the history of Earth at geophysically active boundary regions. These regions included fumaroles and volcanic vents on continents and continental shelves, deep-sea plate spreading centres, island–arc volcanic vents, the land–air interface, and the sea–air interface. It is in these environments that biology, chemistry and physics interplay. The role of volcanism in the origin and propagation of boundaries and subsystems and its relevance to the origin of life was emphasized early on by Sylvester-Bradley (1976) and others (see §2). The tidal lagoon and periodically evaporating pond environments for probiotic evolution are also pertinent to this context (see, for example, Lahav & Chang 1976).

More recently, however, Lerman (1986) has made the very interesting suggestion that in the vicinity of underwater or near surface sites of volcanism, the liquid–gas interface of bubbles provides a unique reaction zone for selective concentration of reactants, synthesis of organic compounds, and recycling of previously formed chemicals toward development of further chemical complexity. His scheme of cycles of bubble formation and dissipation affords a simple, ubiquitous example of a 'protometabolic' process, the physical–chemical mechanism of which has existed ever since there were water and waves. And the efficacy of the model can be tested experimentally.

From the perspective of this discussion, evolution of Earth's biota may be viewed in the planetary context as the diversification and distribution of a self-organizing heterogeneous catalyst that mediates the cycling of biogenic elements between reservoirs, sources and sinks in the atmosphere, hydrosphere and lithosphere. From this perspective the earliest interplay between biology and the physical environment represents the beginning of interlocked tectonic, biogeochemical and meteorological cycles, forming global feedback loops, which, though perturbed by anthropogenic activities today, are thought to have regulated climate, habitability of environments and biological productivity over time.

Although this discussion has been entirely qualitative, it has some quantitative implications. If the fluxes of matter and energy through a medium and its boundary regions drives the formation of self-organizing structures, can their measurement provide a metric for assessing the potentiality of environmental domains for the origin and sustenance of life? If, for instance, one were to plot all available data on an energy against mass flux diagram for environments occupied by living systems and for those where life does not occur, would data for the former define a field distinct from the latter? Would such an endeavour aid in determining the biological potential of planets in the Solar System and beyond?

6. Prospects for life on Mars

Mars continues to offer the best prospect for life elsewhere in the Solar System. It has differentiated into core, mantle and crust and outgassed an atmosphere containing the biogenic elements hydrogen, carbon and nitrogen. In these respects the history of Mars and Earth are grossly similar. Although Mars shows no evidence of plate motion, it does display a long record of volcanism with greatest intensity between about 4.0–2.5 Ga BP. It is also in the early half of this time frame that most of the canyons and channels attributable to groundwater and fluvial activity are believed to have formed. Moreover, the presence of rhythmically layered sediments in some canyons has been interpreted to suggest deposition in a lake-like setting (see discussion in Carr 1986). If Mars ever had a primitive ocean, Carr (1986) estimates that its average depth would have been 0.5–1 km. But for liquid water to have persisted in liquid form 1–5 bars of atmospheric carbon dioxide would have been required (Pollack *et al.* 1987). This requirement could have been satisfied if Mars had a massive early atmosphere as has been hypothesized for Earth (§3).

Even though the martian epoch of liquid water was short, it apparently coincided with the period of Earth history when life originated. Gross similarities in the early geophysical history of the two planets hold open the possibility that life arose on Mars as well. From the perspective developed in § 5, however, the apparent absence of plate tectonism argues against that possibility in that the hierarchy of self-organizing structures would have been less complex and interactive and, therefore, endowed with less potential for life. Only further geophysical and biogeochemical exploration can place these qualitative speculations on firm ground. (A discussion of the biological potential of Venus, whose early geophysical history bears resemblance to that of Mars, would lead to the same conclusion.) Therefore, the search for evidence of extinct life on Mars should be among the highest scientific priorities in future explorations of the planet.

The prospect of extant life on Mars today, though at odds with the criteria in § 5, cannot be considered a completely closed issue. Although the *Viking* mission found no evidence of extant life (Klein 1979), the search was limited and not directed at optimum sites. A definitive answer must await return of samples for study in terrestrial laboratories.

Furthermore, the chemistry of the martian surface soils, manifested in the biomimetic responses elicited by the *Viking* biology experiments, continues to be intriguing and inadequately understood; it may reveal important clues to the role of minerals and inorganic chemistry in probiotic evolution before the development of a planetary organic chemistry or following the dissipation of bodies of water on the surface. Elucidation of this chemistry and its relation to the mineralogy and surface processes on Mars remain to be accomplished, an elusive goal that is unlikely to be attained until samples of Mars are available for detailed study.

7. Conclusion

In a proper search for knowledge about the origin of life as a natural manifestation of processes operating in the Solar System, it is essential to explore as many as possible of the extraterrestrial bodies for the relevant information they can supply. The search should involve exploration of a continuum of planetary possibilities including bodies totally devoid of organic chemicals, those conceivably undergoing (or having undergone) organic or inorganic probiotic evolution and those possibly harbouring life. The study of lifeless planets would provide examples of environments where probiotic or biological evolution ended. On them it may be possible to find the remnants of probiotic evolution or of past life and to learn how planetary evolution may have broken the thread of probiotic or biological evolution. Examination of planets devoid of organic compounds can provide either a calibration point in the process of probiotic evolution which corresponds to a time before the formation of organic matter or insight into how the relicts of probiotic evolution may have been obliterated by processes of planetary evolution. Clearly, even the discovery that there is no life, extant or extinct, or no organic matter on a planet is of high interest and importance because the conditions on the planet and what we can learn of its past history constitute basic data pertinent to a general theory of the origin of life.

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