

Prebiotic Chemistry on the Primitive Earth

Stanley L. Miller & H. James Cleaves

The origin of life remains one of the humankind's last great unanswered questions, as well as one of the most experimentally challenging research areas. It also raises fundamental cultural issues that fuel at times divisive debate. Modern scientific thinking on the topic traces its history across millennia of controversy, although current models are perhaps no older than 150 years. Much has been written regarding pre-nineteenth-century thought regarding the origin of life. Early views were wide-ranging and often surprisingly prescient; however, since this chapter deals primarily with modern thinking and experimentation regarding the synthesis of organic compounds on the primitive Earth, the interested reader is referred to several excellent resources [1–3].

Despite recent progress in the field, a single definitive description of the events leading up to the origin of life on Earth some 3.5 billion years ago remains elusive. The vast majority of theories regarding the origin of life on Earth speculate that life began with some mixture of organic compounds that somehow became organized into a self-replicating chemical entity. Although the idea of panspermia (which postulates that life was transported preformed from space to the early sterile Earth) cannot be completely dismissed, it seems largely unsupported by the available evidence, and in any event would simply push the problem to some other location. Panspermia notwithstanding, any discussion of the origin of life is of necessity a discussion of organic chemistry. Not surprisingly, ideas regarding the origin of life have developed to a large degree concurrently with discoveries in organic chemistry and biochemistry. This chapter will attempt to summarize key historical and recent findings regarding the origin of organic building blocks thought to be important for the origin of life on Earth.

In addition to the background readings regarding historical perspectives suggested above, the interested reader is referred to several additional excellent texts which remain scientifically relevant [4,5; see also the journal *Origins of Life and the Evolution of the Biosphere*].

BOTTOM-UP AND TOP-DOWN APPROACHES

There are two fundamental complementary approaches to the study of the origin of life. One, the top-down approach, considers the origin of the constituents of modern biochemistry and their present organization. The other, the bottom-up approach, considers the compounds thought to be plausibly produced under primitive planetary conditions and how they may have come to be assembled. The crux of the study of the origin of life is the overlap between these two regimes. The top-down approach is biased by the general uniformity of modern biochemistry across the three major extant domains of life (Archaea, Bacteria, and Eukarya). These clearly originated from a common ancestor based on the universality of the genetic code they use to form proteins and the homogeneity of their metabolic processes. Investigations have assumed that whatever the first living being was, it must have been composed of similar biochemicals as one would recover from a modern organism (lipids, nucleic acids, proteins, cofactors, etc.), that somehow were organized into a self-propagating assemblage. This bias seems to be legitimized by the presence of biochemical compounds in extraterrestrial material and the relative success of laboratory syntheses of these compounds under simulated prebiotic conditions. It would be a simpler explanatory model if the components of modern biochemistry and the components of the first living things were essentially similar, although this need not necessarily be the case. The bottom-up approach is similarly biased by present-day biochemistry; however, some more exotic chemical schemes are possible within this framework.

All living things are composed of but a few atomic elements (CHNOPS in addition to other trace components), which do not necessarily reflect their cosmic or terrestrial abundances, and which begs the question why these elements were selected for life. This may be due to some intrinsic aspect of their chemistry, or some of the components may have been selected based on the metabolism of more complicated already living systems, or there may have been selection based on prebiotic availability, or some mixture of the three.

HISTORICAL FOUNDATIONS OF MODERN THEORY

The historical evolution of thinking on the origin of life is intimately tied to developments of other fields, including chemistry, biology, geology, and astronomy. Importantly, the concept of biological evolution proposed by Darwin led to the early logical conclusion that there must have been a first organism, and a distinct origin of life.

In part of a letter that Darwin sent in 1871 to Joseph Dalton Hooker, Darwin summarized his rarely expressed ideas on the emergence of

life, as well as his views on the molecular nature of basic biological processes:

It is often said that all the conditions for the first production of a living being are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, -light, heat, electricity &c present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present such matter wd be instantly devoured, or absorbed, which would not have been the case before living creatures were formed....

By the time Darwin wrote to Hooker DNA had already been discovered, although its role in genetic processes would remain unknown for almost eighty years. In contrast, the role that proteins play in biological processes had already been firmly established, and major advances had been made in the chemical characterization of many of the building blocks of life. By the time Darwin wrote this letter the chemical gap separating organisms from the nonliving world had been bridged in part by laboratory syntheses of organic molecules. In 1827 Berzelius, probably the most influential chemist of his day, had written, "art cannot combine the elements of inorganic matter in the manner of living nature." Only one year later his former student Friedrich Wöhler demonstrated that urea could be formed in high yield by heating ammonium cyanate "without the need of an animal kidney" [6].

Wöhler's work represented the first synthesis of an organic compound from inorganic starting materials. Although it was not immediately recognized as such, a new era in chemical research had begun. In 1850 Adolph Strecker achieved the laboratory synthesis of alanine from a mixture of acetaldehyde, ammonia, and hydrogen cyanide. This was followed by the experiments of Butlerov showing that the treatment of formaldehyde with alkaline catalysts leads to the synthesis of sugars.

By the end of the nineteenth century a large amount of research on organic synthesis had been performed, and led to the abiotic formation of fatty acids and sugars using electric discharges with various gas mixtures [7]. This work was continued into the twentieth century by Löb, Baudish, and others on the synthesis of amino acids by exposing wet formamide (HCONH_2) to a silent electrical discharge [8] and to UV light [9]. However, since it was generally assumed that the first living beings had been autotrophic organisms, the abiotic synthesis of organic compounds did not appear to be a necessary prerequisite for the emergence of life. These organic syntheses were not conceived as laboratory simulations of Darwin's warm little pond,

but rather as attempts to understand the autotrophic mechanisms of nitrogen assimilation and CO₂ fixation in green plants.

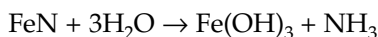
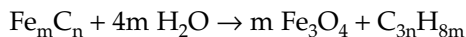
It is generally believed that after Pasteur disproved spontaneous generation using his famous swan-necked flask experiments, the discussion of life beginning's had been vanquished to the realm of useless speculation. However, scientific literature of the first part of the twentieth century shows many attempts by scientists to solve this problem. The list covers a wide range of explanations from the ideas of Pflüger on the role of hydrogen cyanide in the origin of life, to those of Arrhenius on panspermia. It also includes Troland's hypothesis of a primordial enzyme formed by chance in the primitive ocean, Herrera's sulphocyanide theory on the origin of cells, Harvey's 1924 suggestion of a heterotrophic origin in a high-temperature environment, and the provocative 1926 paper that Hermann J. Muller wrote on the abrupt, random formation of a single, mutable gene endowed with catalytic and replicative properties [10].

Most of these explanations went unnoticed, in part because they were incomplete, speculative schemes largely devoid of direct evidence and not subject to experimentation. Although some of these hypotheses considered life an emergent feature of nature and attempted to understand its origin by introducing principles of evolutionary development, the dominant view was that the first forms of life were photosynthetic microbes endowed with the ability to fix atmospheric CO₂ and use it with water to synthesize organic compounds.

Oparin's proposal stood in sharp contrast with the then prevalent idea of an autotrophic origin of life. Trained as both a biochemist and an evolutionary biologist, Oparin found it was impossible to reconcile his Darwinian beliefs in a gradual evolution of complexity with the commonly held suggestion that life had emerged already endowed with an autotrophic metabolism, which included chlorophyll, enzymes, and the ability to synthesize organic compounds from CO₂. Oparin reasoned that since heterotrophic anaerobes are metabolically simpler than autotrophs, the former would necessarily have evolved first. Thus, based on the simplicity and ubiquity of fermentative metabolism, Oparin [11] suggested in a small booklet that the first organisms must have been heterotrophic bacteria that could not make their own food but obtained organic material present in the primitive milieu.

Careful reading of Oparin's 1924 pamphlet shows that, in contrast to common belief, at first he did not assume an anoxic primitive atmosphere. In his original scenario he argued that while some carbides, that is, carbon-metal compounds, extruded from the young Earth's interior would react with water vapor leading to hydrocarbons, others would be oxidized to form aldehydes, alcohols, and ketones.

These molecules would then react among themselves and with NH_3 originating from the hydrolysis of nitrides:



to form “very complicated compounds,” as Oparin wrote, from which proteins and carbohydrates would form.

Oparin’s ideas were further elaborated in a more extensive book published with the same title in Russian in 1936. In this new book his original proposal was revised, leading to the assumption of a highly reducing milieu in which iron carbides of geological origin would react with steam to form hydrocarbons. Their oxidation would yield alcohols, ketones, aldehydes, and so on, which would then react with ammonia to form amines, amides, and ammonium salts. The resulting protein-like compounds and other molecules would form a hot, dilute soup, which would aggregate to form colloidal systems, that is, coacervates, from which the first heterotrophic microbes evolved. Like Darwin, Oparin did not address in his 1938 book the origin of nucleic acids, because their role in genetic processes was not yet suspected. At around the same time, J.B.S. Haldane [12] published a similar proposal, and thus the theory is often credited to both scientists.

For Oparin [13], highly reducing atmospheres corresponded to mixtures of CH_4 , NH_3 , and H_2O with or without added H_2 . The atmosphere of Jupiter contains these chemical species, with H_2 in large excess over CH_4 . Oparin’s proposal of a primordial reducing atmosphere was a brilliant inference from the then fledgling knowledge of solar atomic abundances and planetary atmospheres, as well as from Vernadky’s idea that since O_2 is produced by plants, the early Earth would be anoxic in the absence of life. The benchmark contributions of Oparin’s 1938 book include the hypothesis that heterotrophs and anaerobic fermentation were primordial, the proposal of a reducing atmosphere for the prebiotic synthesis and accumulation of organic compounds, the postulated transition from heterotrophy to autotrophy, and the considerable detail in which these concepts are addressed.

The last major theoretical contribution to the modern experimental study of the origin of life came from Harold Clayton Urey. An avid experimentalist with a wide range of scientific interests, Urey offered explanations for the composition of the early atmosphere based on then popular ideas of solar system formation, which were in turn based on astronomical observations of the atmospheres of the giant planets and star composition. In 1952 Urey published *The Planets, Their Origin and Development* [14], which delineated his ideas of the formation

of the solar system, a formative framework into which most origin of life theories are now firmly fixed, albeit in slightly modified fashions.

In contrast, shortly thereafter, Rubey [15] proposed an outgassing model based on an early core differentiation and assumed that the early atmosphere would have been reminiscent of modern volcanic gases. Rubey estimated that a CH_4 atmosphere could not have persisted for much more than 10^5 to 10^8 years due to photolysis. The Urey/Oparin atmospheres (CH_4 , NH_3 , H_2O) models are based on astrophysical and cosmochemical models, while Rubey's CO_2 , N_2 , H_2O model is based on extrapolation of the geological record.

Although this early theoretical work has had a great influence on subsequent research, modern thinking on the origin and evolution of the chemical elements, the solar system, the Earth, and the atmosphere and oceans have not been shaped largely with the origin of life as a driving force. On the contrary, current origin of life theories have been modified to fit contemporary models in geo- and cosmochemistry.

Life, Prebiotic Chemistry, Carbon, and Water

A brief justification is necessary for the discussion that will follow. One might ask why the field of prebiotic chemistry has limited itself to aqueous reactions that produce reduced carbon compounds. First, the necessary bias introduced by the nature of terrestrial organisms must be considered. There is only one example of a functioning biology, our own, and it is entirely governed by the reactions of reduced carbon compounds in aqueous media. The question naturally arises whether there might be other types of chemistry that might support a functioning biology.

Hydrogen is the most abundant atom in the universe, tracing its formation to the time shortly after the Big Bang. Besides helium and small amounts of lithium, the synthesis of the heavier elements had to await later cycles of star formation and supernova explosions. Due to the high proportion of oxygen and hydrogen in the early history of the solar system, most other atomic nuclei ended up as either their oxides or hydrides. Water can be considered as the hydride of oxygen or the oxide of hydrogen. Water is one of the most abundant compounds in the universe. Life in the solid state would be difficult, as diffusion of metabolites would occur at an appallingly slow pace. Conversely, it is improbable that life in the gas phase would be able to support the stable associations required for the propagation of genetic information, and large molecules are generally nonvolatile. Thus it would appear that life would need to exist in a liquid medium. The question then becomes what solvent molecules are prevalent and able to exist in the liquid phase over the range of temperatures where reasonable reaction rates might proceed while at the same time preserving the integrity of the solute compounds. The high temperature limit is set by the

decomposition of chemical compounds, while the low temperature limit is determined by the reactivity of the solutes. Water has the largest liquid stability range of any known common molecular compound at atmospheric pressure, and the dielectric constant of water and the high heat capacity are uniquely suited to many geochemical processes.

There are no other elements besides carbon that appear to be able to furnish the immense variety of chemical compounds that allow for a diverse biochemistry. Carbon is able to bond with a large variety of other elements to generate stable heteroatomic bonds, as well as with itself to give a huge inventory of carbon-based molecules. In addition, carbon has the exceptional ability to form stable double-bonded structures with itself, which are necessary for generating fixed molecular shapes and planar molecules necessary for molecular recognition. Most of the fundamental processes of life at the molecular level are based on molecular recognition, which depends on the ability of molecules to possess functional groups that allow for weak interactions such as hydrogen bonding and π -stacking. Carbon appears unique in the capacity to form stable alcohols, amines, ketones, and so on.

While silicon is immediately below carbon in the periodic table, its polymers are generally unstable, especially in water, and silicon is unable to form stable double bonds with itself. Organisms presently use energy, principally sunlight, to transform environmental precursors such as CO_2 , H_2O , and N_2 into their constituents. While silicon is more prevalent in the Earth's crust than carbon, and both are generated copiously in stars, silicon is unable to support the same degree of molecular complexity as carbon. Silicon is much less soluble in water than are carbon species, and does not have an appreciably abundant gas phase form such as CH_4 or CO_2 , making the metabolism of silicon more difficult for a nascent biology.

THE PRIMITIVE EARTH AND SOURCES OF BIOMOLECULES

The origin of life can be constrained into a relatively short period of the Earth's history. On the upper end, the age of the solar system has been determined to be approximately 4.65 billion years from isotopic data from terrestrial minerals, lunar samples, and meteorites, and the Earth-moon system is estimated to be approximately 4.5 billion years old. The early age limit for the origin of life on Earth is also constrained by the lunar cratering record, which suggests that the flux of large asteroids impacting the early Earth's surface until ~3.9 billion years ago was sufficient to boil the terrestrial oceans and sterilize the planet. On the more recent end, there is putative isotopic evidence for biological activity from ~3.8 billion years ago (living systems tend to incorporate the lighter isotope of carbon, ^{12}C , preferentially over ^{13}C during carbon fixation due to metabolic kinetic isotope effects).

There is more definitive fossil evidence from ~3.5 billion years ago in the form of small organic inclusions in cherts morphologically similar to cyanobacteria, as well as stromatolitic assemblages (layered mats reminiscent of the layered deposits created by modern microorganismal communities). Thus the time window for the origin of the predecessor of all extant life appears to be between ~3.9 billion and 3.8 billion years ago. The accumulation and organization of organic material leading to the origin of life must have occurred during the same period. While some authors have attempted to define a reasonable time frame for biological organization based on the short time available [16], it has been pointed out that the actual time required could be considerably longer or shorter [17]. It should be borne in mind that there is some uncertainty in many of the ages mentioned above. In any event, life would have had to originate in a relatively short period, and the synthesis and accumulation of the organic compounds for this event must have preceded it in an even shorter time period. The synthesis and survival of organic biomonomers on the primitive Earth would have depended on the prevailing environmental conditions. Unfortunately, to a large degree these conditions are poorly defined by geological evidence.

Solar System Formation and the Origin of the Earth

If the origin of life depends on the synthesis of organic compounds, then the source and nature of these is the crucial factor in the consideration of any subsequent discussions of molecular organization. The origin of terrestrial prebiotic organic compounds depends on the primordial atmospheric composition. This in turn is determined by the oxidation state of the early mantle, which depends on the manner in which the Earth formed. Discussions of each of these processes are unfortunately compromised by the paucity of direct geological evidence remaining from the time period under discussion, and are therefore somewhat speculative. While a complete discussion of each of these processes is outside the scope of this chapter, they are crucial for understanding the uncertainty surrounding modern thinking regarding the origin of the prebiotic compounds necessary for the origin of life.

According to the current model, the solar system is thought to have formed by the coalescence of a nebular cloud which accreted into small bodies called planetesimals which eventually aggregated to form the planets [18]. In brief, the sequence of events is thought to have commenced when a gas cloud enriched in heavier elements produced in supernovae began to collapse gravitationally on itself. This cool diffuse cloud gradually became concentrated into denser regions where more complex chemistry became possible, and in so doing began to heat up. As this occurred, the complex components of the gas cloud began to differentiate in what may be thought of as a large distillation process. The cloud condensed, became more disk-like, and

began to rotate to conserve angular momentum. Once the center of the disk achieved temperatures and pressures high enough to begin hydrogen fusion, the sun was born. The intense radiative power of the nascent sun drove the lower boiling point elements outward toward the edge of the solar system where they condensed and froze out.

Farther out in the disk, dust-sized grains were also in the process of coalescing due to gravitational attraction. These small grains slowly agglomerated to form larger and larger particles that eventually formed planetesimals and finally planets. It is noteworthy that the moon is thought to have formed from the collision of a Mars-sized body with the primitive Earth. The kinetic energy of such a large collision must have been very great, so great in fact that it would have provided enough energy to entirely melt the newly formed Earth and probably strip away its original atmosphere.

Discussions of planetary formation and atmospheric composition are likely to be relevant to various other planets in our solar system and beyond, thus the following discussion may be generalizable.

The Early Atmosphere

The temperature at which the planets accreted is important for understanding the early Earth's atmosphere, which is essential for understanding the possibility of terrestrial prebiotic organic synthesis. This depends on the rate of accretion. If the planet accreted slowly, more of the primitive gases derived from planetesimals, likely reminiscent of the reducing chemistry of the early solar nebula, could have been retained. If it accreted rapidly, the model favored presently, the original atmosphere would have been lost and the primitive atmosphere would have been the result of outgassing of retained mineral-associated volatiles and subsequent extraterrestrial delivery of volatiles.

CH_4 , CO_2 , CO , NH_3 , H_2O , and H_2 are the most abundant molecular gas species in the solar system, and this was likely true on the early Earth as well, although it is the relative proportions of these that is of interest. It remains contentious whether the Earth's water was released via volcanic exhalation of water associated with mineral hydrates accreted during planetary formation or whether it was accreted from comets and other extraterrestrial bodies during planet formation.

It seems unlikely that the Earth kept much of its earliest atmosphere during early accretion, thus the primordial atmosphere would have been derived from outgassing of the planet's interior, which is thought to have occurred at temperatures between 300 and 1500 °C. Modern volcanoes emit a wide range of gas mixtures. Most modern volcanic emissions are CO_2 and SO_2 , rather than CH_4 and H_2S (table 1.1). It seems likely that most of the gases released today are from the reactions of reworked crustal material and water, and do not represent components of the Earth's deep interior. Thus modern volcanic gases may tell us little about the early Earth's atmosphere.

Table 1.1 Gases detected in modern volcanic emissions (adapted from Miller and Orgel [4])

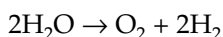
Location	CO ₂	CO	CH ₄	NH ₃	H ₂	HCl	H ₂ S	SO ₂	H ₂ O
White Island, New Zealand	57.9	—	0.5	—	41.5	—	—	—	—
Nyerogongo Lava Lake, Congo	84.4	5.1	—	—	1.6	—	—	9.0	43.2
Mount Hekla, Iceland	23	3	—	—	16	52	—	6	—
Lipari Island, Italy	93.0	—	—	—	—	0.5	2.9	3.6	98.9
Larderello, Italy	92.7	—	0.92	1.72	1.76	—	—	2.45	—
Zavaritskii crater, Kamchatka	—	67	—	—	—	33	—	—	—
Same crater, B1	—	21	—	—	42	25	—	12	—
Unimak Island, Alaska	47	—	—	—	—	—	—	53	95

Values for gases (except water) are given in volume percent. The value for water is its percentage of the total gases

The oxidation state of the early mantle likely governed the distribution of reducing gases released during outgassing. Holland [19] proposed a multistage model based on the Earth being formed through cold homogeneous accretion in which the Earth's atmosphere went through two stages, an early reduced stage before complete differentiation of the mantle, and a later neutral/oxidized stage after differentiation. During the first stage, the redox state of the mantle was governed by the Fe⁰/Fe²⁺ redox pair, or iron-wüstite buffer. The atmosphere in this stage would be composed of H₂O, H₂, CO, and N₂, with approximately $0.27\text{--}2.7 \times 10^{-5}$ atm of H₂. Once Fe⁰ had segmented into the core, the redox state of magmas would have been controlled by the Fe²⁺/Fe³⁺ pair, or fayalite-magnetite-quartz buffer.

In reconstructing the early atmosphere with regard to organic synthesis, there is particular interest in determining the redox balance of the crust-mantle-ocean-atmosphere system. Endogenous organic synthesis seems to depend, based on laboratory simulations, on the early atmosphere being generally reducing, which necessitates low O₂ levels in the primitive atmosphere.

Little is agreed upon about the composition of the early atmosphere, other than that it almost certainly contained very little free O₂. O₂ can be produced by the photodissociation of water:



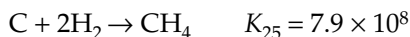
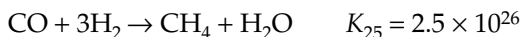
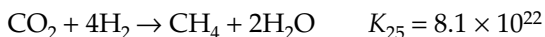
Today this occurs at the rate of $\sim 10^{-8}$ g cm⁻² yr⁻¹, which is rather slow, and it seems likely that the steady state would have been kept low early in the Earth's history due to reaction with reduced metals in the crust and oceans such as Fe²⁺.

Evidence in favor of high early O₂ levels comes from morphological evidence that fossil bacteria appear to have been photosynthetic, although this is somewhat speculative. On the other hand, uranite (UO₂) and galena (PbS) deposits from 2–2.8 bya testify to low atmospheric O₂ levels until relatively recently, since both of these species are easily oxidized to UO₃ and PbSO₄, respectively. More evidence that O₂ is the result of buildup from oxygenic photosynthesis and a relatively recent addition to the atmosphere comes from the banded iron formations (BIFs). These are distributed around the world from ~ 1.8 –2.2 mya and contain extensive deposits of magnetite Fe₃O₄, which may be considered a mixture of FeO and hematite (Fe₂O₃), interspersed with bands of hematite. Hematite requires a higher pO_2 to form.

On the modern Earth, high O₂ levels allow for the photochemical formation of a significant amount of ozone. Significantly, O₃ serves as the major shield of highly energetic UV light on the Earth's surface today. Even low O₂ levels may have created an effective ozone shield on the early Earth [20]. The oceans could also have served as an important UV shield protecting the nascent organic chemicals [21]. It is important to note that while UV can be a significant source of energy for synthesizing organics, it is also a means of destroying them.

While this suggests that the early atmosphere was probably not oxidizing, it does not prove or offer evidence that it was very reducing. Although it is generally accepted that free oxygen was generally absent from the early Archean Earth's atmosphere, there is no agreement on the composition of the primitive atmosphere; opinions vary from strongly reducing (CH₄ + N₂, NH₃ + H₂O, or CO₂ + H₂ + N₂) to neutral (CO₂ + N₂ + H₂O).

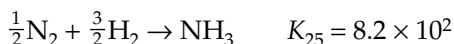
The modern atmosphere is not thermodynamically stable, and the modern atmosphere is not in equilibrium with respect to the biota, the oceans, or the continents. It is unlikely that it ever was. In the presence of large amounts of H₂, the thermodynamically stable form of carbon is CH₄:



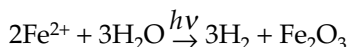
In the absence of large amounts of H₂, intermediate forms of carbon, such as formate and methanol, are unstable with respect to CO₂

and CH_4 , and thus these are the stable forms at equilibrium. Even large sources of CO would have equilibrated with respect to these in short geological time spans.

In the presence of large amounts of H_2 , NH_3 is the stable nitrogen species, although not to the extreme extent of methane:



If a reducing atmosphere was required for terrestrial prebiotic organic synthesis, the crucial question becomes the source of H_2 . Miller and Orgel [4] have estimated the $p\text{H}_2$ as 10^{-4} to 10^{-2} atm. Molecular hydrogen could have been supplied to the primitive atmosphere from various sources. For example, if there had been extensive weathering of Fe^{2+} -bearing rocks which had not been equilibrated with the mantle, followed by photooxidation in water [22]:



although this reaction may also have been equilibrated during volcanic outgassing.

The major sink for H_2 is Jeans escape, whereby gas molecules escape the Earth's gravitational field. This equation is important for all molecular gas species, and thus we will include it here:

$$L = N(RT/2\pi\mu)^{1/2} (1 + x)e^{-x}, \text{ where } x = GM\mu/RTa_\epsilon$$

where

L = rate of escape (in atoms $\text{cm}^{-2} \text{s}^{-1}$)

N = density of the gas in the escape layer

R = gas constant

μ = atomic weight of the gas

G = gravitational constant

M = mass of the Earth

T = absolute temperature in the escape layer

a_ϵ = radius at the escape layer.

The escape layer on the Earth begins ~600 km above the Earth's surface. Molecules must diffuse to this altitude prior to escape. The major conduits of H to the escape layer are CH_4 , H_2 , and H_2O , since H_2O and CH_4 can be photodissociated at this layer. Water is, however, frozen out at lower altitudes, and thus does not contribute significantly to this process.

The importance of the oxidation state of the atmosphere may be linked to the production of HCN, which is essential for the synthesis of amino acids and purine nucleobases, as well as cyanoacetylene

for pyrimidine nucleobase synthesis. In CH_4/N_2 atmospheres HCN is produced abundantly [23,24], but in CO_2/N_2 atmospheres most of the N atoms produced by splitting N_2 recombine with O atoms to form NO.

The Early Oceans

The pH of the modern ocean is governed by the complex interplay of dissolved salts, atmospheric CO_2 levels, and clay mineral ion exchange processes. The pH and concentrations of Ca^{2+} , Mg^{2+} , Na^+ and K^+ are maintained by equilibria with clays rather than by the bicarbonate buffer system. The bicarbonate concentration is determined by the pH and Ca^{2+} concentrations. After deriving these equilibria, the $p\text{CO}_2$ can be derived from equilibrium considerations with clay species, which gives a $p\text{CO}_2$ of 1.3×10^{-4} atm to 3×10^{-4} atm [4]. For comparison, presently CO_2 is ~ 0.03 volume %. This buffering mechanism and $p\text{CO}_2$ would leave the primitive oceans at $\sim \text{pH } 8$, which is coincidentally a favorable pH for many prebiotic reactions. The cytosol of most modern cells is also maintained via a series of complicated cellular processes near pH 8, suggesting that early cells may have evolved in an environment close to this value.

Our star appears to be a typical G2 class star, and is expected to have followed typical stellar evolution for its mass and spectral type. Consequently the solar luminosity would have been $\sim 30\%$ less during the time period we are concerned with, and the UV flux would have been much higher [20]. A possible consequence of this is that the prebiotic Earth may have frozen completely to a depth of ~ 300 m [25]. There is now good evidence for various completely frozen “Snowball Earth” periods later during the Earth’s history [26]. There is some evidence that liquid water was available on the Archean Earth between 4.3 and 4.4 bya [27,28], thus the jury is still out as to whether the early Earth was hot or cold, or perhaps had a variety of environments. The presence of liquid surface water would have necessitated that the early Earth maintained a heat balance that offset the postulated 30% lesser solar flux from the faint young sun. Presently the Earth’s temperature seems to be thermostatted by the so-called BLAG [29] model. The model suggests that modern atmospheric CO_2 levels are maintained at a level that ensures moderate temperatures by controlling global weathering rates and thus the flux of silicates and carbonates through the crust–ocean interface. When CO_2 levels are high, the Earth is warmed by the greenhouse effect and weathering rates are increased, allowing a high inflow of Ca^{2+} and silicates to the oceans, which precipitates CO_2 as CaCO_3 , and lowers the temperature. As the atmosphere cools, weathering slows, and the buildup of volcanically outgassed CO_2 again raises the temperature. On the early Earth, however, before extensive recycling of the crust became common, large amounts of CO_2 may have been sequestered as CaCO_3 in sediments, and the environment may have been considerably colder.

Energy Sources on the Early Earth

Provided the early atmosphere had a sufficiently reducing atmosphere, energy would have been needed to dissociate these gases into radicals which could recombine to form reactive intermediates capable of undergoing further reaction to form biomolecules. The most abundant energy sources on Earth today are shown in table 1.2. Energy fluxes from these sources may have been slightly different in the primitive environment. As mentioned earlier, the dim young sun would have provided a much higher flux of UV radiation than the modern sun. It is also likely that volcanic activity was higher than it is today, and radioactive decay would have been more intense, especially from ^{40}K [30], which is the probable source of the high concentrations of Ar in the modern atmosphere. Shock waves from extraterrestrial impactors and thunder were also probably more common during the tail of the planetary accretion process. Presently huge amounts of energy are discharged atmospherically in the form of lightning; it is difficult to estimate the flux early in the Earth's history. Also significant is the energy flux associated with the van Allen belts and static electricity discharges.

Some energy sources may have been more important for some synthetic reactions. For example, electric discharges are very effective at producing HCN from CH_4 and NH_3 or N_2 , but UV radiation is not. Electric discharge reactions also occur near the Earth's surface whereas UV reactions occur higher in the atmosphere. Any molecules created would have to be transported to the ocean, and might be destroyed on the way. Thus transport rates must also be taken into account

Table 1.2 Energy sources on the modern Earth (adapted from Miller and Orgel [4])

Source	Energy ($\text{cal cm}^{-2} \text{yr}^{-1}$)	Energy ($\text{J cm}^{-2} \text{yr}^{-1}$)
Total radiation from sun	260,000	1,090,000
Ultraviolet light < 300 nm	3400	14,000
Ultraviolet light < 250 nm	563	2360
Ultraviolet light < 200 nm	41	170
Ultraviolet light < 150 nm	1.7	7
Electric discharges	4.0 ^a	17
Cosmic rays	0.0015	0.006
Radioactivity (to 1.0 km)	0.8	3.0
Volcanoes	0.13	0.5
Shock waves	1.1 ^b	4.6

^a3 $\text{cal cm}^{-2} \text{yr}^{-1}$ of corona discharge and 1 $\text{cal cm}^{-2} \text{yr}^{-1}$ of lightning.

^b1 $\text{cal cm}^{-2} \text{yr}^{-1}$ of this is the shock wave of lightning bolts and is also included under electric discharges.

when considering the relative importance of various energy sources in prebiotic synthesis.

Atmospheric Syntheses

Urey's early assumptions as to the constitution of the primordial atmosphere led to the landmark Miller-Urey experiment, which succeeded in producing copious amounts of biochemicals, including a large percentage of those important in modern biochemistry.

Yields of intermediates as a function of the oxidation state of the gases involved have been investigated and it has been shown that reduced gas mixtures are generally much more conducive to organic synthesis than oxidizing or neutral gas mixtures. This appears to be because of the likelihood of reaction-terminating O radical collisions where the partial pressure of O-containing species is high. Even mildly reducing gas mixtures produce copious amounts of organic compounds. The yields may have been limited by carbon yield or energy yield. It seems likely that energy was the not the limiting factor [24].

Small Reactive Intermediates

Small reactive intermediates are the backbone of prebiotic organic synthesis. They include HCHO, HCN, ethylene, cyanoacetylene, and acetylene which can be recombined to form larger and more complex intermediates that ultimately form stable biochemicals. Most of these reactive intermediates would have been produced at relatively slow rates, resulting in low concentrations in the primitive oceans, where many of the reactions of interest would occur. Subsequent reactions which would have produced more complicated molecules would have depended on the balance between atmospheric production rates and rain-out rates of small reactive intermediates, as well as the degradation rates, which would have depended on the temperature and pH of the early oceans. It is difficult to estimate the concentrations of the compounds that could have been achieved without knowing the source production rates or loss rates in the environment. Nevertheless, low temperatures would have been more conducive to prebiotic organic synthesis, using the assumptions above. For example, steady-state concentrations of HCN would have depended on production rates as well as on the energy flux and the reducing nature of the early atmosphere. Sinks for HCN would have been photolysis and hydrolysis of HCN [31], as well as the pH and temperature of the early oceans and the rate of circulation of the oceans through hydrothermal vents.

Ultraviolet irradiation of reduced metal sulfides has been shown to be able to reduce CO₂ to various low molecular weight compounds including methanol, HCHO, HCOOH, and short fatty acids [32]. This may have been an important source of biomolecules on the early Earth.

Concentration Mechanisms

When aqueous solutions are frozen, as the ice lattice forms solutes are excluded and extremely concentrated brines may be formed. In the case of HCN, the final eutectic mixture contains 75% HCN. In principle any degree of concentration up to this point is possible. Salt water, however, cannot be concentrated to the same degree as fresh water in a eutectic; for example, from 0.5 M NaCl, similar to the concentration in the modern ocean, the eutectic of the dissolved salt is the limit, which is only a concentration factor of ~10. Eutectic freezing has been shown to be an excellent mechanism for producing biomolecules such as amino acids and adenine from HCN [33]. This would of course require that at least some regions of the early Earth were cold enough to freeze, which would require that atmospheric greenhouse warming due to CO₂, CH₄, and NH₃ or organic aerosols was not so great as to prohibit at least localized freezing.

Concentration by evaporation is also possible for nonvolatile compounds, as long as they are stable to the drying process [34]. Some prebiotic organic syntheses may have depended on the availability of dry land areas. Although continental crust had almost certainly not yet formed, the geological record contains some evidence of sedimentary rocks that must have been deposited in shallow environments on the primitive Earth. It is not unreasonable to assume that some dry land was available on the primitive Earth in environments such as island arcs.

There is the possibility that hydrophobic compounds could have been concentrated in lipid phases if such phases were available. Calculations and some experiments suggest that an early reducing atmosphere might have been polymerized by solar ultraviolet radiation in geologically short periods of time. An oil slick 1–10 m thick could have been produced in this way and could have been important in the concentration of hydrophobic molecules [35].

Clays are complex mineral assemblages formed from dissolved aluminosilicates. Such minerals form templates for the formation of subsequent layers of mineral, leading to speculation that the first organisms may have been mineral-based [36]. Clays are also capable of binding organic material via ionic and van der Waals forces, and may have been locations for early prebiotic synthesis. Early ion exchange processes would also have concentrated ⁴⁰K⁺, which would have exposed early prebiotic organics to high fluxes of ionizing radiation [30].

SYNTHESIS OF THE MAJOR CLASSES OF BIOCHEMICALS

The top-down approach to origin of life research operates on the premise that the earliest organisms were composed of the same, or similar,

biochemicals as modern organisms. The following sections will consider biomolecules and experimental results demonstrating how these may have come to be synthesized on the primitive Earth via plausible geochemical processes.

Amino Acids

Experimental evidence in support of Oparin's hypothesis of chemical evolution came first from Urey's laboratory, which had been involved with the study of the origin of the solar system and the chemical events associated with this process.

Urey considered the origin of life in the context of his proposal of a highly reducing terrestrial atmosphere [37]. The first successful prebiotic amino acid synthesis was carried out with an electric discharge (figure 1.1) and a strongly reducing model atmosphere of CH_4 , NH_3 , H_2O , and H_2 [38]. The result of this experiment was a large yield of racemic amino acids, together with hydroxy acids, short aliphatic acids, and urea (table 1.3). One of the surprising results of this experiment was that the products were not a large random mixture of organic compounds, but rather a relatively small number of compounds were produced in substantial yield. Moreover, with a few exceptions, the compounds were of biochemical significance. The synthetic routes to prebiotic bioorganic compounds and the geochemical

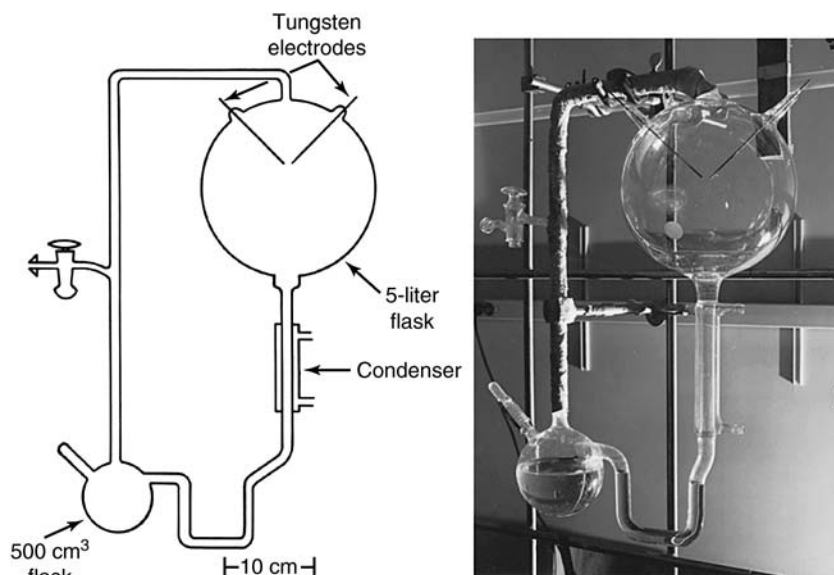


Figure 1.1 The apparatus used in the first electric discharge synthesis of amino acids and other organic compounds in a reducing atmosphere. It was made entirely of glass, except for the tungsten electrodes [38].

Table 1.3 Yields of small organic molecules from sparking a mixture of methane, hydrogen, ammonia, and water (yields given based on input carbon in the form of methane [59 mmoles (710 mg)])

Compound	Yield (μ moles)	Yield (%)
Glycine	630	2.1
Glycolic acid	560	1.9
Sarcosine	50	0.25
Alanine	340	1.7
Lactic acid	310	1.6
<i>N</i> -Methylalanine	10	0.07
α -Amino- <i>n</i> -butyric acid	50	0.34
α -Aminoisobutyric acid	1	0.007
α -Hydroxybutyric acid	50	0.34
β -Alanine	150	0.76
Succinic acid	4	0.27
Aspartic acid	4	0.024
Glutamic acid	6	0.051
Iminodiacetic acid	55	0.37
Iminoaceticpropionic acid	15	0.13
Formic acid	2330	4.0
Acetic acid	150	0.51
Propionic acid	130	0.66
Urea	20	0.034
<i>N</i> -Methyl urea	15	0.051

plausibility of these became experimentally tractable as a result of this experimental demonstration.

The mechanism of synthesis of the amino and hydroxy acids formed in the spark discharge experiment was investigated [39]. The presence of large quantities of hydrogen cyanide, aldehydes, and ketones in the water flask (figure 1.2), which were clearly derived from the methane, ammonia, and hydrogen originally included in the apparatus, showed that the amino acids were not formed directly in the electric discharge, but were the outcome of a Strecker-like synthesis that involved aqueous phase reactions of reactive intermediates. The mechanism is shown in figure 1.3.

Detailed studies of the equilibrium and rate constants of these reactions have been performed [40]. The results demonstrate that both amino and hydroxy acids could have been synthesized at high dilutions of HCN and aldehydes in the primitive oceans. The reaction rates depend on temperature, pH, HCN, NH_3 , and aldehyde concentrations, and are rapid on a geological time scale. The half-lives for the hydrolysis of the intermediate products in the reactions, amino and hydroxy nitriles, can be less than a thousand years at 0 °C [41].

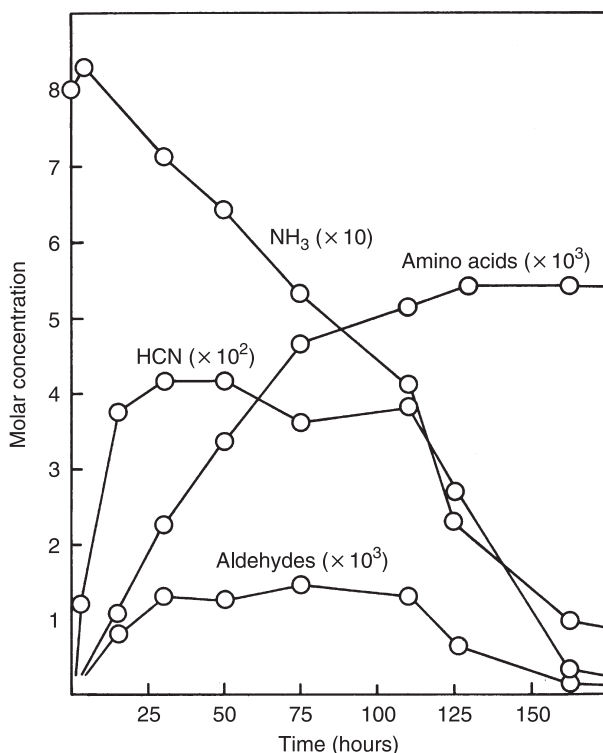


Figure 1.2 The concentrations of ammonia (NH_3), hydrogen cyanide (HCN), and aldehydes (CHO-containing compounds) present in the lowermost U-tube of the apparatus shown in figure 1.1. The concentrations of the amino acids present in the lower flask are also shown. These amino acids were produced from the sparking of a gaseous mixture of methane (CH_4), ammonia (NH_3), water vapor (H_2O), and hydrogen in the upper flask. The concentrations of NH_3 , HCN, and aldehydes decrease over time as they are converted to amino acids.

The slow step in amino acid synthesis is the hydrolysis of the amino nitrile which could take 10,000 years at pH 8 and 25 °C. An additional example of a rapid prebiotic synthesis is that of amino acids on the Murchison meteorite (which will be discussed later), which apparently took place in less than 10^5 years [42]. These results suggest that if the prebiotic environment was reducing, then the synthesis of the building blocks of life was efficient and did not constitute the limiting step in the emergence of life.

The Strecker synthesis of amino acids requires the presence of ammonia (NH_3) in the prebiotic environment. As discussed earlier,

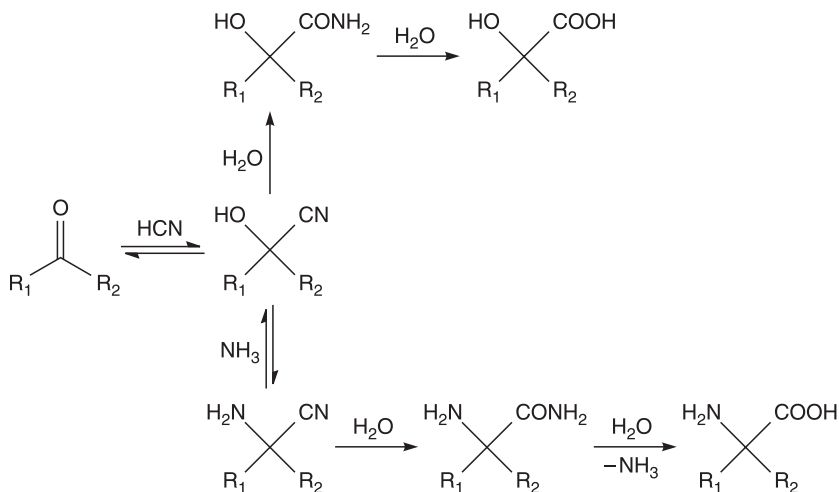


Figure 1.3 The Strecker and cyanohydrin mechanisms for the formation of amino and hydroxy acids from ammonia, aldehydes and ketones, and cyanide.

gaseous ammonia is rapidly decomposed by ultraviolet light [43], and during early Archean times the absence of a significant ozone layer would have imposed an upper limit to its atmospheric concentration. Since ammonia is very soluble in water, if the buffer capacity of the primitive oceans and sediments was sufficient to maintain the pH at ~ 8 , then dissolved NH_4^+ (the pK_a of NH_3 is ~ 9.2) in equilibrium with dissolved NH_3 would have been available. Since NH_4^+ is similar in size to K^+ and thus easily enters the same exchange sites on clays, NH_4^+ concentrations were probably no higher than 0.01 M. The ratio of hydroxy acids to amino acids is governed by the ammonia (NH_3) concentration which would have to be ~ 0.01 M at 25°C to make a 50/50 mix; equal amounts of the cyanohydrin and aldehyde are generated at CN^- concentrations of 10^{-2} to 10^{-4} M. A more realistic atmosphere for the primitive Earth may be a mixture of CH_4 with N_2 with traces of NH_3 . There is experimental evidence that this mixture of gases is quite effective with electric discharges in producing amino acids [41]. Such an atmosphere, however, would nevertheless be strongly reducing.

Alternatively, amino acids can be synthesized from the reaction of urea, HCN, and an aldehyde or a ketone (the Bucherer-Bergs synthesis, figure 1.4). This reaction pathway may have been significant if little free ammonia were available.

A wide variety of direct sources of energy must have been available on the primitive Earth (table 1.2). It is likely that in the prebiotic environment solar radiation, and not atmospheric electricity, was the major

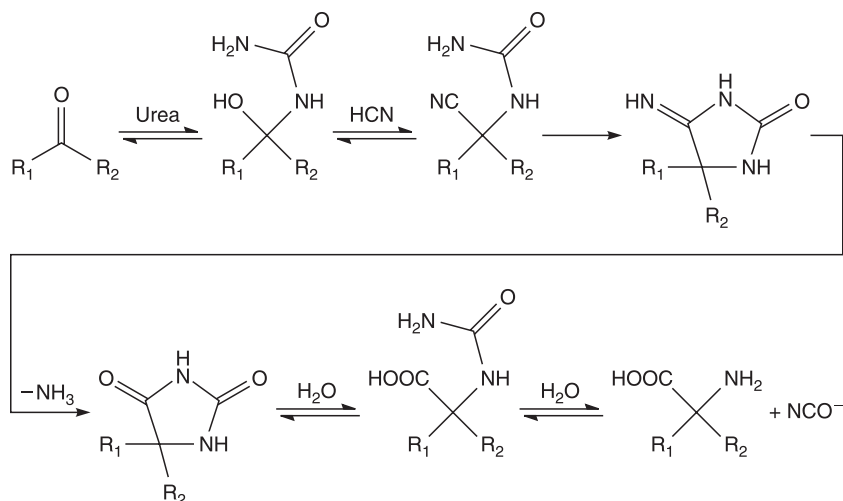


Figure 1.4 The Bucherer–Bergs mechanism of synthesis of amino acids, which uses urea instead of ammonia as the source of the amino group.

source of energy reaching the Earth's surface. However, it is unlikely that any single one of the energy sources listed in table 1.2 can account for all organic compound syntheses. The importance of a given energy source in prebiotic evolution is determined by the product of the energy available and its efficiency in generating organic compounds. Given our current ignorance of the prebiotic environment, it is impossible to make absolute assessments of the relative significance of these different energy sources. For instance, neither the pyrolysis (800 to 1200 °C) of a CH_4/NH_3 mixture or the action of ultraviolet light acting on a strongly reducing atmosphere give good yields of amino acids. However, the pyrolysis of methane, ethane, and other hydrocarbons gives good yields of phenylacetylene, which upon hydration yields phenylacetaldehyde. The latter could then participate in a Strecker synthesis and act as a precursor to the amino acids phenylalanine and tyrosine in the prebiotic ocean.

The available evidence suggests that electric discharges were the most important source of hydrogen cyanide, which is recognized as an important intermediate in prebiotic synthesis. However, the hot H atom mechanism suggested by Zahnle could also have been significant [44]. In addition to its central role in the formation of amino nitriles during the Strecker synthesis, HCN polymers have been shown to be a source of amino acids. Ferris et al. [45] have demonstrated that, in addition to urea, guanidine, and oxalic acid, hydrolysis of HCN polymers

produces glycine, alanine, aspartic acid, and aminoisobutyric acid, although the yields are not particularly high except for glycine (~1%).

Modern organisms construct their proteins from ~20 universal amino acids which are almost exclusively of the L enantiomer. The amino acids produced by prebiotic syntheses would have been racemic. It is unlikely that all of the modern amino acids were present in the primitive environment, and it is unknown which, if any, would have been important for the origin of life.

Acrolein would have been produced in fairly high yield from the reaction of acetaldehyde with HCHO [46], which has several very robust atmospheric syntheses. Acrolein can be converted into several of the biological amino acids via reaction with various plausible prebiotic compounds [47] (figure 1.5).

There has been less experimental work with gas mixtures containing CO and CO₂ as carbon sources instead of CH₄, although CO-dominated atmospheres could not have existed except transiently. Spark discharge experiments using CH₄, CO, or CO₂ as a carbon source with various

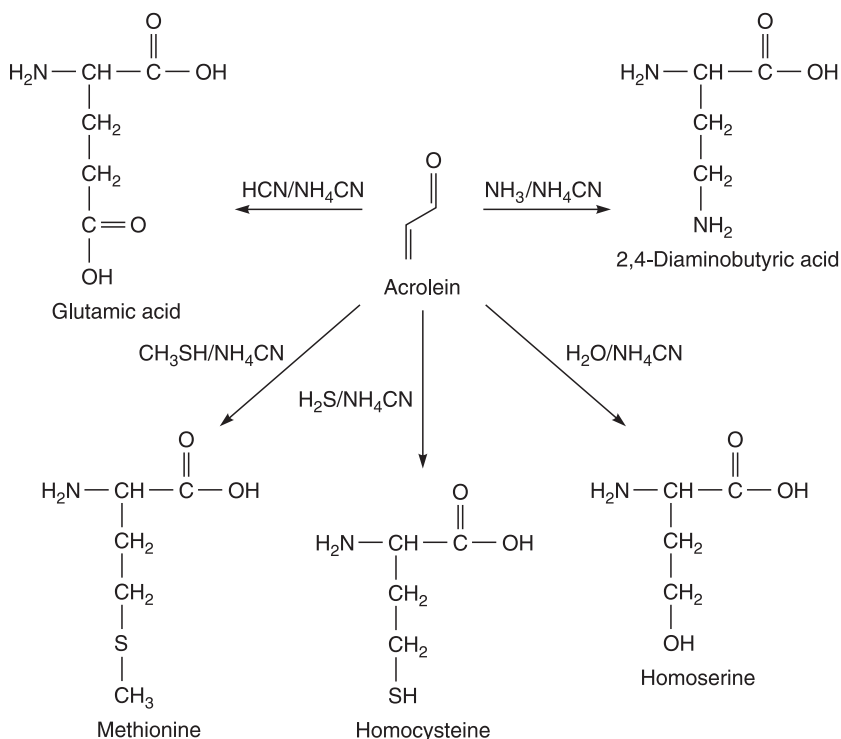


Figure 1.5 Acrolein may serve as an important precursor in the prebiotic synthesis of several amino acids.

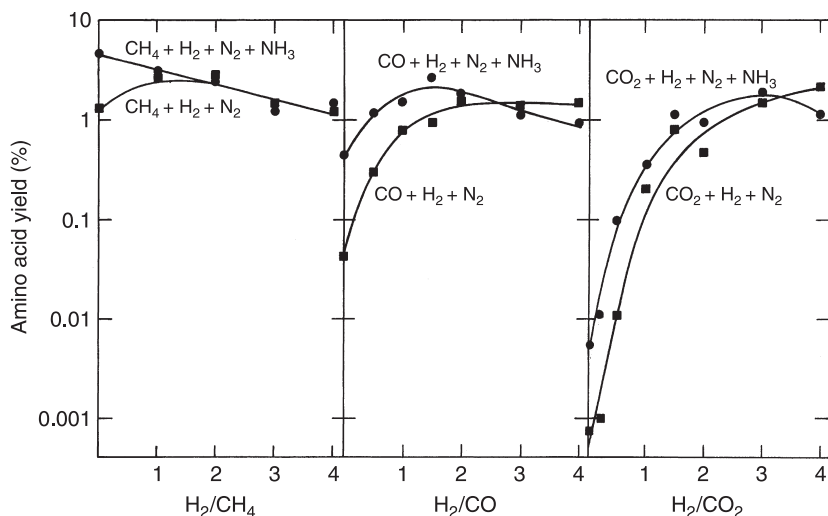


Figure 1.6 Amino acid yields based on initial carbon. In all experiments reported here, the partial pressure of N_2 , CO, or CO_2 was 100 torr. The flask contained 100 ml of water with or without 0.05M NH_4Cl brought to pH 8.7. The experiments were conducted at room temperature, and the spark generator was operated continuously for two days.

amounts of H_2 have shown that methane is the best source of amino acids, but CO and CO_2 are almost as good if a high H_2/C ratio is used (figure 1.6). Without added hydrogen, however, the amino acid yields are very low, especially when CO_2 is the sole carbon source. The amino acid diversity produced in CH_4 experiments is similar to that reported by Miller [38]. With CO and CO_2 , however, glycine was the predominant amino acid, with little else besides alanine produced [41].

The implication of these results is that CH_4 is the best carbon source for abiotic synthesis. Although glycine was essentially the only amino acid produced in spark discharge experiments with CO and CO_2 , as the primitive ocean matured the reaction between glycine, H_2CO , and HCN could have led to the formation of other amino acids such as alanine, aspartic acid, and serine.

Such simple mixtures may have lacked the chemical diversity required for prebiotic evolution and the origin of the first life forms. However, since it is not known which amino acids were required for the emergence of life, we can say only that CO and CO_2 are less favorable than CH_4 for prebiotic amino acid synthesis, but that amino acids produced from CO and CO_2 may have been adequate. The spark discharge yields of amino acids, HCN, and aldehydes are about the same using CH_4 , $H_2/CO > 1$, or $H_2/CO_2 > 2$. However, it is not clear how such high molecular hydrogen-to-carbon ratios for the last

two reaction mixtures could have been maintained in the prebiotic atmosphere.

Synthesis of Nucleic Acid Bases

Nucleic acids are the central repository of the information that organisms use to construct enzymes via the process of protein synthesis. In all living organisms genetic information is stored in DNA, which is composed of repeating units of deoxyribonucleotides (figure 1.7), which is transcribed into linear polymers of RNA, which are composed of repeating polymers of ribonucleotides. The difference between these two is the usage of deoxyribose in DNA and ribose in RNA, and uracil in RNA and thymine in DNA. It is generally agreed that one of the principal characteristics of life is the ability to transfer information from one generation to the next. Nucleic acids seem uniquely structured for this function, and thus a considerable amount of attention has been dedicated to elucidating their prebiotic synthesis.

PURINES

The first evidence that the components of nucleic acids may have been synthesized abiotically was provided in 1960 [48]. Juan Oró, who was at the time studying the synthesis of amino acids from aqueous solutions of HCN and NH_3 , reported the abiotic formation of adenine, which may be considered a pentamer of HCN ($\text{C}_5\text{H}_5\text{N}_5$) from these same mixtures.

Oró found that concentrated solutions of ammonium cyanide which were refluxed for a few days produced adenine in up to 0.5% yield along with 4-aminoimidazole-5-carboxamide and an intractable polymer [48,49]. The polymer also yields amino acids, urea, guanidine, cyanamide, and cyanogen. It is surprising that a synthesis requiring at least five steps should produce such high yields of adenine. The mechanism of synthesis has since been studied in some detail. The initial step is the dimerization of HCN followed by further reaction to give HCN trimer and HCN tetramer, diaminomaleonitrile (DAMN) (figure 1.8).

As demonstrated by Ferris and Orgel [50], a two-photon photochemical rearrangement of diaminomaleonitrile proceeds readily with high yield in sunlight to amino imidazole carbonitrile (AICN) (figure 1.9). Further reaction of AICN with small molecules generated in polymerizing HCN produces the purines (figure 1.10).

The limits of the synthesis as delineated by the kinetics of the reactions and the necessity of forming the dimer, trimer, and tetramer of HCN have been investigated, and this has been used to delineate the limits of geochemically plausible synthesis. The steady-state concentrations of HCN would have depended on the pH and temperature of the early oceans and the input rate of HCN from atmospheric synthesis.

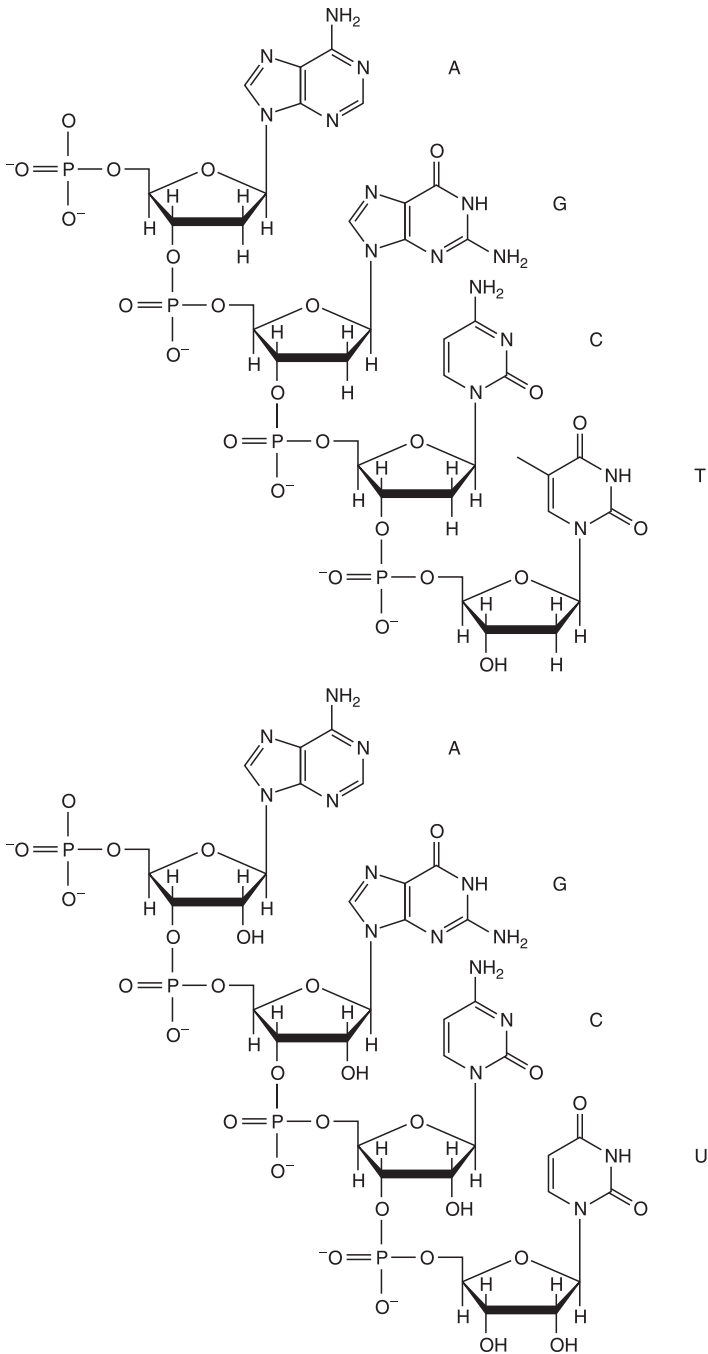


Figure 1.7 The structures of DNA and RNA (A = adenine, G = guanine, C = cytosine, T = thymine, U = uracil).

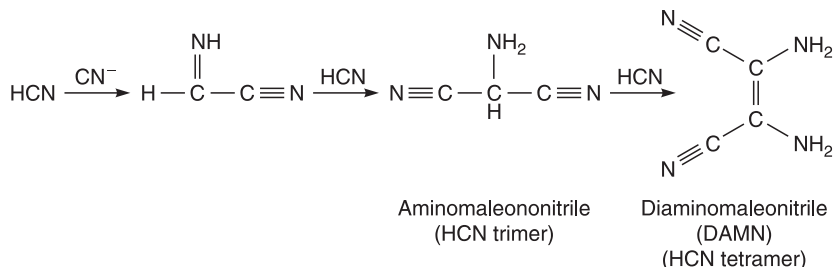


Figure 1.8 The mechanism of formation of DAMN from HCN.

Assuming favorable production rates, Miyakawa et al. [31] estimated steady-state concentrations of HCN of $2 \times 10^{-6} \text{ M}$ at pH 8 and 0°C in the primitive oceans. At 100°C and pH 8 the steady-state concentration would have been $7 \times 10^{-13} \text{ M}$. HCN hydrolyzes to formamide, which then hydrolyzes to formic acid and ammonia. It has been estimated that oligomerization and hydrolysis compete at approximately 10^{-2} M concentrations of HCN at pH 9 [51], although it has been shown that adenine is still produced from solutions as dilute as 10^{-3} M [52].

If the concentration of HCN were as low as estimated, it is possible that HCN tetramer formation may have occurred on the primitive Earth in eutectic solutions of HCN–H₂O, which may have existed in the polar regions of an Earth of the present average temperature. High yields of the HCN tetramer have been reported by cooling dilute cyanide solutions to temperatures between -10 and -30°C for a few months [51]. Production of adenine by HCN polymerization is accelerated by the presence of formaldehyde and other aldehydes, which could have also been available in the prebiotic environment [53].

The prebiotic synthesis of guanine was first studied under conditions that required unrealistically high concentrations of a number of precursors, including ammonia [54]. Purines, including guanine,

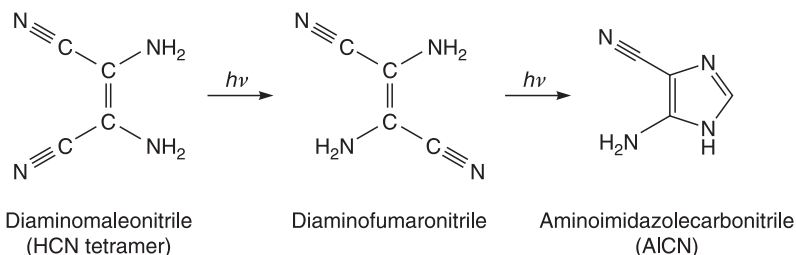


Figure 1.9 The synthesis of AICN via photoisomerization of DAMN.

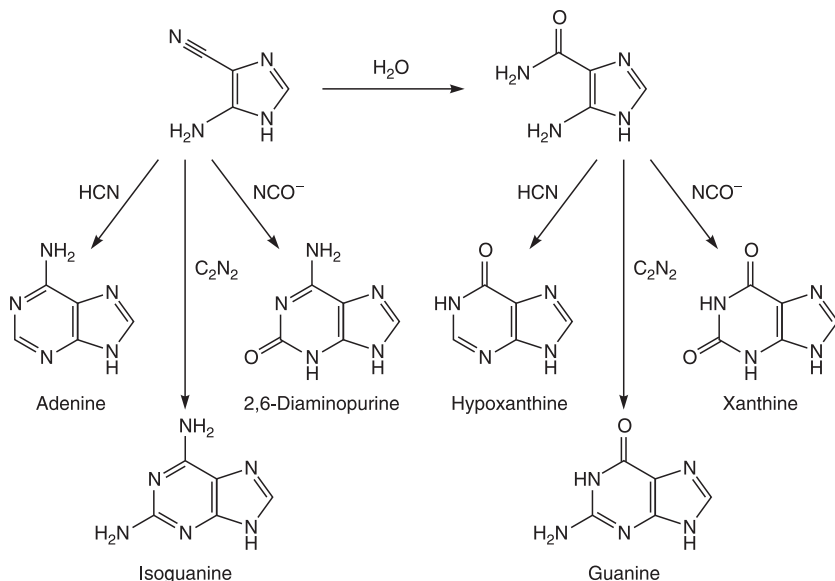


Figure 1.10 Prebiotic synthesis of purines from AICN.

hypoxanthine, xanthine, and diaminopurine, could have been produced in the primitive environment by variations of the adenine synthesis using aminoimidazole carbonitrile and aminoimidazole carboxamide [55] with other small molecule intermediates generated from HCN.

Reexamination of the polymerization of concentrated NH_4CN solutions has shown that, in addition to adenine, guanine is also produced at both -80 and -20°C [56]. It is probable that most of the guanine obtained from the polymerization of NH_4CN is the product of 2,6-diaminopurine hydrolysis, which reacts readily with water to give guanine and isoguanine. The yields of guanine in this reaction are 10 to 40 times less than those of adenine. Adenine, guanine, and a simple set of amino acids dominated by glycine have also been detected in dilute solutions of NH_4CN which were kept frozen for 25 years at -20 and -78°C , as well as in the aqueous products of spark discharge experiments from a reducing experiment frozen for 5 years at -20°C [33].

The mechanisms described above are likely an oversimplification. In dilute aqueous solutions adenine synthesis may also involve the formation and rearrangement of other precursors such as 2-cyano and 8-cyano adenine [53].

PYRIMIDINES

The prebiotic synthesis of pyrimidines has also been investigated extensively. The first synthesis investigated was that of uracil from

malic acid and urea [57]. The abiotic synthesis of cytosine in an aqueous phase from cyanoacetylene (HCCCN) and cyanate (NCO^-) was later described [58,59]. Cyanoacetylene is abundantly produced by the action of a spark discharge on a mixture of methane and nitrogen, and cyanate is produced from cyanogen (NCCN) or from the decomposition of urea (H_2NCONH_2). Cyanoacetylene is apparently also a Strecker synthesis precursor to aspartic acid. However, the high concentrations of cyanate ($> 0.1 \text{ M}$) required in this reaction are unrealistic, since cyanate is rapidly hydrolyzed to CO_2 and NH_3 . Urea itself is fairly stable, depending on the concentrations of NCO^- and NH_3 . Later, it was found that cyanoacetaldehyde (the hydration product of cyanoacetylene) and urea react to form cytosine and uracil. This was extended to a high yield synthesis that postulated drying lagoon conditions. The reaction of uracil with formaldehyde and formate gives thymine in good yield [60]. Thymine may also be synthesized from the UV-catalyzed dehydrogenation of dihydrothymine. This is produced from the reaction of β -aminoisobutyric acid with urea [61].

The reaction of cyanoacetaldehyde (which is produced in high yields from the hydrolysis of cyanoacetylene) with urea produces no detectable levels of cytosine [62]. However, when the same nonvolatile compounds are concentrated in laboratory models of "evaporating pond" conditions simulating primitive lagoons or pools on drying beaches on the early Earth, surprisingly high amounts of cytosine ($>50\%$) are observed [63]. These results suggest a facile mechanism for the accumulation of pyrimidines in the prebiotic environment (figure 1.11).

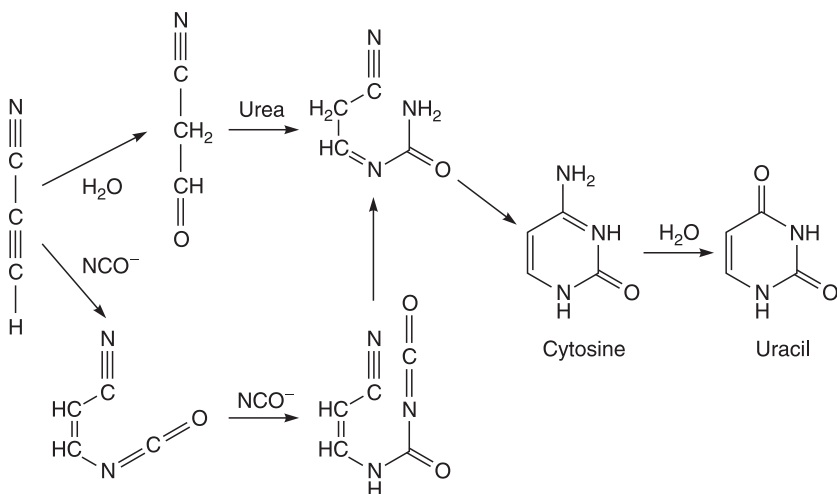


Figure 1.11 Two possible mechanisms for the prebiotic synthesis of the biological pyrimidines.

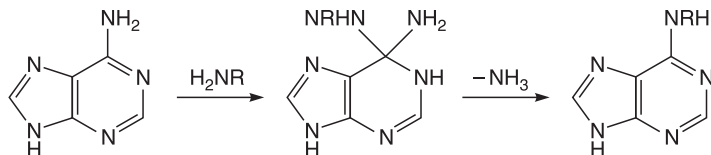


Figure 1.12 One possible mechanism for the formation of N⁶ modified purines.

A related synthesis under evaporating conditions uses cyanoacetaldehyde with guanidine, which produce diaminopyrimidine [62] in very high yield [64], which then hydrolyzes to uracil and small amounts of cytosine. Uracil (albeit in low yields), as well as its biosynthetic precursor orotic acid, have also been identified among the hydrolytic products of hydrogen cyanide polymer [45,65].

A wide variety of other modified nucleic acid bases may also have been available on the early Earth. The list includes isoguanine, which is a hydrolytic product of diaminopurine [56], and several modified purines which may have resulted from side reactions of both adenine and guanine with a number of alkylamines under the concentrated conditions of a drying pond [66], including N⁶-methyladenine, 1-methyladenine, N⁶,N⁶-dimethyladenine, 1-methylhypoxanthine, 1-methylguanine, and N²-methylguanine (figure 1.12).

Modified pyrimidines may have also been present in the primitive Earth. These include dihydrouridine, which is formed from NCO⁻ and β-alanine [67], and others like diaminopyrimidine, thiocytosine [64], and 5-substituted uracils, formed via reaction of uracil with formaldehyde, whose functional side groups may have played an important role in the early evolution of catalysis prior to the origin of proteins, and which are efficiently formed under plausible prebiotic conditions [68] (figure 1.13).

Carbohydrates

Most biological sugars are composed of the empirical formula (CH₂O)_{*n*}, a point that was underscored by Butlerow's 1861 discovery of the formose reaction [69], which showed that a complex mixture of the sugars of biological relevance could be formed by the reaction of HCHO under basic conditions. The Butlerow synthesis is complex and incompletely understood. It depends on the presence of suitable inorganic catalysts, with calcium hydroxide (Ca(OH)₂) or calcium carbonate (CaCO₃) being the most completely investigated. In the absence of basic catalysts, little or no sugar is obtained. At 100 °C, clays such as kaolin serve to catalyze the formation of sugars, including ribose,

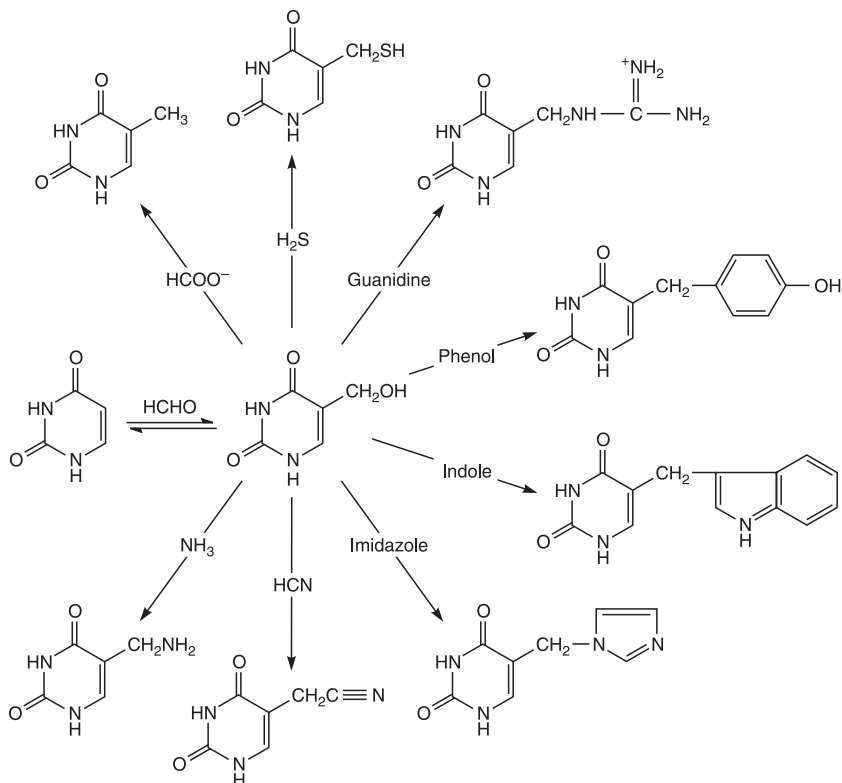


Figure 1.13 The reaction of uracil with formaldehyde to produce 5-hydroxymethyl uracil, and functional groups attached to 5-substituted uracil. Incorporation of these amino acid analogs into polyribonucleotides during the “RNA world” stage may have led to a substantial widening of the catalytic properties of ribozymes.

in small yields from dilute (0.01 M) solutions of formaldehyde [70–72]. This reaction has been extensively investigated with regard to catalysis and several interesting phenomena have been observed. For instance, the reaction is catalyzed by glycolaldehyde, acetaldehyde, and various organic catalysts [73].

Ribose was among the last of life’s building blocks characterized by chemists. Suggestions for the existence of an “RNA world,” a period during early biological evolution when biological systems used RNA both as a catalyst and an informational macromolecule, make it possible that ribose may have been among the oldest carbohydrates to be employed by living beings. Together with the other sugars that are produced by the condensation of formaldehyde under alkaline conditions [69],

it is also one of the organic compounds to be synthesized in the laboratory under conditions that are relevant from a prebiotic perspective.

The Butlerow synthesis is autocatalytic and proceeds through glycoaldehyde, glyceraldehyde, and dihydroxyacetone, four-carbon sugars, and five-carbon sugars to give finally hexoses, including biologically important carbohydrates such as glucose and fructose. The detailed reaction sequence may proceed as shown in figure 1.14.

The reaction produces a complex mixture of sugars including various 3-, 4-, 5-, 6-, and 7-membered carbohydrates, including all isomers (for the addition of each CH_2O unit, both isomers are produced) (figure 1.11) and generally is not particularly selective, although methods of overcoming this have been investigated. Inclusion of acetaldehyde in the reaction may lead to the formation of deoxyribose [74] (figure 1.15).

The reaction tends to stop when the formaldehyde has been consumed and ends with the production of higher C4–C7 sugars that can form cyclic acetals and ketals. The reaction produces all of the epimers and isomers of the small C2–C6 sugars, some of the C7 ones, and various dendroaldoses and dendroketoses, as well as small molecules such as glycerol and pentaerythritol. Schwartz and De Graaf [72] have discovered an interesting photochemical formose reaction that generates pentaerythritol almost exclusively.

Both L- and D-ribose occur in this complex mixture, but are not particularly abundant. Since all carbohydrates have somewhat similar chemical properties, it is difficult to envision simple mechanisms that could lead to the enrichment of ribose from this mixture, or how the relative yield of ribose required for the formation of RNA could be enhanced. However, the recognition that the biosynthesis of sugars leads not to the formation of free carbohydrates but of sugar phosphates, led Albert Eschenmoser and his associates to show that, under slightly basic conditions, the condensation of glycoaldehyde-2-phosphate in the presence of formaldehyde results in the considerably selective synthesis of ribose-2,4-diphosphate [75]. This reaction has also been shown to take place under neutral conditions and low concentrations in the presence of minerals [76], and is particularly attractive given the properties of pyranosyl-RNA (p-RNA), a 2',4'-linked nucleic acid analog whose backbone includes the six-member pyranose form of ribose-2,4-diphosphate [77]. The major problem with this work is that a reasonable source of the starting material, oxirane carbonitrile (which hydrolyzes to glycolaldehyde-2-phosphate), has not been identified.

There are three major obstacles to the relevance of the formose reaction as a source of sugars on the primitive Earth. The first problem is that the Butlerow synthesis gives a wide variety of straight-chain and branched sugars. Indeed, more than 40 different sugars have

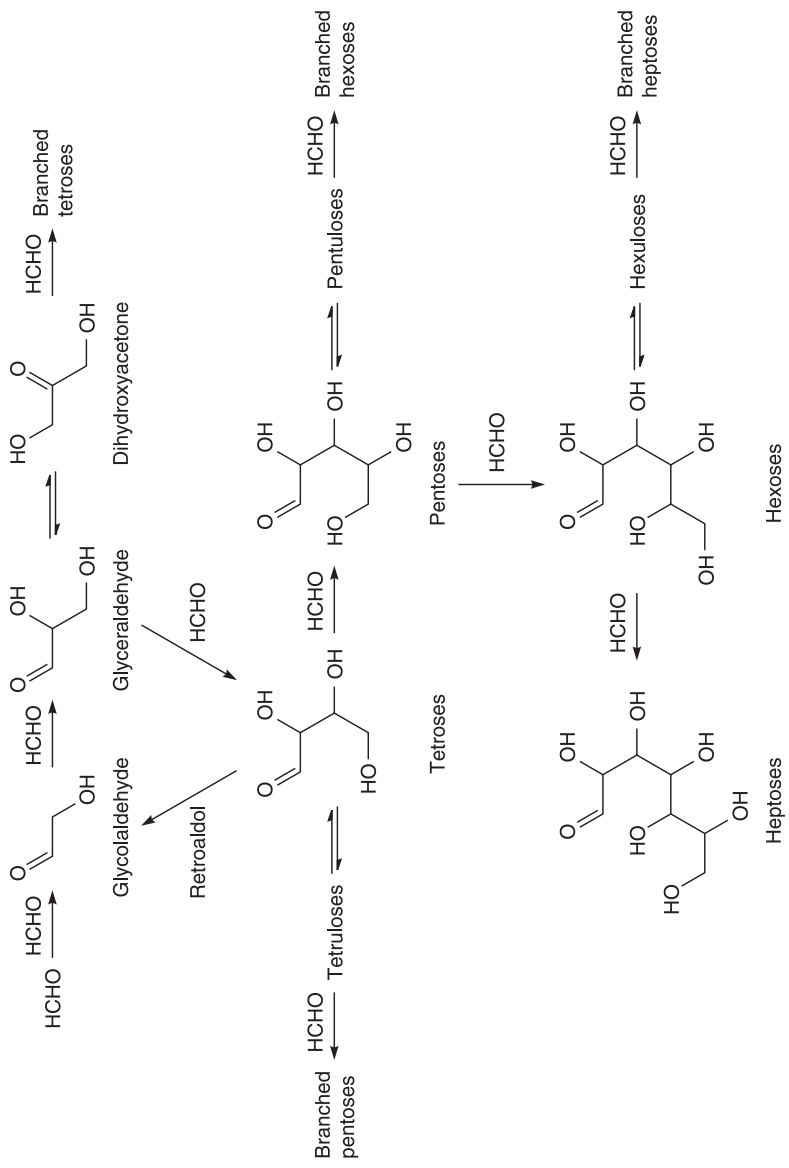


Figure 1.14 A simplified scheme of the formose reaction.

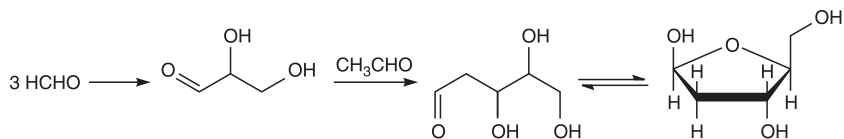


Figure 1.15 Possible prebiotic synthesis of deoxyribose from glyceraldehyde and acetaldehyde.

been identified in one reaction mixture [78] (figure 1.16). The second problem is that the conditions of synthesis are also conducive to the degradation of sugars [71]. Sugars undergo various diagenetic reactions on short geological time scales that are seemingly prohibitive to the accumulation of significant amounts on the primitive Earth. At pH 7, the half-life for decomposition of ribose is 73 minutes at 100 °C, and 44 years at 0 °C [79]. The same is true of most other sugars, including ribose-2,4-diphosphate. The third problem is that the concentrations of HCHO required appear to be prebiotically implausible, although the limits of the synthesis have not been determined.

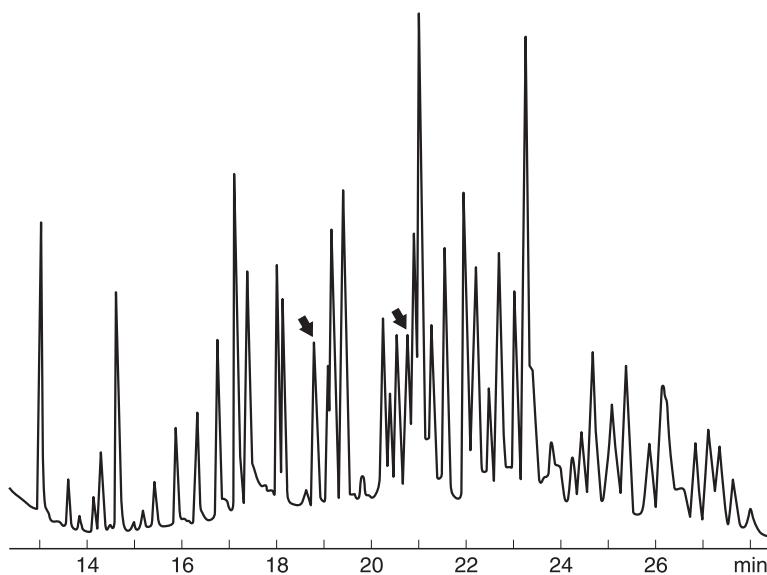


Figure 1.16 Gas chromatogram of derivatives of the sugars formed by the formose reaction. The arrows point to the two ribose isomers (adapted from Decker et al. [78]).

There are a number of possible ways to stabilize sugars; the most interesting one is to attach the sugar to a purine or pyrimidine, that is, by converting the carbohydrate to a glycoside, but the synthesis of nucleosides is notoriously difficult under plausible prebiotic conditions. It therefore has become apparent that ribonucleotides could not have been the first components of prebiotic informational macromolecules [80]. This has led to propositions of a number of possible substitutes for ribose in nucleic acid analogs, in what has been dubbed the “pre-RNA world” [81].

A Paradox?

When aqueous solutions of HCN and HCHO are mixed, the predominant product is glycolonitrile [82], which seems to preclude the formation of sugars and nucleic acid bases in the same location [83]. Nevertheless both sugars and nucleic acid bases have been found in the Murchison meteorite [84,85] and it seems likely that the chemistry which produced the compounds found in the Murchison meteorite was from reactions such as the Strecker synthesis. This suggests that the conditions for the synthesis of sugars, amino acids, and purines from HCHO and HCN, either exist at very limited concentrations of NH_3 , HCN, and HCHO and pH, or the two precursors were produced under different regimes in different locations.

Lipids

Amphiphilic molecules are especially interesting due to their propensity to spontaneously assemble into micelles and vesicles. Cell membranes are almost universally composed of phosphate esters of fatty acid glycerides. Fatty acids are biosynthesized today by multifunctional enzymes or enzyme complexes. Nevertheless, as all life we know of is composed of cells, these compounds seem crucial. Eukaryotic and bacterial cell membranes are composed of largely straight-chain fatty acid acyl glycerols while those of the Archaea are often composed of polyisoprenoid glycerol ethers. Either type may have been the primordial lipid component of primitive cells.

Most prebiotic simulations fail to generate large amounts of fatty acids, with the exception of simulated hydrothermal vent reactions, which arguably use unreasonably high concentrations of reactants [86]. Heating glycerol with fatty acids and urea has been shown to produce acylglycerols [87]. A prebiotic synthesis of long-chain isoprenoids has been suggested by Ourisson based on the Prins reaction of formaldehyde with isobutene [88].

The Murchison meteorite contains small amounts of higher straight-chain fatty acids, some of which may be contamination [89]. Amphiphilic components have been positively identified in the Murchison meteorite [90], although the yields of these molecules are poor in typical spark discharge experiments [91].

Cofactors

It might be assumed that most of the inorganic cofactors (Mo, Fe, Mn, etc.) were present as soluble ions in the prebiotic seas to some degree. Many of the organic cofactors, however, are either clearly byproducts of an extant metabolism or have syntheses so complex that their presence on the early Earth cannot reasonably be postulated. Most enzyme-catalyzed reactions use a cofactor, and these are often members of a small set of small biochemicals known collectively as vitamins. The most widely used is nicotinamide, and several prebiotic syntheses of this compound have been devised [92,93]. Other interesting vitamins that have prebiotic syntheses include components of coenzyme A and coenzyme M [94–96] and analogs of pyridoxal [97]. There have been reports of flavin-like compounds generated from dry-heated amino acids, but these have not been well characterized [98]. It may be that many compounds that do not have prebiotic syntheses were generated later once a functioning biochemistry was in place [99].

Interestingly, many of these are able to carry out their catalyses, albeit to a lesser degree, in the absence of the enzyme. Nonenzymatic reactions that occur in the presence of vitamin cofactors include thiamin-mediated formose reactions [100] and transamination with pyridoxal [101]. These may have some relevance to prebiotic chemistry, or perhaps to the early development of metabolism.

It is unclear whether porphyrins were necessary for the origin of life, although they are now a part of every terrestrial organism's biochemistry as electron carriers and photopigments. They can be formed rather simply from the reaction of pyrroles and HCHO [102,103] (figure 1.17).

Small Molecules Remaining to be Synthesized

There are numerous biochemicals that do not appear to be prebiotically accessible, despite some interesting prebiotic syntheses that have been developed. Tryptophan, phenylalanine, tyrosine, histidine, arginine, lysine, and the cofactors pyridoxal, thiamin, riboflavin, and folate are notable examples. These may not be necessary for the origin of life and may be instead byproducts of a more evolutionarily sophisticated metabolism.

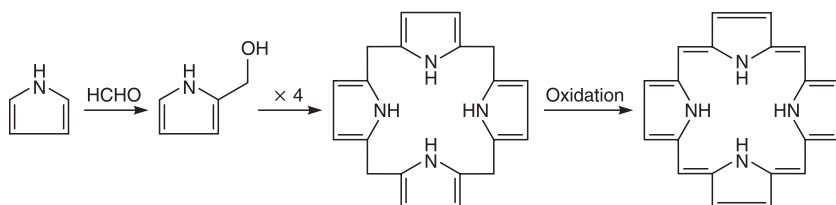


Figure 1.17 Prebiotic synthesis of porphyrins from pyrroles and formaldehyde.

Nucleosides

One popular theory for the origin of life posits the existence of an RNA world, a time when RNA molecules played the roles of both catalysts and genetic molecule [104]. A great deal of research has been carried out on the prebiotic synthesis of nucleosides and nucleotides. Although few researchers still consider this idea plausible for the origin of life, it is possible that an RNA world existed as an intermediary stage in the development of life once a simpler self-replicating system had evolved.

Perhaps the most promising nucleoside syntheses start from purines and pure D-ribose in drying reactions, which simulate conditions that might occur in an evaporating basin. Using hypoxanthine and a mixture of salts reminiscent of those found in seawater, up to 8% of β -D-inosine is formed, along with the α -isomer. Adenine and guanine gave lower yields, and in both cases a mixture of α - and β -isomers was obtained [105].

Pyrimidine nucleosides have proven to be much more difficult to synthesize. Direct heating of ribose and uracil or cytosine has thus far failed to produce uridine or cytidine. Pyrimidine nucleoside syntheses have been demonstrated which start from ribose, cyanamide, and cyanoacetylene; however, α -D-cytidine is the major product [106]. This can be photoanomerized to β -D-cytidine in low yield; however, the converse reaction also occurs. Sutherland and coworkers [107] demonstrated a more inventive approach, showing that cytidine-3'-phosphate can be prepared from arabinose-3-phosphate, cyanamide, and cyanoacetylene in a one-pot reaction. The conditions may be somewhat forced, and the source of arabinose-3-phosphate is unclear, nevertheless the possibility remains that more creative methods of preparing the pyrimidine nucleosides may be possible.

Alternatively, the difficulties with prebiotic ribose synthesis and nucleoside formation have led some to speculate that perhaps a simpler genetic molecule with a more robust prebiotic synthesis preceded RNA. A number of alternatives have been investigated. Some propose substituting other sugars besides ribose. When formed into sugar phosphate polymers, these also often form stable base-paired structures with both RNA/DNA and themselves [77,108–110], opening the possibility of genetic takeover from a precursor polymer to RNA/DNA. These molecules would likely suffer from the same drawbacks as RNA, such as the difficulty of selective sugar synthesis, sugar instability, and the difficulty of nucleoside formation. Recently it has been demonstrated, based on the speculations of Joyce et al. [81] and the chemistry proposed by Nelsestuen [111] and Tohidi and Orgel [112], that backbones based on acyclic nucleoside analogs may be more easily obtained under reasonable prebiotic conditions, for example by the reaction of nucleobases with acrolein during mixed

formose reactions [113]. This remains a largely unexplored area of research.

More exotic alternatives to nucleoside formation have been proposed based on the peptide nucleic acid (PNA) analogs of Nielsen and coworkers [114]. Miller and coworkers [115] were able to demonstrate the facile synthesis of all of the components of PNA in very dilute solution or under the same chemical conditions required for the synthesis of the purines or pyrimidines. The assembly of the molecules into oligomers has not yet been demonstrated and may be unlikely due to the instability of PNA to hydrolysis and cyclization [116]. Nevertheless, there may be alternative structures which have not yet been investigated that may sidestep some of the problems with the original PNA backbone.

Nucleotides

Condensed phosphates are the universal biological energy currency; however, abiological dehydration reactions are extremely difficult in aqueous solution due to the high water activity. Phosphate concentrations in the modern oceans are extremely low, partially due to rapid scavenging of phosphates by organisms, but also because of the extreme insolubility of calcium phosphates. Indeed, almost all of the phosphate present on the Earth today is present as calcium phosphate deposits such as apatite. There is some evidence, however, that condensed phosphates are emitted in volcanic fumaroles [117]. An extensive review of the hydrolysis and formation rates of condensed phosphates has not been conducted; however, it has been suggested that condensed phosphates are not likely to be prebiotically available materials [118]. Heating orthophosphate at relatively low temperatures in the presence of ammonia results in a high yield of condensed phosphates [119]. Additionally, trimetaphosphate (TMP) has been shown to be an active phosphorylating agent for various prebiological molecules including amino acids and nucleosides [120,121].

Early attempts to produce nucleotides used organic condensing reagents such as cyanamide, cyanate, or dicyanamide [122]. Such reactions were generally inefficient due to the competition of the alcohol groups of the nucleosides with water in an aqueous environment.

Nucleosides can be phosphorylated with acidic phosphates such as NaH_2PO_4 when dry heated [123]. The reactions are catalyzed by urea and other amides, particularly if ammonium is included in the reaction. Heating ammonium phosphate with urea also gives a mixture of high molecular weight polyphosphates [119].

Nucleosides can be phosphorylated in high yield by heating ammonium phosphate with urea at moderate temperatures, as might occur in a drying basin [124]. For example, by heating uridine with urea and ammonium phosphate yields of phosphorylated nucleosides as high as

70% have been achieved. In the case of purine nucleosides, however, there is also considerable glycosidic cleavage due to the acidic microenvironment created. This is another problem with the RNA world, that the synthesis of purine nucleosides is somewhat robust, but nucleotide formation may be difficult, while nucleotide formation from pyrimidine nucleosides is robust, but nucleoside formation appears to be difficult.

Hydroxyapatite itself is a reasonable phosphorylating reagent. Yields as high as 20% of nucleosides were achieved by heating nucleosides with hydroxyapatite, urea, and ammonium phosphate [124].

Heating ammonium phosphates with urea leads to a mixture of high molecular weight polyphosphates [119]. Although these are not especially good phosphorylating reagents under prebiotic conditions, they tend to degrade, especially in the presence of divalent cations at high temperatures, to cyclic phosphates such as trimetaphosphate, which have been shown to be promising phosphorylating reagents [121]. *cis*-Glycols react readily with trimetaphosphate under alkaline conditions to yield cyclic phosphates, and the reaction proceeds somewhat reasonably under more neutral conditions in the presence of magnesium cation [125].

HYDROTHERMAL VENTS AND THE ORIGIN OF LIFE

The discovery of hydrothermal vents at the oceanic ridge crests and the appreciation of their significance in the element balance of the hydrosphere represents a major development in oceanography [126]. Since the process of hydrothermal circulation probably began early in the Earth's history, it is likely that vents were present in the Archean oceans. Large amounts of ocean water now pass through the vents, with the whole ocean going through them every 10 million years [127]. This flow was probably greater during the early history of the Earth, since the heat flow from the planet's interior was greater during that period. The topic has received a great deal of attention, partly because of doubts regarding the oxidization state of the early atmosphere.

Following the first report of the vents' existence, a detailed hypothesis suggesting a hydrothermal emergence of life was published [128], in which it was suggested that amino acids and other organic compounds are produced during passage through the temperature gradient of the 350 °C vent waters to the 0 °C ocean waters. Polymerization of the organic compounds thus formed, followed by their self-organization, was also proposed to take place in this environment, leading to the first forms of life.

At first glance, submarine hydrothermal springs would appear to be ideally suited for creating life, given the geological plausibility of a hot early Earth. More than a hundred vents are known to exist along

the active tectonic areas of the Earth, and at least in some of them catalytic clays and minerals interact with an aqueous reducing environment rich in H_2 , H_2S , CO , CO_2 , and perhaps HCN , CH_4 , and NH_3 .

Unfortunately it is difficult to corroborate these speculations with the findings of the effluents of modern vents, as a great deal of the organic material released from modern sources is diagenized biological material, and it is difficult to separate the biotic from the abiotic components of these reactions. Much of the organic component of hydrothermal fluids may be formed from diagenetically altered microbial matter.

So far, the most articulate autotrophic hypothesis stems from the work of Wächtershäuser [129,130], who has argued that life begun with the appearance of an autocatalytic, two-dimensional chemolithotrophic metabolic system based on the formation of the highly insoluble mineral pyrite (FeS_2).

The reaction $FeS + H_2S \rightarrow FeS_2 + H_2$ is very favorable. It is irreversible and highly exergonic with a standard free energy change $\Delta G^\circ = -9.23$ kcal/mol, which corresponds to a reduction potential $E^\circ = -620$ mV. Thus, the FeS/H_2S combination is a strong reducing agent, and has been shown to provide an efficient source of electrons for the reduction of organic compounds under mild conditions. The scenario proposed by Wächtershäuser [129,130] fits well with the environmental conditions found at deep-sea hydrothermal vents, where H_2S , CO_2 , and CO are quite abundant. The FeS/H_2S system does not reduce CO_2 to amino acids, purines, or pyrimidines, although there is more than adequate free energy to do so [131]. However, pyrite formation can produce molecular hydrogen, and reduce nitrate to ammonia, and acetylene to ethylene [132]. More recent experiments have shown that the activation of amino acids with carbon monoxide and $(Ni,Fe)S$ can lead to peptide-bond formation [133]. In these experiments, however, the reactions take place in an aqueous environment to which powdered pyrite has been added; they do not form a dense monolayer of ionically bound molecules or take place on the surface of pyrite.

None of the experiments using the FeS/H_2S system reported so far suggests that enzymes and nucleic acids are the evolutionary outcome of surface-bounded metabolism. The results are also compatible with a more general model of the primitive soup in which pyrite formation is an important source of electrons for the reduction of organic compounds. It is possible that under certain geological conditions the FeS/H_2S combination could have reduced not only CO but also CO_2 released from molten magna in deep-sea vents, leading to biochemical monomers [134]. Peptide synthesis could have taken place in an iron and nickel sulfide system [133] involving amino acids formed by electric discharges via a Strecker-type synthesis, although this scenario requires the transportation of compounds formed at the surface to the deep-sea vents [135]. It seems likely that concentrations of reactants

would be prohibitively low based on second-order reaction kinetics. If the compounds synthesized by this process did not remain bound to the pyrite surface, but drifted away into the surrounding aqueous environment, then they would become part of the prebiotic soup, not of a two-dimensional organism.

In general, organic compounds are decomposed rather than created at hydrothermal vent temperatures, although of course temperature gradients exist. As has been shown by Sowerby and coworkers [136], concentration on mineral surfaces would tend to concentrate any organics created at hydrothermal vents in cooler zones, where other reaction schemes would need to be appealed to.

The presence of reduced metals and the high temperatures of hydrothermal vents have also led to suggestions that reactions similar to those in Fischer–Tropsch-type (FTT) syntheses may be common under such regimes. It is unclear to what extent this is valid, as typical FTT catalysts are easily poisoned by water and sulfide. It has been argued that some of the likely environmental catalysts such as magnetite may be immune to such poisoning [137].

Stability of Biomolecules at High Temperatures

A thermophilic origin of life is not a new idea. It was first suggested by Harvey [138], who argued that the first life forms were heterotrophic thermophiles that had originated in hot springs such as those found in Yellowstone Park. As underlined by Harvey, the one advantage of high temperatures is that the chemical reactions could go faster and the primitive enzymes could have been less efficient. However, high temperatures are destructive to organic compounds. Hence, the price paid is loss of biochemical compounds to decomposition.

Although some progress has been made in synthesizing small molecules under hydrothermal vent type conditions, the larger trend for biomolecules at high-temperature conditions is decomposition. As has been demonstrated by various authors, most biological molecules have half-lives to hydrolysis on the order of minutes to seconds at the high temperatures associated with hydrothermal vents. As noted above, ribose and other sugars are very thermolabile compounds [79]. The stability of ribose and other sugars is problematic, but pyrimidines and purines, and many amino acids, are nearly as labile. At 100 °C the half-life for deamination of cytosine is 21 days, and 204 days for adenine [139,140]. Some amino acids are stable, for example, alanine with a half-life for decarboxylation of approximately 19,000 years at 100 °C, but serine decarboxylates to ethanolamine with a half-life of 320 days [141]. White [142] measured the decomposition of various compounds at 250 °C and pH 7 and found half-lives of amino acids from 7.5 s to 278 min, half-lives for peptide bonds from <1 min to 11.8 min, half-lives for glycoside cleavage in nucleosides from <1 s to 1.3 min, decomposition

of nucleobases from 15 to 57 min, and half-lives for phosphate esters from 2.3 to 420 min. It should be borne in mind that the half-lives for polymers would be even shorter as there are so many potential breakage points in a polymer. Thus, while the vents may serve as synthesis sites for simpler compounds such as acetate or more refractory organic compounds such as fatty acids, it is unlikely they played a major role in synthesizing most biochemicals or their polymers.

350 °C submarine vents do not seem to presently synthesize organic compounds, more likely they decompose them in a time span ranging from seconds to a few hours. Thus, the origin of life in the vents is improbable. This does not imply that the hydrothermal springs were a negligible factor on the primitive Earth. If the mineral assemblages were sufficiently reducing, the rocks near the vents may have been a source of atmospheric CH₄ or H₂. As stated earlier, the concentrations of biomolecules which could have accumulated on the primitive Earth is governed largely by the rates of production and the rates of destruction. Submarine hydrothermal vents would have also been important in the destruction rather than in the synthesis of organic compounds, thus fixing the upper limit for the organic compound concentration in the primitive oceans. Although it is presently not possible to state which compounds were essential for the origin of life, it does seem possible to preclude certain environments if even fairly simple organic compounds were involved [143].

EXTRATERRESTRIAL SYNTHESSES

Regardless of what the early Earth's atmosphere was like, the planet was undoubtedly bombarded then, as it is now, by extraterrestrial material such as meteorites and comets. The presence of extraterrestrial organic compounds had been recognized since the mid-nineteenth century, when Berzelius analyzed in 1834 the Aläis meteorite, a carbonaceous C1 chondrite, and confirmed a few years later when Wöhler studied the Kaba meteorite, a C2 carbonaceous chondrite. Today the presence of a complex array of extraterrestrial organic molecules in meteorites, comets, interplanetary dust, and interstellar molecules is firmly established, and has led some to propose them as exogenous sources of the prebiotic organic compounds necessary for the origin of life [144–147]. One reason for proposing an extraterrestrial origin of the components of the prebiotic soup is the CO₂-rich model of the primitive Earth's atmosphere [148], which would not be as conducive to atmospheric organic synthesis.

The Apollo missions revealed few if any organic materials on the moon; however, doubts as to the occurrence of organic materials in the solar system were laid to rest in 1969 when a meteorite fell in Murchison, Australia. This meteorite was seen to fall and was rapidly

Table 1.4 Relative abundances of amino acids detected in the Murchison meteorite and a spark discharge experiment (adapted from Wolman et al. [158])

Amino acid	Murchison	Electric discharge
Glycine	****	****
Alanine	****	****
α -Amino- <i>n</i> -butyric acid	***	****
α -Aminoisobutyric acid	****	**
Valine	***	**
Norvaline	***	***
Isovaline	**	**
Proline	***	*
Pipecolic acid	*	<*
Aspartic acid	***	***
Glutamic acid	***	**
β -Alanine	**	**
β -Amino- <i>n</i> -butyric acid	*	*
β -Aminoisobutyric acid	*	*
γ -Aminobutyric acid	*	**
Sarcosine	**	***
<i>N</i> -Ethylglycine	**	***
<i>N</i> -Methylalanine	**	**

collected, thus minimizing field contamination, and analyzed in the laboratory. A host of organic compounds was revealed to be present which were indubitably of extraterrestrial origin. These organics strongly resemble those produced in laboratory syntheses under presumed prebiotic conditions (table 1.4). Questions remain regarding the survival of the organic material from extraterrestrial bodies, although obviously those in the Murchison meteorite did survive. There is also a large abundance of extraterrestrial amino acids associated with the 65-million-year-old impact event, concurrent with the decline of the dinosaurs and recorded geologically [149].

Chyba and Sagan [147] estimated the flux of extraterrestrial organics to the Earth based on the lunar cratering record. They then extrapolated an organic content and a yield based on the survival of these organics during entry, and estimated that exogenous delivery would have made a significant contribution to the primitive Earth's organic inventory. Survival of extraterrestrial organic material would have been higher if the Earth's atmosphere were denser. The estimated flux of HCN equivalents compared with that produced in a reducing atmosphere is shown in figure 1.18. Thus even if the early Earth's atmosphere were oxidizing, the case can be made that significant amounts of prebiotic organic compounds resembling the types made in terrestrial atmospheric synthesis would have been delivered to the Earth.

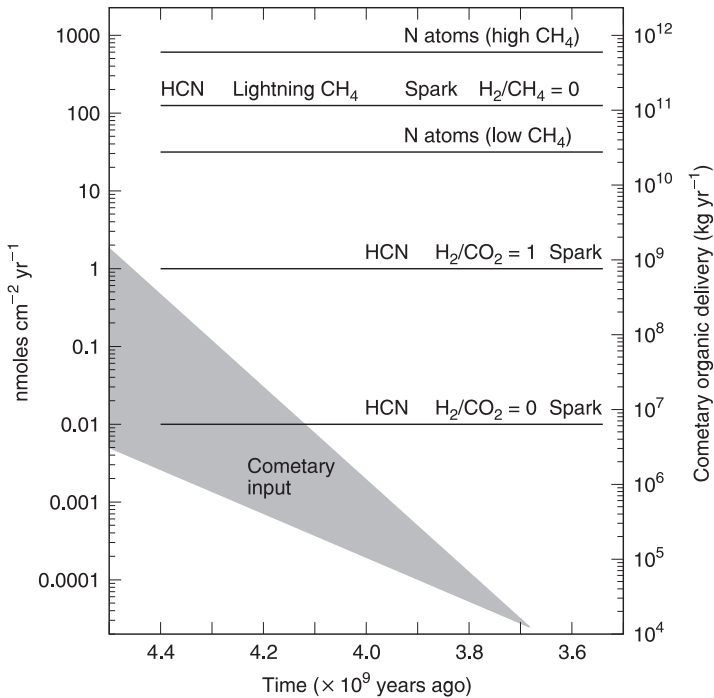


Figure 1.18 Estimated inputs of HCN from various energy sources and organic compounds from comets. The cometary inputs are from Chyba and Sagan [147]. The area is shaded because of the uncertainty of the fall-off of dust input on the early Earth. The cometary input has been converted to nmoles $\text{cm}^{-2} \text{yr}^{-1}$ assuming a molecular weight of 100. The HCN production is discussed in Stribling and Miller [24].

The question is what was the relative percentage of prebiotic organic matter contributed by each source. Although there is a wide variety of interstellar molecules, including formaldehyde, hydrogen cyanide, acetaldehyde, cyanoacetylene, and other prebiotic compounds, and their total amount in a nebular dust cloud is high, it is generally felt that they played at most a minor role in the origin of life. The major sources of exogenous compounds would appear to be comets and dust, with asteroids and meteorites being minor contributors. Asteroids would have impacted the Earth frequently in prebiotic times, but the amount of organic material brought in would have been small, even if the asteroid were a Murchison meteorite-type object. The Murchison meteorite contains approximately 1.8% organic carbon, but most of this is a polymer, and there are only about 100 parts per million of amino acids. Assuming a density of approximately 2.0, for the 10-km asteroid believed to have hit the Earth at the end of the Cretaceous

this would be equivalent to some 1.2×10^{17} g of amino acids, or 10^{-6} M amino acids if distributed evenly in oceans of the present size. However, it apparently left amino acids at the K/T boundary that are detectable by the most sensitive modern analytical methods [149]. The same considerations would apply to carbonaceous chondrites, although the survival of the organics on impact would be much better than with asteroids. As suggested by recent measurements, a significant percentage of meteoritic amino acids and nucleobases could survive the high temperatures associated with frictional heating during atmospheric entry, and become part of the primitive broth [150].

Comets are perhaps the most promising source of exogenous compounds [151]. The first proposal for the prebiotic importance of comets was by Oró [144]. Cometary nuclei contain about 80% H_2O , 1% HCN, and 1% H_2CO , as well as important amounts of CO_2 and CO. Thus, assuming that cometary nuclei have a 1 g cm^{-3} density, a 1-km-diameter comet would contain 2×10^{11} M HCN, or 40 nmoles cm^{-2} of the Earth's surface. This is comparable to the yearly production of HCN in a reducing atmosphere from electric discharges, and would be quite important if the Earth did not have a reducing atmosphere. This calculation assumes a complete survival of the HCN on impact. In fact, there is little understanding of what happens during the impact of such an object, but much of it would be heated to temperatures above 300°C , which would decompose HCN and other cometary compounds. However, these highly reactive chemical species could then be used as precursors in the abiotic syntheses of biochemical monomers.

The input from interplanetary dust may have also been important. The present infall is approximately 40×10^6 kg/yr [152], but on the primitive Earth it may have been greater by a factor of 100 to 1000. Unfortunately, the organic composition of cosmic dust is poorly known [153]. The only individual molecules that have been detected are polycyclic aromatic hydrocarbons [154,155]. Much of the dust could be organic polymers called tholins, which are produced by electric discharges, ionizing radiation, and ultraviolet light. Although quite resilient, a few percent of amino acids are released from tholins on acid hydrolysis. A more promising role for the tholins would be as a source of prebiotic precursors such as HCN, cyanoacetylene, and aldehydes. On entry to the Earth's atmosphere, the dust particles would be heated and the tholins pyrolyzed, releasing HCN and other molecules, which could then participate in prebiotic reactions [156,157].

CONCLUSION

Given adequate expertise and experimental conditions, it is possible to synthesize almost any organic molecule in the laboratory under

simulated prebiotic conditions. However, the fact that a number of molecular components of contemporary cells can be formed nonenzymatically in the laboratory does not necessarily mean that they were essential for the origin of life, or that they were available in the prebiotic milieu. The primitive soup must have been a complex mixture, but it could not reasonably have included all the compounds or molecular structures found today in even the simplest prokaryotes.

The basic tenet of the heterotrophic theory of the origin of life is that the origin and reproduction of the first living system depended primarily on abiotically synthesized organic molecules. As summarized here, there has been no shortage of discussion about how the formation of the primitive soup took place. It is unlikely that any single mechanism can account for the wide range of organic compounds that may have accumulated on the primitive Earth. The prebiotic soup was undoubtedly formed by contributions from endogenous atmospheric synthesis, deep-sea hydrothermal vent synthesis, and exogenous delivery from sources such as comets, meteorites, and interplanetary dust. This eclectic view does not beg the issue of the relative significance of the different sources of organics; it simply recognizes the wide variety of potential sources of organic compounds, the raw material required for the emergence of life.

The existence of different abiotic mechanisms by which biochemical monomers can be synthesized under plausible prebiotic conditions is well established. Of course, not all prebiotic pathways are equally efficient, but the wide range of experimental conditions under which organic compounds can be synthesized demonstrates that prebiotic syntheses of the building blocks of life are robust, that is, the abiotic reactions leading to them do not take place under a narrow range defined by highly selective reaction conditions, but rather under a wide variety of environmental settings. Although our ideas on the prebiotic synthesis of organic compounds are based largely on experiments in model systems, the robustness of this type of chemistry is supported by the occurrence of most of these biochemical compounds in the Murchison meteorite. It is therefore plausible, but not proven, that similar synthesis took place on the primitive Earth. For all the uncertainties surrounding the emergence of life, it appears that the formation of the prebiotic soup is one of the most firmly established events that took place on the primitive Earth.

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