THE ROLE OF OXYGEN

Until the age of extraterrestrial space exploration opened, the theory of evolution of life on planet earth did not correspond at all precisely to the story of life as told by the fossils in the rocks of the planet's crust. There were great gaps in the fossil record that no one could explain. But when rockets went out through earth's atmosphere to look closely at the sun, the reports they radioed back suggested a rational cause for the fossil sequence to Dr. Lloyd V. Berkner, father of the International Geophysical Year (1957-8). Below is a description of original research Dr. Berkner has done in company with Professor Lauriston Marshall of the Graduate Research Center of the Southwest. The findings are as revolutionary as the Darwin-Wallace theory of evolution itself. Their conclusion: Life evolved explosively with oxygen as fuel.

By LLOYD V. BERKNER and LAURISTON C. MARSHALL

THE record of life on earth, as it has been kept in the rocks of the planet's crust, still mystifies those who examine it closely. The story begins about two-thirds of the way back in the 4,500 million years of earth's existence. Judging from their fossils, all creatures that lived during the 2,500 million years of that time were one-celled organisms. Fossils of creatures containing more than a single cell do not appear until about 600 million years ago. Then suddenly the layers of rock which at that time were under water are filled with skeletons of many different kinds of multicellular life, and this is true of rocks all over the globe.

What could account for such a remarkable change everywhere on the planet simultaneously?

Charles Darwin pondered this question long and hard. Because he could not solve it in a straightforward manner, he delayed publication of his theory of evolution through natural selection (adaptation) of species. Darwin finally went around the problem by making an assumption: there must have been a long, gradual process of evolution from unicellular to multicellular life that left no recognizable trace behind. In the century since Darwin, the tools of rock study have grown progressively more sophisticated; but the connecting links in the chain of life he speculated on have not yet been discovered. Modern paleontologists wonder whether that phase of evolution occurred according to the time scale Darwin imagined or in another way.

About 150 million or so years after multicelled life appeared in the waters of earth, the fossil record shows spores on the land beside the water.

Some 10,000,000 years after that, green plants began to grow on the land.

About the same time, the first land animals appeared.

It seems evident from the sequence of these events that the spores were blown onto the land from aquatic plants that stuck their heads above the water, and then plants grown from those spores on the land provided a means of sustenance for animals that could then evolve ashore, finding there a physiological advantage over life in the water.

Among the fossils of this period are those of the lungfish (which breathe through snorkel-like tubes while buried in the mud) and of the four-finned fish —the crossopterygians—that are believed to be the progenitors of four-legged animals and thus of all amphibians: the reptiles and the mammals, including man.

The reason for the sudden migration of many forms of life from the water to the land at the time it occurred is as mysterious as the reason for the sudden proliferation of multicellular life in the water at an earlier time. Could it be a similar reason?

We believe so. A classically elegant confirmation seems implicit in the rocks. The message of the fossils needs only to be read exactly as it lies in place. The gist of the message, as we translate it, is that life proliferated explosively when the energy required to power life's functions became available in suitable form.

The oxygen atom is an incredibly efficient energy container, whether in the lone state or coupled in oxygen molecules or bonded triply in molecules of ozone. When fueling the respiratory process on which all animal life depends, it releases 674 calories of energy for every gram molecular weight of its substance. By contrast, fermentation (the other chemical process able to sustain life) frees only twenty-eight calories per gram at most and fifteen calories on the average.

THE great paradox of earthly life is that (except for certain parasites) all of its forms consisting of more than one cell need oxygen in order to obtain enough energy to survive; yet the vital components of all cells are fatally poisoned by oxygen. How did nature resolve this fundamental contradiction?

Logic suggests one reasonable answer. It is that ancestors of the cell in the life chain must have come into being in absence of oxygen. Such a supposition is supported from several directions. First, we know that many primitive organisms can exist without oxygen. Second, we know that independent multicellular organisms have not evolved by using fermentation. From this knowledge we deduce that nature, in experimenting with different ways of putting single cells together into multicelled structures, found no advantage—and perhaps a disadvantage—in the form of energy obtainable through the fermentation process. Third, what has been surmised about the origin of earth fits the conception that no appreciable amount of free oxygen was available for some time after the planet took shape.

According to the most widely accepted present-day thinking on this matter,

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the earth was formed by condensation of debris and dust from the matter that also created the sun. Condensation of some of these planetesimals may have been as big as the moon, or slightly bigger, but the whole probably condensed from dust. Hence no fragment of the aggregated mass was great enough to produce a gravitational attraction competent to retain an atmosphere with it. The atmosphere which now envelops earth had to be generated from within the planet.

In order to retain the volume of complex compounds which today make up its crust, earth appears not to have existed in any substantially molten state at any time. Consequently, it can be assumed that the minerals composing the planet's interior originally held captive within them large quantities of gases. These gases were released gradually by volcanic eruptions caused by internal heating of radioactive elements, earthquakes, and local melting and separation of compounds in response to gravity. The volcanoes are believed to have built up the continents in this way, since estimates of the volume of solids belched along with the gases during the earth's lifetime approximately match estimates of the volume of the continental masses. Chemical analysis of ancient rocks indicates that no free oxygen was in the gaseous volcanic effluent, and this conclusion is supported by detailed study of gases vented by still active volcanic cones such as in the Hawaiian islands.

Nothing in the logic we have pursued so far conflicts with prevailing theories on evolution of life. All these theories (and laboratory experiments in which the amino acid building blocks of life have been synthesized by passing ultraviolet light through a vacuum containing other chemical elements but no free oxygen) hold that, until the life process reached the stage where it created a cell internally organized to protect itself, presence of free oxygen would stop the process dead.

But where do we go from here? How did life which could not exist in its earliest stages coeval with oxygen come to burgeon with the help of oxygen?

Theoretical explanations for life's beginnings were advanced in the 1930s by Alexander I. Oparin of Russia and John B. S. Haldane and J. D. Bernal of England; these have been much discussed since. But only in this last decade of intensive exploration of earth's atmosphere and the space beyond has it become possible to fit actual numbers into mathematical models which can be tested experimentally. Pictures of the sun, taken through telescopes riding on rockets and high-flying balloons, have disclosed the energy carried by wave lengths of ultraviolet light which can exert a most powerful influence on life (2,200 to 3,000 angstroms). This radiation originates in the sun's photosphere. Comparison of these pictures with pictures of thousands of stars comparable to the sun and at different ages show that the photosphere's output of ultraviolet in the life-giving range must have occurred at a steady rate throughout the duration of the earth's existence. Therefore, it is acceptable to calculate backwards in time, applying numbers derived from today's experiments to conditions that existed millions of years ago.

IF we begin our calculations with gases poured into the sky by volcanic action, we have the following chemical elements to consider as possible constituents of the primitive atmosphere: water vapor (up to 97 per cent by volume), nitrogen, carbon dioxide, hydrogen, sulfur dioxide, chlorine, hydrogen sulfide, carbon monoxide, methane, ammonia, and trace amounts of others.

Note that although oxygen in the free state is lacking from the list above, oxygen is present in combination with carbon, with sulfur, and with hydrogen in the water vapor. Since water vapor molecules are dissociated into hydrogen and oxygen atoms by ultraviolet light, a certain amount of free oxygen would thus become available. But here we encounter a natural mechanism which limits the oxygen that thus might be freed. What happens is that the oxygen atoms dissociated from the water vapor move further out into the atmosphere. There they become a screen to absorb the ultraviolet light before it can reach and act upon the water vapor. Hence, whenever dissociation of the water vapor reaches a certain point, the process stops itself. Nobelist Harold Urey some time ago suggested that there must be such an upper limit of oxygen produced in this way. We have calculated this limit as about one-thousandth of the present-day level of oxygen in the atmosphere. From these facts it is evident that oxygen derived from photodissociation would not have been sufficient to encourage life to reach the complex forms we know today.

HOW did oxygen-burning life forms evolve?

Nature's only oxygen manufacturing process other than the self-restricting photodissociation of water vapor is photosynthesis, through which living plants capture sunlight, rain water, and carbon dioxide from the air—so forming carbohydrate to feed the plants' own growth, and giving off free oxygen. Once the photosynthetic process got started, it could proceed without reference to the limiting "Urey effect" on photodissociation because photosynthesis employs visible light, in ranges of intensity well below those of the ultraviolet wave lengths captured by oxygen. But how did photosynthesis get started?

If we go back for a moment to the ventings of the primitive volcanoes, we find the element nitrogen high on the list of effluents. Nitrogen makes up four-fifths of our present-day atmosphere and is the principal intermediary in facilitating combination of three oxygen atoms into one molecule of ozone. It is the thick blanket of ozone manufactured by this method that hangs within twenty miles of earth's surface today and screens out the most ferocious radiations of the sun. But in the primitive atmos-

phere with only little oxygen, a thin layer of ozone formed close to earth in the first birthdays of life on the planet.

If we now add the attenuating effects of the atomic oxygen screen high in the atmosphere to the water vapor screen in the atmosphere just below that and to the thin ozone screen just above the earth, we find that the energy in the solar ultraviolet after passing through all three screens is still too powerful to permit life. Only if we place thirty to forty feet of water beneath the thin surface-layer of ozone do we absorb the murderous force of the raw sunlight on the primitive earth.

AFTER we add the effect of the water to our equations, however, we discover a curious coincidence. The barriers we have assembled afford greatest protection against wave lengths of sunlight around 2,600 angstroms. This happens to be the region of the solar spectrum where present-day nucleic acids (2,630 angstroms) and proteins (2,750 angstroms) are most sensitive to damage. The coincidence suggests that the materials of which most living tissue is built and the genetic controls on replication of life forms might have had a selective advantage in the struggle for survival.

In other words, life on earth could have originated on the bottoms of pools, ponds, small lakes, or shallow protected seas fed perhaps by hot springs from thermal sources rich in nutrient chemicals which have demonstrated ability to form cell-like membranes about themselves in the presence of heat alone.

We can imagine organic compounds synthesized perhaps through the energy of ultraviolet light at the surface of the water and gently convected downward away from ultraviolet damage into regions where more complex organisms could be synthesized in the presence of visible nonlethal radiation. This model of primitive ecology calls for pool depths sufficient to absorb the deadly ultraviolet but not so deep as to cut off too much of the visible light. The model also calls for convection currents in the water sufficient to carry organic nutrients downward from the surface yet too slight to sweep the primitive organisms up from the bottom. Large lakes, or deep seas, or oceans would have been inhospitable to life at this early stage because the waves and currents would be violent enough to drive the primitive organisms to the lethal surface or disperse them out of reach of life-giving light.

ACCORDING to the fossil record in the rocks of the earth, the first cell life that incorporated photosynthesis appeared about 2,700 million years ago. At first, the effect of photosynthesis would not have made much change in the primitive level of atmospheric oxygen. Gradually, however, as the areas occupied by organisms capable of photosynthesis enlarged, accumulation of significant amounts of oxygen in the air would begin. Our calculations indicate that the limitation of the "Urey effect" would be overcome when the life-bearing pools of water covered somewhat more than 1 per cent of the present land mass of the earth.

On the early continents, then, the land would have been barren of vegetation but punctuated by a multitude of bodies of water in which photosynthetically active organisms were growing.

Nearly a century ago, during his famous studies of the spoilage of wines, Louis Pasteur observed that primitive organisms capable of living either without or with oxygen shift from fermentation (without oxygen) to respiration (with oxygen) whenever the amount of available oxygen reaches one-hundredth of the present-day level of oxygen in the atmosphere. In honor of its discoverer, this phenomenon is called the "Pasteur effect." By applying the "Pasteur effect" to our model of the early atmosphere of earth, we conclude that respiration became the dominant fueling system of life when the photosynthetic process pushed the supply of free oxygen above the one-hundredth-of-present-day level.

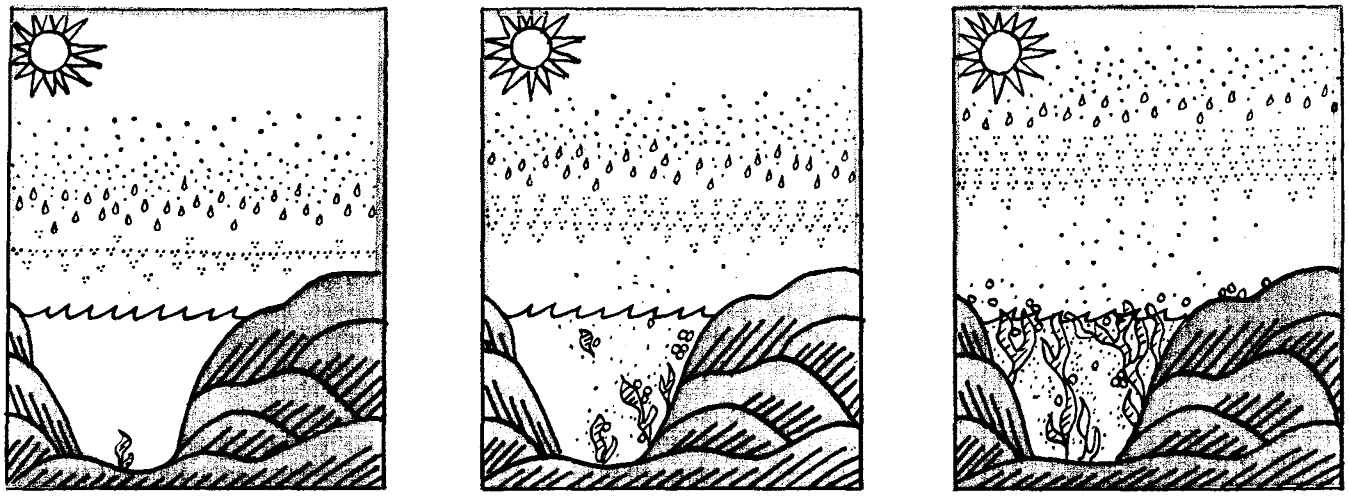
Respiration has always been recognized as a major evolutionary development. What has been overlooked is that only as oxygen concentrations permitted respiration was there an evolutionary demand for complex biological function to maximize energy capture. Respiration created altogether new evolutionary opportunities—for a circulatory system to convey the oxygen, a digestive system to employ it, a nervous system to control the process—in short, for complex multicelled organisms with advanced mechanisms of energy capture, control, and utilization.

The increase in oxygen in the atmosphere to about one-hundredth of its present level was automatically accompanied by a calculable increase in the total ozone content, since the ozone must be made from oxygen. When we incorporate the new ozone figures into our earlier calculations of the absorption of ultraviolet light by oxygen, ozone, and water we find that the lethal rays of ultraviolet are cut off at depths of only a foot or so of water instead of at thirty to forty feet as before.

In our model of the evolving atmosphere, the attainment of an oxygen level one-hundredth as great as the present-day atmospheric level of oxygen is referred to as the *first critical level.* Life then was still confined to the water but could survive at very shallow depths. The spread of life to the oceans became possible, since lethality was limited only to the very surface of the waters and

—American Museum of Natural History.

Artist's conception of how four-finned fish walked ashore.



The upward progression of life from small, warm-water pond bottoms to pond surface and thence to pond-side land . . .

more advanced organisms could evolve some control over their movement in that environment. Indeed, as we read Sir Alister Hardy's charming account (in *The Open Sea,* published by Houghton Mifflin) of the unexplained diurnal depth-control of pelagic (free-swimming) organisms, found so generally in the seas today, we can hardly escape the notion of protective responses inherited from the time of *the first critical level.*

Was there a sudden evolutionary spurt at any time in geological history that would correspond to this vast new evolutionary opportunity provided when oxygen reached a hundredth part of its present concentration?

Yes, just one—at the beginning of the Palaeozoic era, 600 million years ago.

There is no evidence before that time of organisms more advanced than the most primitive of very ancient times. Yet within a few million years, with the opening of the Cambrian, there is widespread evidence of more advanced life forms. In a period of the order of 20,000,000 years, life branched out in such a variety of forms in the oceans, rivers, and lakes as to lay the foundation for all modern forms. At least 1,200 new species appeared during the ensuing Cambrian period in North American geological horizons alone. Some of these were quite large: skeletons of trilobites and large shellfish comparable to modern scallops or abalone, some as much as three feet in diameter.

Following this evolutionary explosion, marine photosynthesis further accelerated the build-up of oxygen in the atmosphere. Again the depth of the ozone layer increased. But the lethal glare of solar ultraviolet would still wither any organism that tried to raise its head above the water.

Continually life reached for the open air to maximize its energy for photosynthesis and was continually prevented from doing so by the burning radiation.

As oxygen built up, living processes could take place at shallower and shallower depths until oxygen reached a level of about one-tenth of the present atmospheric concentration. We have defined this point in our model as the *second critical level.* Then life could finally exist at or near the surface of the water. And for hardier forms of life, at least, the thickening depth of the atmospheric ozone layer opened the opportunity to evolve ashore, to spread in great profusion over the land surface to still further accelerate the processes of photosynthesis and respiration.

Can we identify this era in the fossil record?

Yes. There was an explosion of life on land about the time of the late Silurian: 400 to 420 million years ago.

Before that, in the mid-Silurian, there are fossil spores—the first evidence that plants were growing above the level of the waters in protected localities.

By the late Silurian, many classes of both plants and animals had moved ashore, and before long (early Devonian, 380 million years ago) great forests had appeared. As dense plant life spread over most of the land surface, it added to the rapid build-up of oxygen. With the accompanying increase in the thickness of the protective ozone layer, more sensitive forms of life began to appear on land. By the end of the Devonian

—Sketches by Doug Anderson.

. . . is suggested by sketches. Read from top left to bottom right. Dots represent oxygen, droplets water vapor, triangles ozone.

period—350 million years ago—many forms of life pre-existing in the water had projected onto the land their evolutionary counterparts, including the amphibians and insects.

The oxygen content of the atmosphere may, in fact, have built up to a level *exceeding* our present atmospheric content by the time of the Carboniferous. This represented an overswing, with photosynthesis generating large quantities of oxygen and consuming comparable amounts of carbon dioxide. We can speculate that such an overswing would eventually correct itself. For carbon dioxide produces the so-called "greenhouse effect" by absorbing the infrared radiation returned toward space by the earth. Diminution of the "greenhouse effect" during the Carboniferous might have cooled the earth to such a degree as to account for the extensive ice ages of the Permian period, over 200 million years ago.

As organisms were constrained by the changed climate, a severe disturbance would occur in the delicate balance between photosynthetic build-up of the oxygen supply and oxygen losses to carbohydrate synthesis and to combination with metals, especially with iron. Oxygen would disappear from the atmosphere entirely in 2,000 years if the supply were not constantly renewed by growing plants (including aquatic plants, which account for at least four-fifths of present-day photosynthesis on the earth). So a sharp decline in photosynthetic activity certainly would lead to an abrupt catastrophic reduction in oxygen concentration.

We might find supporting evidence for such speculation on the cause of the ice ages if we could determine whether the great reptiles of the Mesozoic era attempted to acquire a greater lung capacity before they disappeared suddenly near the end of the Cretaceous from both land and sea.

Let us, in conclusion, consider the implications of these events in historic geology and palaeontology. Evolution during any geological period must be interpreted as a complex interaction between the level of oxygen generated by living organisms and the way in which that level produces new opportunities for evolution. Our thesis is that, from time to time, critical stages in the level of oxygen are reached, affording vast opportunities that are immediately seized by physiological responses of organisms. Conventional evolutionary thinking is strained by the speed and complexity of these great evolutionary leaps. But we believe the fossil record says that evolution can proceed as rapidly as combination, selection, and adaptation permit. If our interpretation is correct, a considerable step can be taken in quantifying evolution.

The Origin of Life Itself

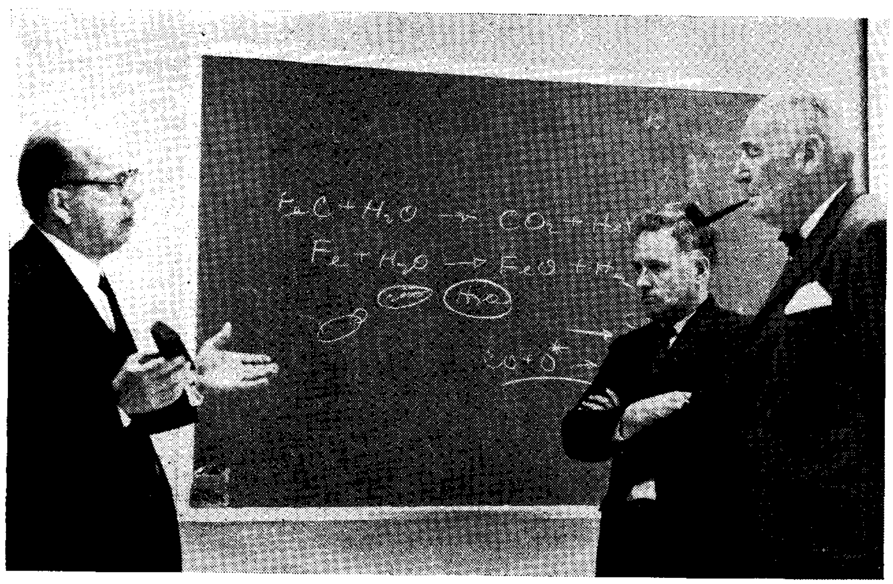
IF EARTH'S ATMOSPHERE CAME INTO BEING in accord with the theoretical model described in adjacent columns of this tenth anniversary issue of *SR*'s Science and Humanity Supplement, the most popular current scientific theory of the origin of life on earth must be drastically revised. For this theory holds that amino acids—the fundamental components of proteins, which constitute most living tissue—were created originally by solar radiation bombarding a dense miasma of methane and ammonia surrounding earth. And the Berkner-Marshall model of the atmosphere begins with the effluent of erupting volcanoes, which includes nitrogen, carbon, hydrogen, and a number of other chemical elements as well as methane or ammonia but is composed predominantly of water vapor. Since ammonia quickly dissolves in water, ammonia could not survive in the environment of the Berkner-Marshall model long enough to become a major component of the atmosphere.

In a recent seminar at the Graduate Research Center of the Southwest at Dallas, Texas, Dr. Philip Abelson, director of the geophysical laboratory of the Carnegie Institution of Washington and editor of *Science,* journal of the American Association for the Advancement of Science, disclosed that he had roughed out a new approach to life's origin based on the Berkner-Marshall atmospheric model. Dr. Abelson told scientists assembled at the Dallas institution that there is no evidence for a methane-ammonia atmosphere at any stage of earth's existence. On the contrary, he said, chemical composition of earth's oldest known rocks and the absence of krypton and xenon from our present atmosphere argue persuasively against the methane-ammonia theory. On the other hand, Dr. Abelson said, there is firm experimental support for the proposition that molecules of hydrogen, carbon, and nitrogen (such as those released by volcanic activity) would produce amino acids if bombarded by sunlight of 2,536 angstrom units wave length.

SR's science editor invited Dr. Abelson to propound his new speculations about the beginnings of life in this anniversary issue of *SR.* Dr. Abelson declined on the ground that his ideas needed to be "cooked" thoroughly, by exposure to qualified critics in pertinent fields of scientific specialty, before being offered for general publication.

A thumbnail summary of Dr. Abelson's new concept can be found in Volume IV, No. 14 of *Clipboard,* a faculty and staff organ of the Graduate Research Center of the Southwest. The picture below is reproduced from that issue of *Clipboard* by courtesy of *Clipboard*'s editor, Alfred Mitchell. Pictured are Dr. Abelson (left) in a blackboard discussion with Dr. John Jagger, of the research center's biology division, and (right) Dr. Lloyd V. Berkner, father of the International Geophysical Year, one of the founders of the GRCSW and co-author of the new model of the atmosphere.

—J.L.



—GRCSW Clipboard.

Dr. Philip Abelson (left) illustrates a point to Drs. John Jagger and Lloyd V. Berkner at Graduate Research Center of the Southwest in Dallas, Texas.