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The Biosphere

Introducing an issue on how the earth's thin film of living matter is sustained by grand-scale cycles of energy and chemical elements. All of these cycles are presently affected by the activities of man

by G. Evelyn Hutchinson

The idea of the biosphere was introduced into science rather casually almost a century ago by the Austrian geologist Eduard Suess, who first used the term in a discussion of the various envelopes of the earth in the last and most general chapter of a short book on the genesis of the Alps published in 1875. The concept played little part in scientific thought, however, until the publication, first in Russian in 1926 and later in French in 1929 (under the title *La Biosphère*), of two lectures by the Russian mineralogist Vladimir Ivanovitch Vernadsky. It is essentially Vernadsky's concept of the biosphere, developed about 50 years after Suess wrote, that we accept today. Vernadsky considered that the idea ultimately was derived from the French naturalist Jean Baptiste Lamarck, whose geochemistry, although archaically expressed, was often quite penetrating.

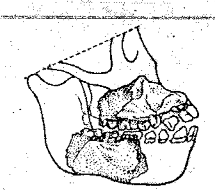
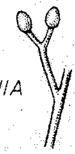
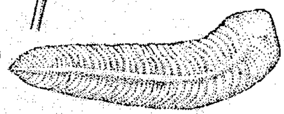
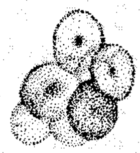
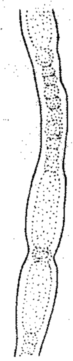
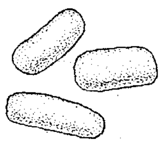
The biosphere is defined as that part of the earth in which life exists, but this definition immediately raises some problems and demands some qualifications. At considerable altitudes above the earth's surface the spores of bacteria and fungi can be obtained by passing air through filters. In general, however, such "aeroplankton" do not appear to be engaged in active metabolism. Even on the surface of the earth there are areas too dry, too cold or too hot to support metabolizing organisms (except technically equipped human explorers), but in such places also spores are commonly found. Thus as a terrestrial envelope the biosphere obviously has a somewhat irregular shape, inasmuch as it is surrounded by an indefinite "parabiospheric" region in which some dormant forms of life are present. Today, of course, life can exist in a space capsule or a space suit far outside the natural biosphere. Such artificial environments may best be regarded as small volumes of the biosphere nipped off and projected temporarily into space.

What is it that is so special about the biosphere as a terrestrial envelope? The answer seems to have three parts. First, it is a region in which liquid water can exist in substantial quantities. Second, it receives an ample supply of energy from an external source, ultimately from the sun. And third, within it there are interfaces between the liquid, the solid and the gaseous states of matter. All three of these apparent conditions for the existence of a biosphere need more detailed study and discussion.

All actively metabolizing organisms consist largely of elaborate systems of organic macromolecules dispersed in an aqueous medium. The adaptability of organisms is so great that even in some deserts or in the peripheral parts of the antarctic ice sheet there may be living beings that contain within themselves the only liquid water in the immediate neighborhood. Although such xerophytic (literally "dry plant") organisms may be able to conserve internal supplies of water for a long time, however, they still need some occasional dew or rain. (The hottest deserts appear to be formally outside the biosphere, although they may be parabiospheric in the sense explained above.) In the immediate past this kind of situation had a certain intellectual interest, since it seemed for a time that organisms might exist on Mars, in an almost waterless environment, by retaining water in their tissues. The most recent studies, however, seem to make any kind of biosphere on Mars quite unlikely.

The energy source on which all terrestrial life depends is the sun. At present the energy of solar radiation can enter the biological cycle only through the photosynthetic production of organic matter by chlorophyll-bearing orga-

REVOLUTION IN THE BIOSPHERE is symbolized by the fossilized blue-green alga in the photomicrograph on the opposite page. The cell, which is one of a variety of similar fossils found in the Gunflint geological formation in southern Ontario by Stanley A. Tyler and Elso S. Barghoorn of Harvard University, is estimated to be approximately two billion years old. The Gunflint algae are the oldest known photosynthetic and nitrogen-fixing organisms. As such they contributed to the original oxygenation of the earth's atmosphere and so prepared the way for all higher forms of plant and animal life in the biosphere.

YEARS BEFORE PRESENT	EVENT	GEOLOGICAL FORMATION	FOSSIL
0	OLDEST HOMINID	SIWALIK HILLS (INDIA)	*RAMAPITHECUS* 
	OLDEST LAND PLANT	LUDLOVIAN SERIES, UPPER SILURIAN (BRITAIN)	*COOKSONIA* 
	OLDEST METAZOAN ANIMAL	EDIACARA HILLS (AUSTRALIA)	*SPRIGGINA* 
1 BILLION			
	OLDEST EUCARYOTIC CELLS	UPPER BECK SPRING DOLOMITE (CALIFORNIA)	UNNAMED 
	FORMATION OF OXIDIZING ATMOSPHERE		
2 BILLION	OLDEST PHOTOSYNTHETIC AND NITROGEN-FIXING ORGANISM	GUNFLINT FORMATION (ONTARIO)	*GUNFLINTIA* 
3 BILLION	OLDEST KNOWN ORGANISM	FIGTREE FORMATION (SOUTH AFRICA)	*EOBACTERIUM* 
	FIRST ROCKS IN EARTH'S CRUST; FORMATION OF OCEAN		
4 BILLION	DIFFERENTIATION OF EARTH'S CRUST, MANTLE AND CORE; CRUST MELTED BY RADIOACTIVE HEATING		
4.5 BILLION	FORMATION OF EARTH		

ROUGH CHRONOLOGY OF THE BIOSPHERE as represented in the fossil record is given on this page, along with the geological formations in which the fossils were found and some other major events in the history of the earth. Data are from various sources.

nisms, namely green and purple bacteria, blue-green algae, phytoplankton and the vast population of higher plants. Such organisms are of course confined to the part of the biosphere that receives solar radiation by day. That includes the atmosphere, the surface of the land, the top few millimeters of soil and the upper waters of oceans, lakes and rivers. The euphotic, or illuminated, zone may be only a few centimeters deep in a very turbid river, or well over 100 meters deep in the clearest parts of the ocean. The biosphere does not end where the light gives out; gravity continues the energy flow downward, since fecal pellets, cast skins and organisms dead and alive are always falling from the illuminated regions into the depths.

The plant life of the open ocean, on which most of the animals of the sea depend for food, is planktonic, or drifting, in a special sense that is often misunderstood. Most of the cells composing a planktonic association are slightly denser than seawater, and under absolutely quiet conditions they would slowly sink to the bottom. That the upper layers are not depleted of plant cells and so of the capacity to generate food and oxygen is attributable entirely to turbulence. The plant cells sink at a speed determined by their size, shape and excess density; as they sink they divide and the population in the upper waters is continually replenished from below by turbulent upwelling water.

The sinking of the phytoplankton cells is in itself the simplest way by which a cell can move from a small parcel of water it has depleted of the available nutrients into a parcel still containing these substances. The mechanism can of course only operate when there is an adequate chance of a lift back to the surface for the cell and some of its descendants. The cellular properties that determine sinking rates, interacting with turbulence, are doubtless as important in the purely liquid part of the biosphere as skeletal and muscular structures, interacting with gravity, are to us as we walk about on the solid-gaseous interface we inhabit. Although this point of view was worked out some 20 years ago, largely through the efforts of the oceanographer Gordon A. Riley, it still seems hardly recognized by many biologists.

In addition to the extension of the biosphere downward, there is a more limited extension upward. On very high mountains the limit above which chlorophyll-bearing plants cannot live appears to be about 6,200 meters (in the Himalayas); it is partly set by a lack of liquid water, but a low carbon dioxide pressure, less than half the pressure at sea level, may also be involved. At still higher altitudes a few animals such as spiders may be found. These probably feed on springtails and perhaps mites that in turn subsist on pollen grains and other organic particles, blown up into what the high-altitude ecologist Lawrence W. Swan calls the aeolian zone.

The rather special circumstances that have just been recognized as needed for the life of simple organisms in the free liquid part of the biosphere emphasize how much easier it is to live at an interface, preferably when one side of the interface is solid, although quite a lot of microorganisms do well at the air-water interface in quiet pools and swamps. It is quite possible, as J. D. Bernal suggested many years ago, that the surface properties of solid materials in contact with water were of great importance in the origin and early development of life.

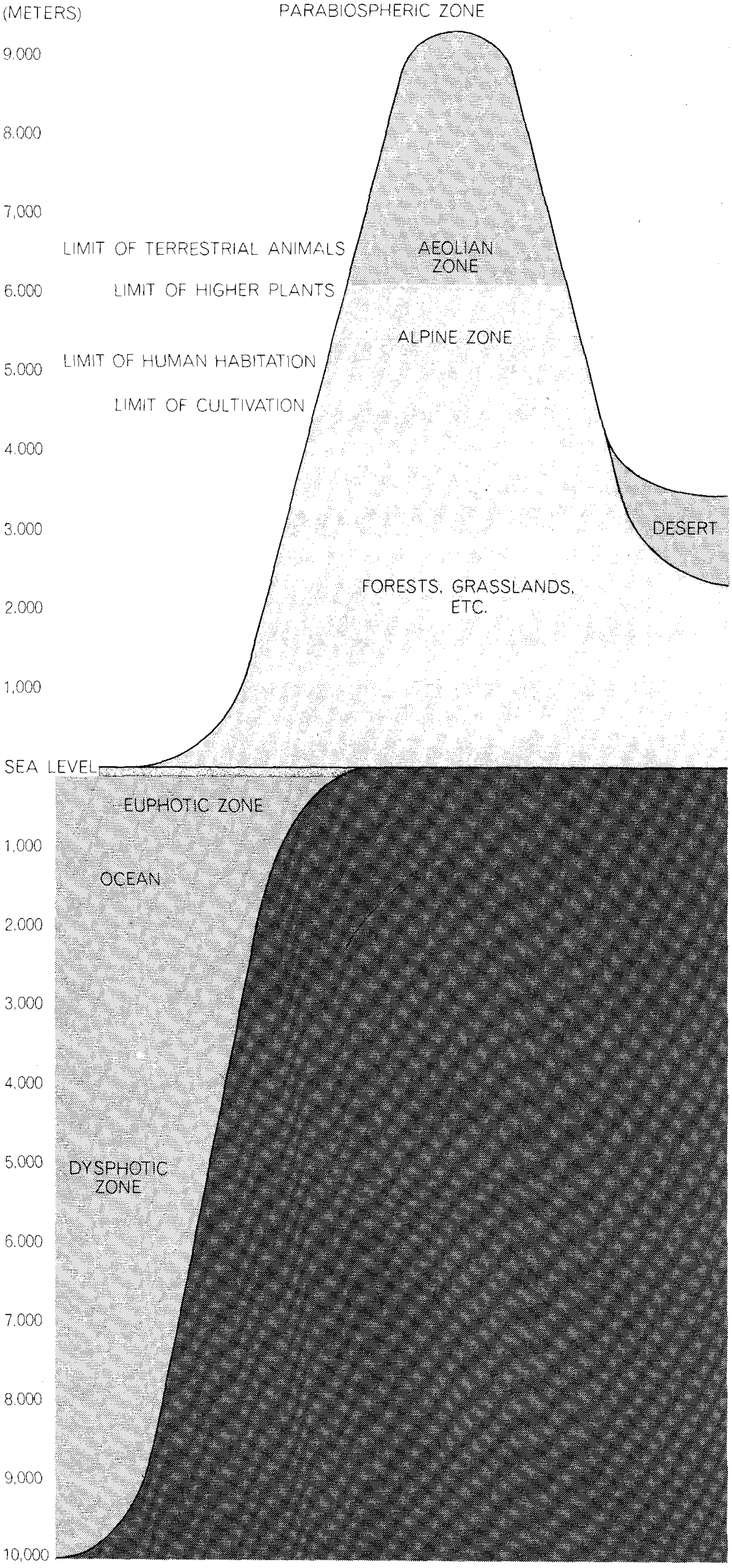
Studies of photosynthetic productivity show that often the plants that can produce the greatest organic yield under conditions of natural illumination are those that make the best of all three possible states, with their roots in sediments under water and their leaves in the air. Sugarcane and the ubiquitous reed *Phragmites communis* provide striking examples. The substances needed by such plants are (1) water, which is taken up by the roots but is maintained at a fairly constant pressure by the liquid layer over the sediments; (2) carbon dioxide, which is most easily taken up from the gaseous phase where the diffusion rate at the absorptive surface is maximal; (3) oxygen (by night), which is also more easily obtained from the air than from the water, and (4) a great number of other elements, which are most likely to be available in solution in the pore water of the sediment.

The present energetics of the biosphere depend on the photosynthetic reduction of carbon dioxide to form organic compounds and molecular oxygen. It is well known, however, that this process is only one of several of the form: $nCO_2 + 2nH_2A + \text{energy} \rightarrow (CH_2O)_n + nA_2 + nH_2O$. In this reaction the hydrogen donor H_2A may be hydrogen sulfide (H_2S), as in the case of the photosynthetic sulfur bacteria, water (H_2O), as in the case of the blue-green algae and higher green plants, or various other organic compounds, as in the case of the nonsulfur purple bacteria. (The last-mentioned case presents a paradox: Why be photosynthetic when there is plenty of metabolizable organic matter in the immediate neighborhood of the photosynthesizing cell?) The actual patterns of the possible reactions are extremely complicated, with several alternative routes in some parts of the process. For the purposes of this discussion, however, the important fact is probably that any set of coupled reactions so complex would take a good deal of mutation and selection to evolve.

The overall geochemical result of photosynthesis is to produce a more oxidized part of the biosphere, namely the atmosphere and most of the free water in which oxygen is dissolved, and a more reduced part, namely the bodies of organisms and their organic decomposition products in litter, soils and aquatic sediments. Some sediments become buried, producing dispersed organic carbon and fossil fuels, and there is a similar loss of oxygen by the oxidation of eroding primary rock. The quantitative relation of the fossilization of the organic (or reduced) carbon and the inorganic (or oxidized) carbon clearly bears on the history of the earth but so far involves too many uncertainties to produce unambiguous answers. From the standpoint of the day-to-day running of the biosphere what is important is the continual oxidation of the reduced part, living or dead, by atmospheric oxygen to produce carbon dioxide (which can be employed again in photosynthesis) and a certain amount of energy (which can be used for physical activity, growth and reproduction). The production of utilizable fossil fuels is essentially an accidental imperfection in this overall reversible cycle, one on which we have come to depend too confidently.

It is necessary to maintain a balance in our attitude by stressing the fragility and inefficiency of the entire process. If one considers a fairly productive lake, for example, it is usual to find about 2.5 milligrams of particulate organic matter under an average square centimeter of lake surface. Assuming that this organic matter is all phytoplankton, with a water content of 90 percent, there are about 25 cubic millimeters of photosynthetic organisms per 100 square millimeters of lake surface. If this were all brought to the surface, it would form a green film a quarter of a millimeter thick. Both assumptions undoubtedly exaggerate the thickness, which may well be no more than a tenth of a millimeter, or the thickness of a sheet of paper.

The total photosynthetic material of the open ocean can hardly be greater and



may well be much less. Similarly, when one looks up from the floor of a broad-leaved forest, there is obviously some overlap of leaves, but five leaves, one above the other, would usually remove almost all the available energy. Moreover, in this case much of the organic material is in the form of skeletal cellulose, which provides support and control of evaporation; as a result there is an even less economical use of the volume of the plant than in the case of the phytoplankton. The machinery by which energy enters the living world is clearly quite tenuous.

Estimates of the efficiency of the photosynthetic process are quite variable and depend greatly on the circumstances. Under conditions of optimum cultivation an annual utilization of several percent of the incoming visible radiation is easily achieved on land, the limit probably being set by the carbon dioxide content of the air, but the overall efficiency of land surfaces as a whole seems to lie between .1 and .3 percent. In water, under special circumstances aimed at maximum yield, very high levels of production, apparently approaching the theoretical quantum efficiency of the photosynthetic process, seem possible, but again in nature as a whole efficiencies of the order of a few tenths of a percent are usual. On land much of the radiant energy falling on a tall plant is not wasted but is needed to maintain the stream of water being transpired from the leaves.

The movement of material through living organisms involves many more elements than those contained in water and carbon dioxide. In addition to carbon, oxygen and hydrogen, all organisms use nitrogen, phosphorus, sulfur, sodium, potassium, calcium, magnesium, iron, manganese, cobalt, copper, zinc and probably chlorine, and some certainly use for special functions aluminum, boron, bromine, iodine, selenium, chromium, molybdenum, vanadium, silicon,

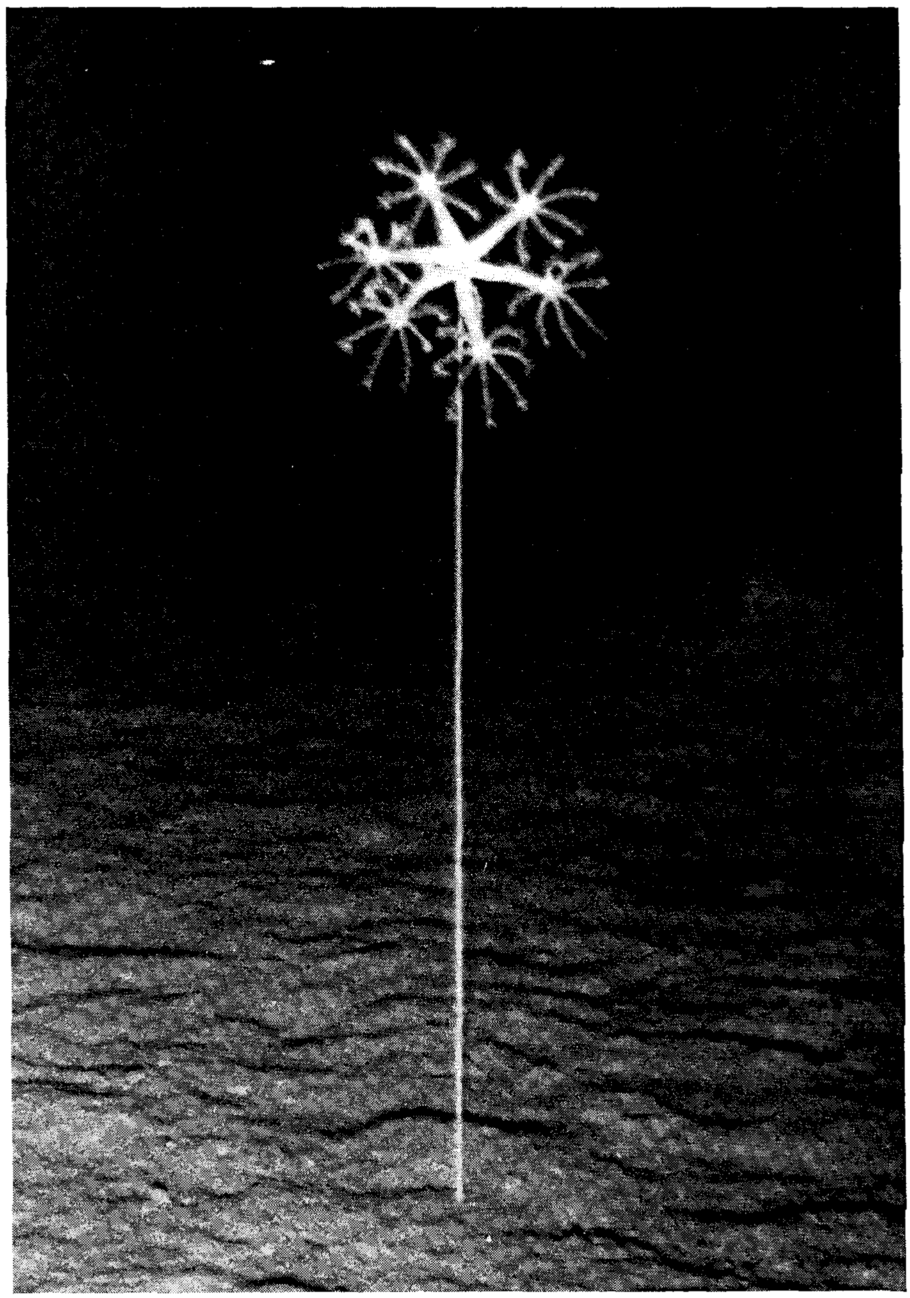
VERTICAL EXTENT of the biosphere is depicted schematically in the illustration at the left. As a terrestrial envelope the biosphere has a somewhat irregular shape inasmuch as it is surrounded by an indefinite "parabiospheric" region in which some dormant forms of life, such as the spores of bacteria and fungi, are present. The euphotic, or illuminated, zone of aqueous bodies may be only a few centimeters deep in a very turbid river or well over 100 meters deep in the clearest parts of the ocean.

strontium, barium and possibly nickel. A few elements that occur fairly regularly in specific compounds or situations, such as cadmium in the vertebrate kidney or rare earths in the hickory leaf, are obviously of interest even if they are not functional. Some of the elements now known to be significant only in a particular group of organisms, such as boron in plants, iodine in many animals, chromium in veretebrates or selenium in some plants, birds and mammals, may ultimately prove to be universally essential. A few more functional elements, germanium perhaps being a good candidate, may remain to be discovered. Even the rarer trace elements, when they are unquestionably functional, are present in metabolically versatile tissues, such as those of the liver, in quantities on the order of a million atoms per cell. Very little substitution of one element by another is possible, although some bacteria and algae can use rubidium in place of potassium with no adverse effects other than a slowed growth rate. We all know that certain elements are highly toxic (lead, arsenic and mercury are obvious examples), whereas many of the functional elements are poisonous when high levels of intake are induced by local concentrations in the environment. This means that the detailed geochemistry of each element, particularly in the process of crossing the solid-liquid interface, is of enormous biological importance.

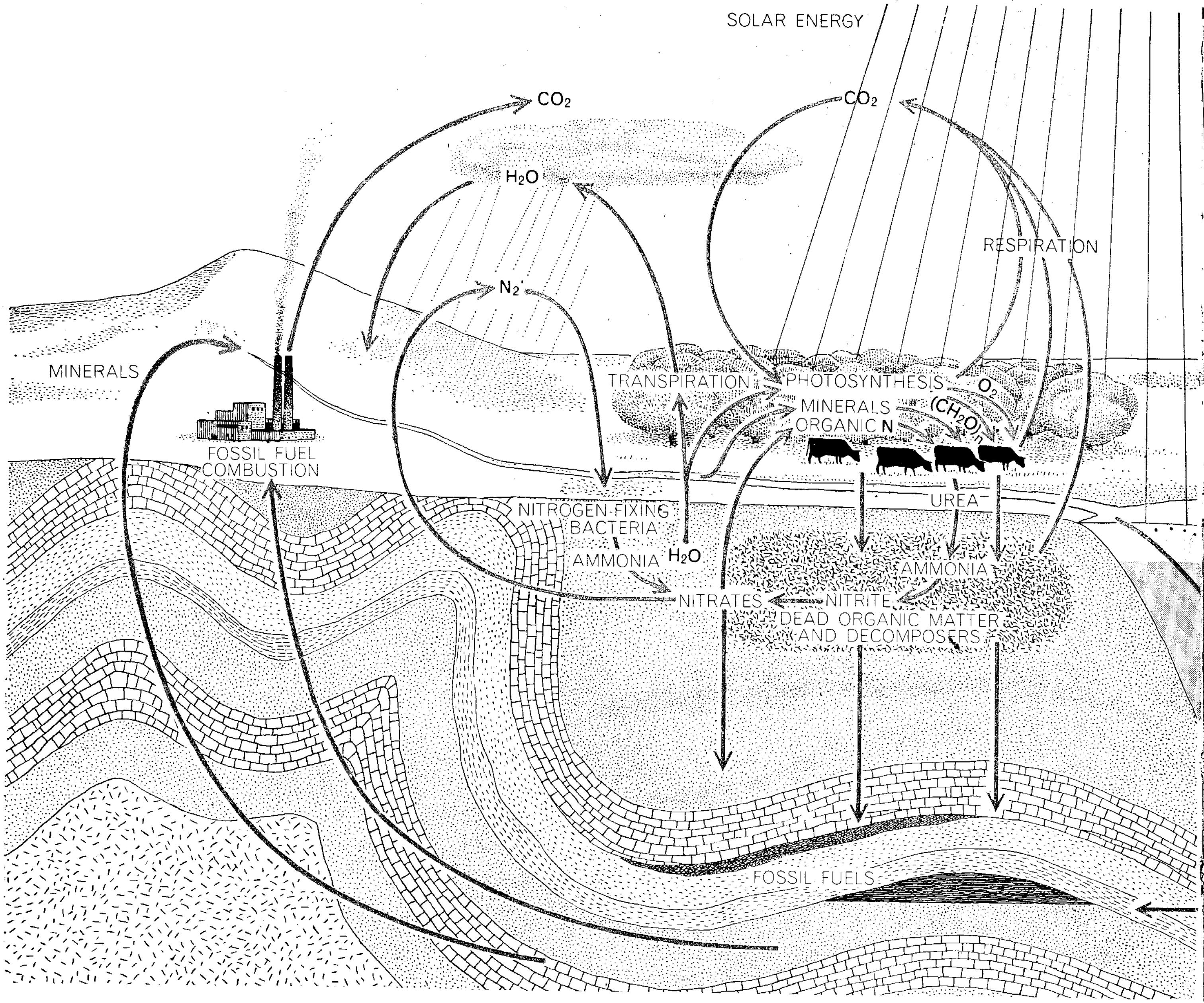
Often the possibility of an element's migrating from the solid state to an ionic form in an aqueous phase (from which an organism can obtain a supply of the element) depends on the state of oxidation at the solid-liquid boundary. Under reducing conditions iron and manganese are freely mobile as divalent (doubly ionized) ions, whereas under oxidizing conditions iron, except when it is complexed organically, is essentially insoluble, and manganese usually precipitates as manganese dioxide. Chromium, selenium and vanadium, all of which are required in minute quantities by some organisms, migrate most easily in an oxidized state as chromate, selenate and vanadate, and so behave in a way opposite from iron. The extreme insolubility of the sulfides of iron, copper, zinc and some other heavy metals may limit the availability of these elements when reduction is great enough to allow hydrogen sulfide to be formed in the decomposition of proteins or by other kinds of bacterial action. Phenomena of this kind mean that under different chemical conditions different materials determine how much living matter can be present.

Expanding this 19th-century agriculturist's idea of limiting factors a little, it is evident that in a terrestrial desert hydrogen and oxygen in the form of water determine the amount of life. In the blue waters of the open ocean the best results indicate that a deficiency of iron is usually limiting, the element probably being present only as dispersed ferric hydroxide, which can be used by phytoplankton cells if it becomes attached to their cell wall. In an intermediate situation, as in a natural terrestrial soil in a fairly humid region, or in a lake or coastal sea, phosphorus is probably the most usual limiting element.

The significance of phosphorus in controlling the quantity of living organisms in nature is due not only to its great biological importance but also to the fact that among the light elements it is relatively scarce. As an element of odd atomic number it is almost two orders of magnitude rarer in the universe than its neighbors in the periodic table, silicon and sulfur. Moreover, in iron meteorites



LIFE AT THE FRINGE of the biosphere is represented by this strange-looking creature photographed recently by an automatic camera lowered to a depth of 15,900 feet from the U.S. Naval oceanographic vessel *Kane*, which at the time was situated in the South Atlantic some 350 miles off the coast of Africa. The plantlike organism is actually an animal: a polyp of the family Umbellulidae. The stem on which its food-gathering tentacles are mounted is approximately three feet long and is leaning toward the camera at an angle of 30 degrees.

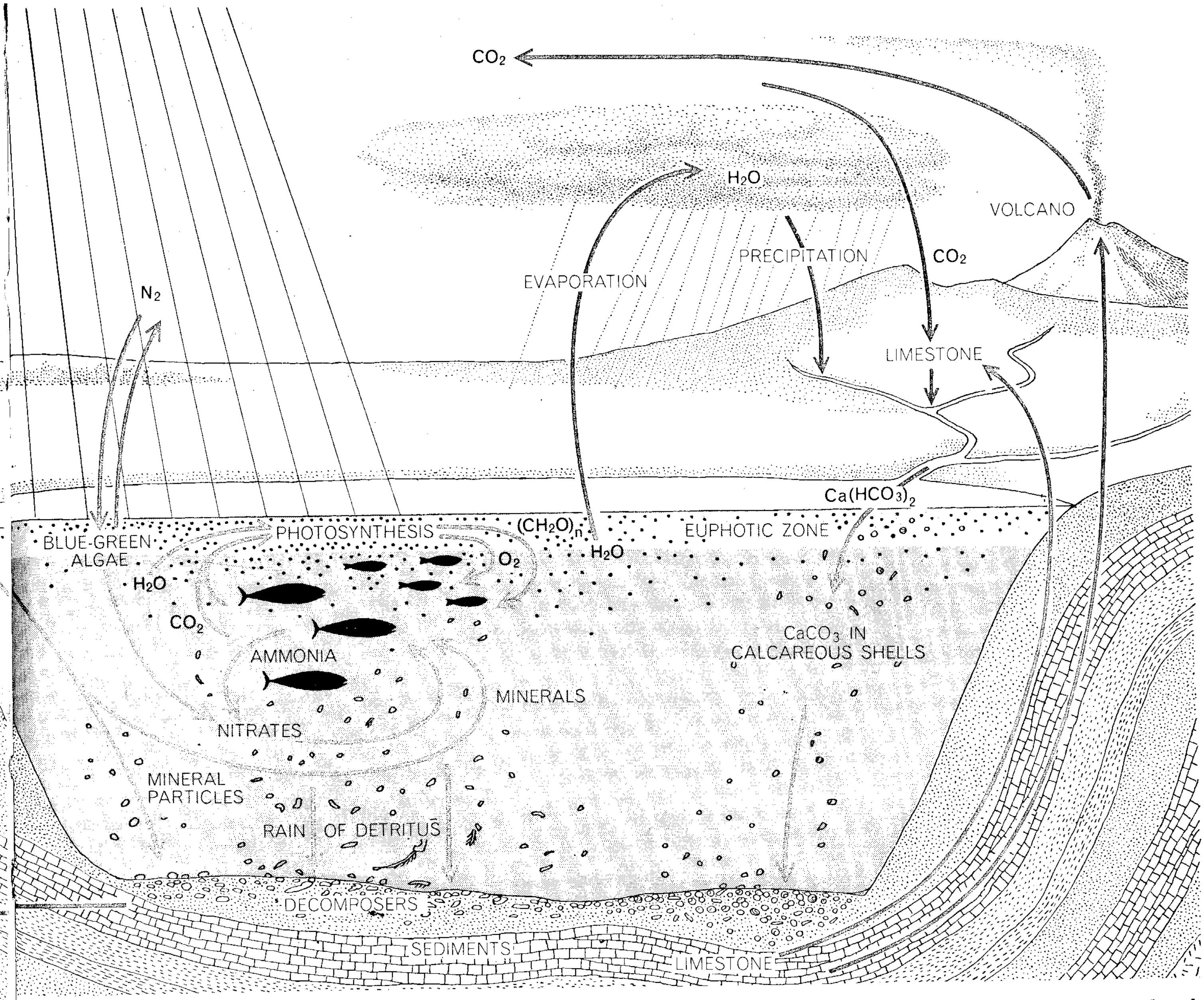


MAJOR CYCLES OF THE BIOSPHERE are indicated in a general way in the illustration on these two pages; more detailed versions of specific cycles accompany the succeeding articles in this issue. In brief, the operation of the biosphere depends on the utili-

phosphorus is found to be enriched in the form of the iron-nickel phosphide schreibersite, so that it is not unlikely that a good part of the earth's initial supply of the element is locked up in the metallic core of our planet. The amount of phosphorus available is thus initially limited by cosmogenic and planetogenic processes. In the biosphere the element is freely mobile under reducing but not too alkaline conditions; since the supply of reduced iron is nearly always much in excess of the phosphorus, oxidation precipitates not only the iron but also the phosphorus as the very insoluble ferric phosphate.

In many richly productive localities where phosphorus is reasonably accessible the quantity of combined nitrogen evidently builds up by biological fixation, so that the ratio of the two elements in water or soil will tend to be about the same as it is in living organisms. In such circumstances both the phosphorus and the nitrogen are limiting; the addition of either one alone produces little or no increase in living matter in a bottle of water or in any other system isolated from the environment, whereas the addition of both often leads to a great increase. Where nitrogen alone is limiting it may be the result of a disturbance of the ecological balance between the nitrogen-fixing organisms (mainly blue-green algae in water and bacteria in soil) and the other members of the biological association. Limitation by nitrogen is never due to a dearth of the element as such, since it is the commonest gas in the atmosphere, but rather depends on the level of activity of the special biological mechanisms, chemically related to photosynthesis but retained only by primitive organisms, for dissociating the two atoms of molecular nitrogen (N_2) and forming from them the amino ($-NH_2$) groups of proteins and other organic compounds.

If the biosphere is to continue in running order, the biologically important materials must undergo cyclical changes so that after utilization they are put back, at the expense of some solar energy, into a form in which they can be reused. The rate at which this happens is quite variable. The rate of circulation of the organic matter of terrestrial organisms, derived from the carbon dioxide of the atmosphere, is measured in decades. In



zation of solar energy for the photosynthetic reduction of carbon dioxide (CO_2) from the atmosphere to form organic compounds on the one hand $(CH_2O)_n$ and molecular oxygen (O_2) on the other. The cycling of certain other vital elements is also indicated.

the case of calcium, which is carried from continental rocks in rivers as calcium bicarbonate ($Ca(HCO_3)_2$) and precipitated as calcium carbonate ($CaCO_3$) in the open ocean largely in the form of the tiny shells of foraminifera, most of the replacement must be due to the movement of the ocean floors toward coastal mountain-building belts; presumably the rate of cyclical replacement would be measured in hundreds of millions of years. Phosphorus would behave rather like calcium, nitrogen more like carbon, although the atmospheric reservoir of nitrogen is of course much larger and the biological fixation of the element is less widespread and energetically more expensive.

At present the artificial injection of some elements in a mobile form into the ocean and atmosphere is occurring much faster than it did in preindustrial days; new cycles have come into being that may distribute very widely and in toxic quantities elements such as lead and mercury, as well as fairly stable new compounds such as insecticides and defoliants. It should be obvious that the possible action of all such substances on the tenuous and geochemically inefficient green mantle of the earth demands intense study if life is to continue in the biosphere.

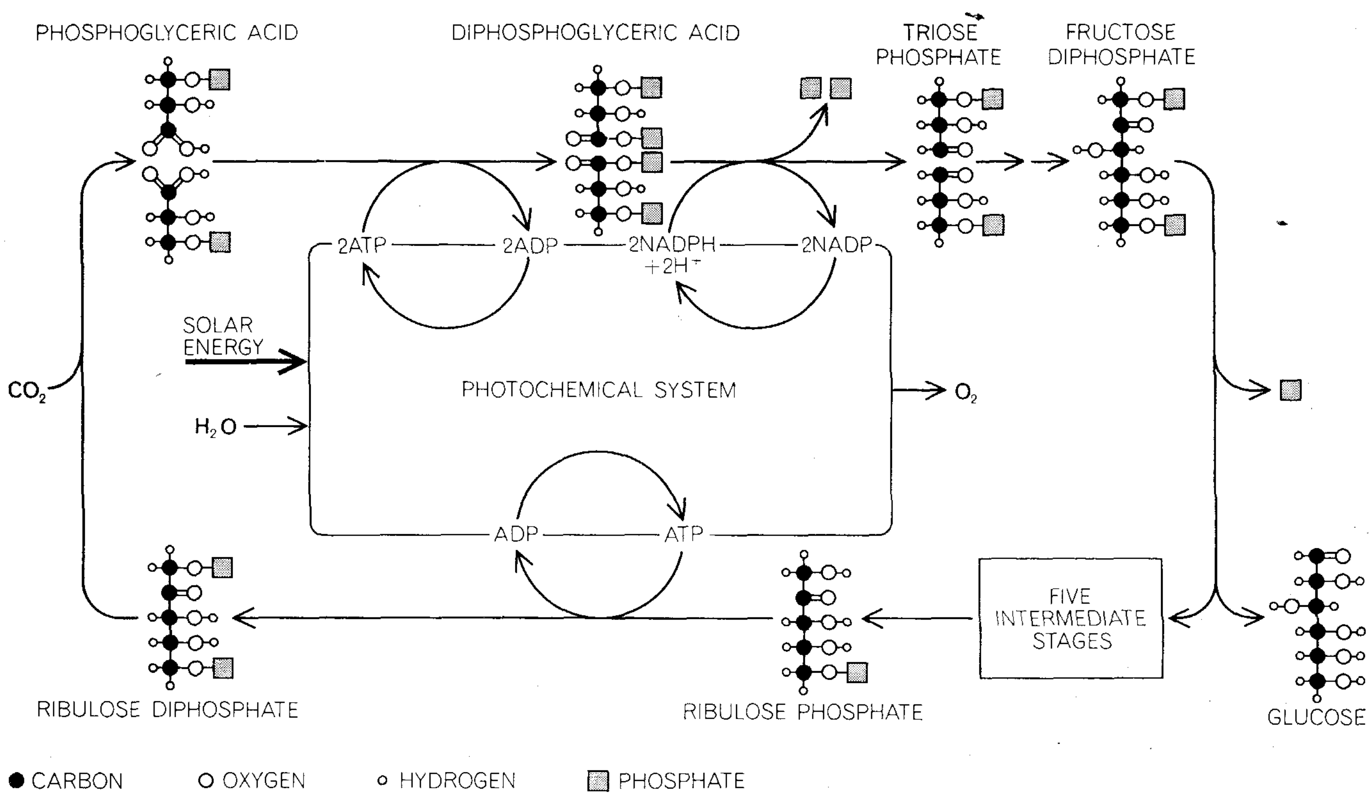
How did the system we have been examining come into being? There are now a few facts that seem clear and a few inferences that are reasonable. We know that the present supply of atmospheric oxygen is continually replenished by photosynthesis, and that if it were not, it would slowly be used up in the process of oxidation of ferrous to ferric iron and sulfides to sulfates in weathering. All the evidence points to the atmosphere of the earth's being secondary. The extreme rarity of the cosmically abundant but chemically inert gas neon compared with water vapor, which has almost the same molecular weight, shows (as Harrison Brown pointed out 25 years ago) that only gases that could be held in combination in the solid earth were available for the formation of the secondary atmosphere. The slow production of oxygen by the photolysis (literally "splitting by light") of water and by the thermal dissociation of water with the loss of hydrogen into space is possible even in the early atmosphere, but nearly everyone agrees that this would merely lead to a little local oxidation of material at or near the earth's crust.

Some mixture of water vapor, methane, carbon monoxide, carbon dioxide, ammonia and nitrogen presumably initiated the secondary atmosphere. We know from laboratory experiments that when an adequate energy source (such as ultraviolet light or an electric discharge) is available, many organic compounds, including practically all the building blocks of biological macromolecules, can be formed in such an atmosphere. We also know from studies of meteorites that such syntheses have occurred under extraterrestrial conditions, but that a good many substances not of biological significance were also formed. It is just possible that ultimately exploration of the asteroids may produce evidence of the kind of environment on a disrupted planet in which these kinds of prebiological organic syntheses took place.

However that may be, we can be reasonably confident that a great deal of prebiological organic synthesis occurred on the earth under reducing conditions at an early stage in our planet's history. The most reasonable energy source would be solar ultraviolet radiation. Since some of the most important compounds are not only produced but also destroyed by the wavelengths available in the absence of an oxygen screen, it is probable that the processes leading to production of the first living matter took place under specific structural conditions. Syntheses may have occurred in the water vapor and gases above a primitive system of pools or a shallow ocean, while at the bottom of the latter, somewhat shielded by liquid water, polymerization of some of the products on clay particles or by other processes may have taken place.

The first hint that organisms had been produced is the presence of bacteria-like structures in the Figtree geological formation of South Africa; these fossils are believed to be a little more than three billion years old. Carbon-containing cherts from Swaziland that are older than that have been examined by Preston Cloud of the University of California at Santa Barbara, who did not find any indication of biological objects. The oldest really dramatic microflora are those described by Stanley A. Tyler and Elso S. Barghoorn of Harvard University from the Gunflint formation of Ontario, which is about two billion years old [*see illustration on page 44*]. Sedimentary rocks from that formation seem to contain genuine filamentous blue-green algae that were doubtless both photosynthetic and nitrogen-fixing. Cellular structures that were probably components of blue-green algal reefs certainly occurred a little earlier than two billion years ago. The most reasonable conclusion that can be drawn from the work of Barghoorn, Cloud and others, who are at last giving us a real Precambrian paleobiological record, is that somewhere around three billion years ago biochemical evolution had proceeded far enough for discrete heterotrophic organisms to appear.

These organisms (which, as their name implies, draw their nourishment from externally formed organic molecules) could utilize the downward-diffusing organic compounds in fermentative metabolism, but they lived at sufficient depths of water or sediment to be shielded from the destructive effect of the solar ultraviolet radiation. After somewhat less than another billion years procaryotic

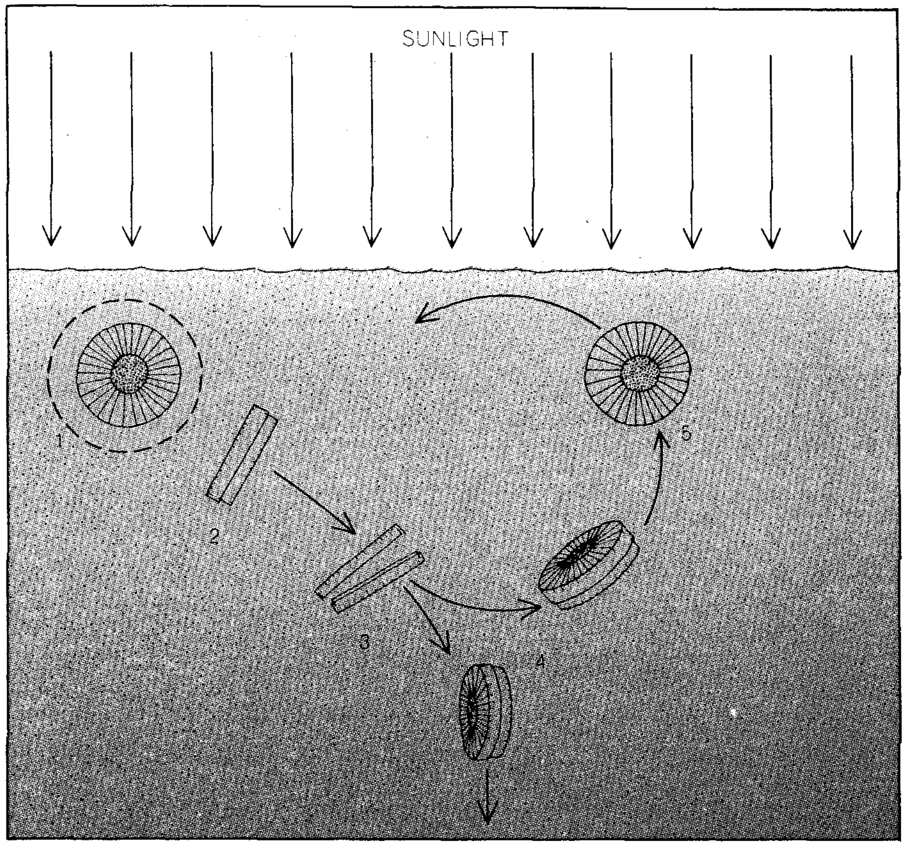


PHOTOSYNTHESIS, the fundamental process for sustaining life on the earth, is accomplished by plants on land, by freshwater algae and by phytoplankton in the sea. Utilizing the energy contained in sunlight, they convert carbon dioxide and water into some form of carbohydrate (for example glucose), releasing oxygen as a waste product. This simplified diagram shows the cyclical process by which a molecule of carbon dioxide is attached to a five-carbon molecule, ribulose-1,5-diphosphate, previously assembled from five molecules of carbon dioxide. The photochemical system packages part of the incoming solar energy by converting adenosine diphosphate (ADP) to adenosine triphosphate (ATP) and by converting nicotinamide adenine dinucleotide phosphate (NADP) to its reduced form (NADPH). Two molecules of NADPH and three of ATP are required to fix one molecule of carbon dioxide. Carbon atoms from CO_2 can be incorporated into a variety of compounds and removed at various points in the cycle.

cells—cells without a fully developed mitotic mechanism for cell division and without mitochondria—had already started photosynthesis. The result of these developments would have ultimately been the complete transformation of the biosphere from the old heterotrophic fermentative regime to the new autotrophic (self-nourishing), respiratory and largely oxidized condition. How fast the change took place we do not know, but it was certainly the greatest biological revolution that has occurred on the earth. The net result of this revolution was no doubt the extermination of a great number of inefficient and primitive organisms that could not tolerate free oxygen and their replacement by more efficient respiring forms.

Cloud and his associates have recently found evidence of eucaryotic cells—cells with a fully developed mitotic mechanism and with mitochondria—some 1.2 to 1.4 billion years old. It is reasonable to regard the rise of the modern eucaryotic cell as a major consequence of the new conditions imposed by an oxygen-containing atmosphere. Moreover, Lynn Margulis of Boston University has assembled most convincingly the scattered but extensive evidence that this response was of a very special kind, involving a multiple symbiosis between a variety of procaryotic cells and so constituting an evolutionary advance quite unlike any other known to have occurred.

If the first eucaryotes arose 1.2 to 1.4 billion years ago, there would be about half of this time available for the evolution of soft-bodied multicellular organisms, since the first fossil animal skeletons were deposited around 600 million years ago at the beginning of the Cambrian period. Although most of the detailed history consists of a series of blanks, we do have a time scale that seems sensible.



PHYTOPLANKTON CELL is slightly denser than seawater and under absolutely quiet conditions would slowly sink to the bottom. In this way the cell can move from a small parcel of water (*broken circle*) from which it has removed all the available nutrients (*black dots*) into a parcel still containing these substances. As the cell sinks it divides, and losses from the population in the surface waters that constitute the euphotic zone are continually made good by upward turbulence, which returns some of the products of cell division to the surface layer. The particular phytoplankton shown is a diatom of the genus *Coscinodiscus*.

Without taking too seriously any of the estimates that have been made of the expectation of the life of the sun and the solar system, it is evident that the biosphere could remain habitable for a very long time, many times the estimated length of the history of the genus *Homo*, which might be two million years old. As inhabitants of the biosphere, we should regard ourselves as being in our infancy, particularly when we throw destructive temper tantrums. Many people, however, are concluding on the basis of mounting and reasonably objective evidence that the length of life of the biosphere as an inhabitable region for organisms is to be measured in decades rather than in hundreds of millions of years. This is entirely the fault of our own species. It would seem not unlikely that we are approaching a crisis that is comparable to the one that occurred when free oxygen began to accumulate in the atmosphere.

Admittedly there are differences. The first photosynthetic organisms that produced oxygen were probably already immune to the lethal effects of the new poison gas we now breathe. On the other hand, our machines may be immune to carbon monoxide, lead and DDT, but we are not. Apart from a slight rise in agricultural productivity caused by an increase in the amount of carbon dioxide in the atmosphere, it is difficult to see how the various contaminants with which we are polluting the biosphere could form the basis for a revolutionary step forward. Nonetheless, it is worth noting that when the eucaryotic cell evolved in the middle Precambrian period, the process very likely involved an unprecedented new kind of evolutionary development. Presumably if we want to continue living in the biosphere we must also introduce unprecedented processes.

Vernadsky, the founder of modern biogeochemistry, was a Russian liberal who grew up in the 19th century. Accepting the Russian Revolution, he did much of his work after 1917, although his numerous philosophic references were far from Marxist. Just before his death on January 6, 1945, he wrote his friend and former student Alexander Petrunkevitch: "I look forward with great optimism. I think that we undergo not only a historical, but a planetary change as well. We live in a transition to the noosphere." By noosphere Vernadsky meant the envelope of mind that was to supersede the biosphere, the envelope of life. Unfortunately the quarter-century since those words were written has shown how mindless most of the changes wrought by man on the biosphere have been. Nonetheless, Vernadsky's transition in its deepest sense is the only alternative to man's cutting his lifetime short by millions of years. The succeeding articles in this issue of *Scientific American* may contain useful hints as to how this alternative may be brought to fruition.