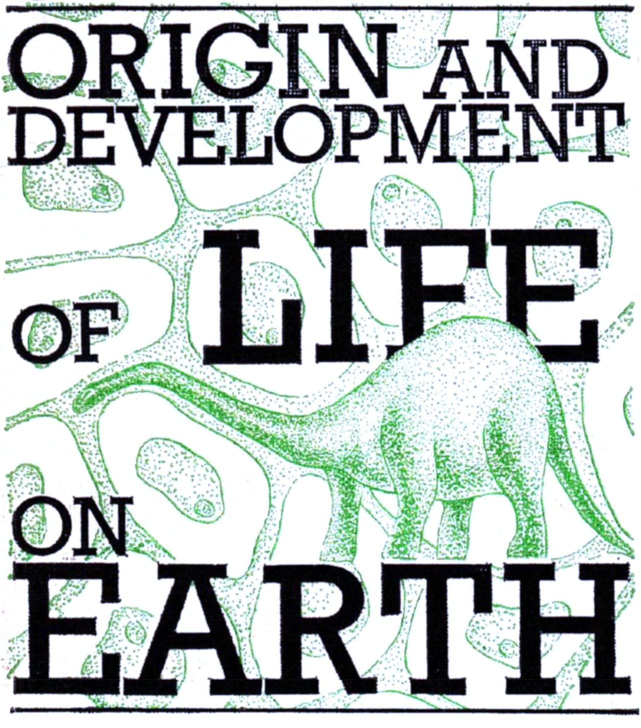
SCIENCE FOR EVERYONE

G. VOITKEVICH

ORIGIN AND DEVELOPMENT OF LIFE ON EARTH



MIR

Science
for Everyone

Г. В. Войткевич

Возникновение и развитие жизни на Земле

Издательство «Наука» Москва

G.V. Voitkevich

Origin and Development of Life on Earth

Translated from the Russian
by G.G. EGROV

Mir
Publishers
Moscow

Preface

The problem of the origin of life is of current importance in contemporary natural sciences. It has become responsible for a great deal of research that is carried out in various scientific centres in this country and elsewhere. The vast amount of incomplete empirical data calls for new approaches and quite novel principles of generalization. The solution of this multilateral problem becomes ever more difficult for any researcher working on his own. While this book was being written and prepared for publication its author fully comprehended the words of the outstanding English physicist and naturalist John Bernal (1901-1971). He had explained that any solution of the problem of the origin of life suggested by an individual irrespective of his or her education or talent was bound to be biased and subject to criticism since it would be based on the ideas or assumed facts referring partially to those fields of science with which the person is not directly familiar.

In spite of the fact that the problem connected with the origin of life is tackled mainly by biochemists and specialists conducting research in the field of molecular biology, its solution cannot be achieved without the participation of scientists who are concerned with the study of the environment in which the origin and development of life occurred, i.e. geologists, paleontologists, geochemists and others. What is also urgently required is the data furnished by present-day cosmochemistry.

In 1976 the author of this book wrote: 'The main prerequisites conditioning the emergence of life on Earth were created at the end of the cooling period of the primary gaseous nebula. In the last stages of cooling and as a result of catalytic reactions of biophile elements numerous organic compounds were formed. They gave rise to the origin of the genetic code and the self-developing molecular systems.

The beginning of the Earth and life represented a unique interrelated process, or the result of the chemical evolution of the solar system matter.'

This statement has been thoroughly substantiated by the achievements in science and the new empirical data provided by geochemistry, cosmochemistry, and experimental biochemistry. A large number of books, including those for the public at large, have been devoted to the development of life on Earth.

However, the latest discoveries in the field of micropaleontology and geochemistry of isotopes render it possible to describe the fascinating history of the development of life on Earth from quite a different angle. This is precisely what has encouraged the author to write this book, in which the problem of the origin of life is regarded in terms that are absolutely new.

Contents

The Earth's Contemporary Biosphere and Its Population

Living organisms together with their habitats with which they are most closely connected by means of energy and metabolism form a very special kind of the Earth's cover known as biosphere. Today our planet's biosphere with all its population owes its origin to a prolonged evolution of the living matter and the changes of the whole environment.

The concept of biosphere first came to light in the works of the famous French naturalist J.B.P. Lamarck (1744-1829). Into geological sciences biosphere was included on the initiative of the Austrian geologist E. Suess (1834-1914). However, a profound scientific study of the biosphere as the Earth's sphere with qualitatively unique energetic and geochemical properties was developed in the USSR by the remarkable naturalist V.I. Vernadsky (1863-1945). In later years this branch of science was further augmented by the new ideas elaborated by A.P. Vinogradov, V.V. Kovalsky, A.A. Polynov, A.I. Perelman and other, mainly Soviet, scientists.

The biosphere represents a highly complicated organization of matter in which its various inorganic forms of movement are related to living substances. Millions of species of organisms, existing in the biosphere, do not live by themselves, but are in regular associations with numerous specimens called biocenoses. As a matter of fact, the origin of the first living organisms on our planet found its expression in the emergence of biocenoses. In other words, any form of life is connected with a particular environment, and, thus, the problem of the origin of life may well be regarded as precisely the problem of the emergence of the biosphere itself.

The metabolism with the outer environment had become *a sine qua non* for the existence of every single organism. Presumably, the whole biosphere of our planet should be regarded as that part of its matter, which undergoes the process of metabolism with the living matter. As regards the medium of their habitat all living organisms are divided into autotrophic and heterotrophic varieties. The autotrophic organisms include those whose source of nutrition is inorganic mineral substances. The most typical process of autotrophic nutrition is photosynthesis, when with the help of the sun's ray organic substances are derived from carbon dioxide and water of the surrounding medium. What serves as the source of nutrition for heterotrophic organisms is the final organic substances. It is not difficult to imagine that autotrophic organisms comprise green plants, while animals are referred to the heterotrophic variety. However, mention should be made of the fact that a smaller part of the biosphere is inhabited by microorganisms that combine in themselves both autotrophic and heterotrophic means of nutrition. This transitional form of organisms between plants and animals is represented by flagellates—euglenas, which retain chlorophyll and have the autotrophic means of nutrition, while some of them, depending on the conditions of the environment and illumination, change the autotrophic means of nutrition for the heterotrophic one.

Most of the organisms of the contemporary biosphere are referred to the aerobic variety that live in the presence of free oxygen of the Earth's atmosphere; a considerably smaller part consists of microorganisms that are the anaerobes inhabiting the medium deprived of oxygen.

Living organisms are settled according to the conditions of their habitat in the uppermost layers of our planet: the atmosphere, hydrosphere, soil, and sedimentary cover or the stratosphere. In the biosphere organisms form markedly diverse concentrations—from single bacteria and spores per cubic metre of atmospheric air to the densest tropical forests of the equatorial belt of our planet and traces of life in the depth of the World Ocean.

The totality of living organisms form

the unit—the living matter of our planet, or its biomass. According to the data supplied by the Soviet scientists N.I. Bazilevich, L.E. Rodin, and N.N. Rozov, the overall amount of biomass and its distribution between land and sea are presented in Table 1.

TABLE 1. The Biomass of Organisms on the Earth

Habitat	Group of organisms	Mass, 10^{12} metric tons	Percentage
Continents	Green plants	2.4	99.2
	Animals and microorganisms	0.02	0.8
	Total	2.42	100.0
Oceans	Green plants	0.0002	6.3
	Animals and microorganisms	0.003	93.7
	Total	0.0032	100.0
	Total	2.4232	

It is not difficult to observe that the biomass of organisms on land (continents) is practically 800 times greater than that of the biomass of the World Ocean. Hence, it would be quite natural to infer that the exit of organisms on land in the middle of the Paleozoic era led to a considerable increase of the whole biomass of the Earth with all the ensuing biogeochemical consequences. In his time V.I. Vernadsky came to the conclusion that the biomass is constant within the whole period of the Earth's history. However, at present this statement should be accepted rather tentatively.

Since the living conditions in the World Ocean were most favourable, it is possible to consider that the Earth's hydrosphere was distinguished by the constancy of the biomass throughout the whole period of its existence. In this case the total amount of the mass of living matter was determined by the surface area of the World Ocean—a value that is apparently variable and dependent on the geological development of the earth's crust.

All the organisms of our planet are most closely connected with water. The famous German physiologist R. Du Bois (1818-1896) wrote that the organism is living water, or *eau animale*. For a living organism bound water, that does not lose its main properties, is a most necessary ingredient. Its amount in living organisms, excluding spores and inert seeds, fluctuates between 60 and 99.7% in weight. The role of water in the vital activity of organisms can hardly be overrated. With the higher animals it is the intensely functioning organs that are most lavishly saturated with water. If in a skeleton there are 22% of water, while in the muscles the figure goes up to 76.6%, whereas the content of water in the heart increases to 79.3%, and reaches 83.3% in the cerebral cortex. In the period of their rapid growth the amount of water in young organisms exceeds 90%. With the mature ones the figure drops to 50%. If we consider the low-organized varieties, we shall find the jellyfish to be the most striking example, since the amount of water in them is equal to 99.9% in weight. But the jellyfish are complex, mobile bodies in the sea environment. At the same time the sea fauna is much more varied as far as the number of different types of animals is concerned, than that of land.

Thus, the evolution of the principal classes and types of animal kingdom was closely connected with aqueous medium, which has left its imprint on the appearance of the now existing organisms.

In chemical terms what is the starting point of active substance is the carbon that possesses the unique property of creating an infinite variety of chemical compounds. Any form of the living organism consists of combinations of few chemical elements. For instance, 96% of the mass of human body are made up of such abundantly spread elements in the biosphere as H, C, N, and O. The other elements enter into the composition of living organisms in relatively insignificant quantities, in spite of the exclusively important role that some of them have in performing physiological functions. We may well think that all the elements of Mendeleev's Table enter into the composition of the living matter of our planet, though in different quantities. The general character of the propagation of

TABLE 2. The Abundance of Chemical Elements in the Living Substance

Content in weight %	Elements	Content in weight %	Elements
10	O, C, H	10^{-5}	Ni, Pb, Sn, As, Co, Rh, Li, Mo, Y, Ce
10^{-1}	N, Ca, K, Si		
10^{-2}	P, S, Mg, Na, Cl, Fe	10^{-6}	Se, U
10^{-3}	Al, Ba, Sr, Mn, B, TR	10^{-7}	Hg
10^{-4}	Br, F, Ti, Zn, Rb, Cu, V, Cr		

chemical elements in the living organism according to the degree of their content is given in Table 2.

Living organisms possess a selective ability of making use of the chemical elements from the environment according to their physiological needs. A large number of elements enter into the composition of both the organic and mineral compounds of living substances. They can be subdivided into the main structural elements (C, H, N, O, P, S, Na, K, F, Mg, Si, Ca) and biocatalytic elements (Fe, Cu, B, Mn, J). The most essential chemical elements of living organisms are called biophilic. The combinations of their atoms give rise to a variety of molecules of organic substances.

However, the diverse forms of life consist of a rather small number of simple molecules that are referred to as monomers. The most significant of them are amino acids, which become responsible for the formation of protein. The living substance of the biosphere predominantly consists of long molecules which have the form of chains. These chains are bound to each other and form polymers, in which certain structures are repeated with minor variations. Within polymers there sometimes occur ring structures and side chains, while chains themselves are coiled into specific complex structures. These structures help some of the protein polymers to find their expression as catalysts accelerating the process of chemical reactions. Organic catalysts of this kind are called ferments. The variety of organic chemical compounds is conditioned by the formation of diverse polymers from monomers and the combinations of polymers with each other by different means. The basis of a living matter is formed by carbohydrates, fats, water, and nucleic acids (Fig. 1).

Carbohydrates are highly spread organic compounds. They represent the simplest compounds of carbon, which consist of C, O, H in different relationships, that are usually expressed by the general formula $C_nH_{2n}O_n$. They include monosaccharides, e.g. glucose and fructose ($C_6H_{12}O_6$). In the tissues of animals we can find the most complicated variety

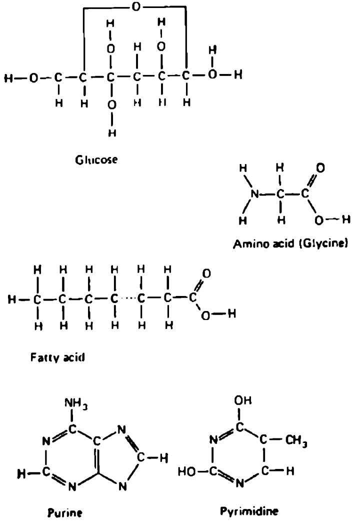


Fig. 1. Structural formulas of important chemical compounds entering into the composition of living matter

of saccharide known as glycogen. Its molecule comprises one thousand molecules of monosaccharides. In the composition of plants a very important function is attributed to cellular tissue (cellulose), of which the walls of the plant cells are built.

Fats are complex organic compounds consisting of combinations of various fatty acids. In the molecules of fats the atoms of carbon form chains that are connected with the atoms of hydrogen. Oxygen is present in very small quantities. The structural formula of one of the fatty acids is given in Fig. 1.

Proteins are exceptionally complex natural organic compounds. Besides C, O, and H, they contain N, and sometimes S. One molecule of ordinary protein consists of several hundred monomers—amino acids. Each type of protein is distinguished from some other by a set of amino acids and the order in which their molecules are arranged in space. Out of a large number of possible amino acids only twenty are relatively widespread in living organisms. Their composition is presented in Table 3. The average molecule of protein consisting of 100 molecules of amino acids, can yield 20^{100} combinations of structures, which markedly exceeds the number of atoms in our Galaxy. However, most of the living organisms synthesize and use less than 100 thousand types of protein molecules.

The organized accumulations of an organic substance capable of self-reproduction and that represent units of heredity are called genes. In general they are made up of purines, pyrimidines, sugar, and phosphate ions. The

TABLE 3. Amino Acids Found in Living Organisms

Amino acid	Chemical formula	Number of atoms
Alanine	$C_3H_7O_2N$	13
Arginine	$C_6H_{15}O_2N_4$	27
Asparagine	$C_4H_8O_3N_2$	17
Asparagine acid	$C_4H_7O_4N$	16
Cysteine	$C_3H_7O_2NS$	14
Glutamic acid	$C_5H_9O_4N$	18
Glutamine	$C_5H_{10}O_3N_2$	20
Glycine	$C_2H_5O_2N$	10
Histidine	$C_6H_9O_2N_3$	20
Isoleucine	$C_6H_{13}O_2N$	22
Leucine	$C_6H_{13}O_2N$	22
Lysine	$C_6H_{15}O_2N$	25
Methionine	$C_5H_{11}O_2NS$	20
Phenylalanine	$C_9H_{11}O_2N$	23
Proline	$C_5H_9O_2N$	17
Serine	$C_3H_7O_3N$	14
Threonine	$C_4H_9O_3N$	17
Tryptophane	$C_{11}H_{12}O_2N$	27
Tyrosine	$C_9H_{11}O_3N$	24
Valine	$C_5H_{11}O_2N$	19

structural formulae of purine and pyrimidine can be found in Fig. 1.

The prerequisite for the existence of living organisms is their ability to reproduce themselves. It has been established that in all living organisms the process of reproduction is governed by one and the same polymer—desoxyribonucleic acid (DNA). The DNA molecules together with the molecules of ribonucleic acid (RNA) that are closely related to them provide the organism with the information as to how it should function.

The DNA molecules retain the genetic code that imparts to the subsequent generation of organisms all that is necessary for metabolism, growth and reproduction. All the genetic information is contained in the sequence of chemical groups that are situated within a DNA molecule along the whole of its length. DNA consists of two chains of molecular constructions that are twisted around each other, thus forming a closed double spiral.

In accordance with the data furnished by genetics and molecular biology, all the living beings on our planet (fish, birds, plants, and other organisms) are structured, as it were, according to a single plan—from similar building blocks composed of proteins, nucleic acids, polysaccharides, and lipids. The set of chemical elements forming the structure of cells is on the whole rather restricted and is mainly determined by biophile elements.

Since for the greater part of geological time the evolution of plants and animals had been taking place in aqueous medium the chemical elements dissolved in it inevitably entered into the composition of these organisms and influenced the general process of some of the living processes. The same can be said of the present period when the relationship of a number of elements in the composition of some elements repeats, so to speak, their relationship in sea water. The comparison of

TABLE 4. The Relative Composition of Blood (or Tissue) of Various Animals (Na = 100) (According to Macallum)

Natural object	K	Ca	Mg	Cl	SO_4
Sea water	3.61	3.91	12.1	181	20.9
Limulus	5.62	4.06	11.2	187	13.4
Aurelia	5.18	4.13	11.4	186	13.2
Homarus	3.73	4.85	1.72	171	6.7
Carcharias	5.75	2.98	2.76	169	—
Acanthias	4.61	2.71	2.46	166	—
Gadus	9.50	3.93	1.41	150	—
Pollachius	4.33	3.10	1.46	138	—
Rana	—	3.17	0.79	136	—
Canis	6.62	2.8	0.76	139	—
Homo	6.75	3.10	0.70	129	—

corresponding relationships for certain elements with the composition of blood or the soft part of the body of various animals is given in Table 4.

In morphological terms the population of the Earth's biosphere is extremely varied. The size of some particular individuals fluctuates within markedly wide limits. Among the plants we can find bacteria that are measured in micrometres, gigantic algae (*Macrocystis*), that reach 300 m in length and eucalyptus the height of which is up to 150 m. Among the animals there are infinitesimal infusorians (tens of micrometres) and gigantic blue whales that are about 33 m long. Since time immemorial the whole living world of our planet has been divided into animals and plants. Nowadays, however, a profound study of the structure of cellular organisms makes it possible to conduct a more substantial and new systematization.

The most low-organized living substances comprise bacteria and blue-green algae. They are distinguished from all other organisms by the absence of a true nucleus in the cell and a specific arrangement of DNA, which is situated in the cell quite freely and does not separate itself from the cytoplasm of the nuclear membrane. These organisms have received the name of prokaryotes because they have a nuclear membrane. The other unicellular and multicellular organisms have distinct nuclei surrounded by the nuclear membrane and that is most distinctly separated from the cytoplasm. These organisms are called eukaryotes. In addition to the differentiated nucleus and cytoplasm, some of their representatives are characterized by the presence of mitochondria, while plastids and complex flagella are typical of a large number of them.

In Fig. 2 we can see the structure of the unicellular representatives of prokaryotes and eukaryotes. The main characteristic features of their organization are given in Table 5. It occurs that the differences between prokaryotes and eukaryotes are far more substantial than, for instance, between the higher plants and higher animals (the former and the latter are eukaryotes). It is precisely the eukaryotes that are divided into two kingdoms—plants and animals. However, at present bacteria and blue-green algae are being excluded from the vegetable kingdom. At the same time there has appeared a clear-cut tendency to single out fungi as an individual kingdom of living organisms. Most of the specialists in

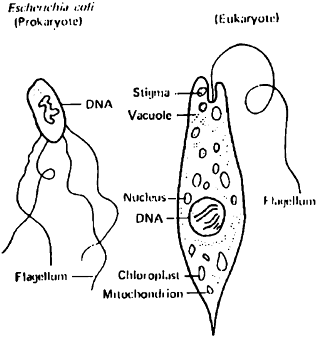


Fig. 2. The structure of *Prokaryotes* (bacteria of *Escherichia coli*) and eukaryotes (the simplest organism of *Euglena*)

the field of mycology consider that the origin of fungi from some group of plants is hardly probable. What presents itself as a more tenable argument is that fungi originated from the heterotrophic simplest amoeboid biflagellate

TABLE 5. The Difference in the Organization of Prokaryotes and Eukaryotes

Main features	Prokaryotes	Eukaryotes
Organisms	Bacteria and cyanobacteria	Fungi, plants and animals
Size	Small, general from 10 to 100 μm.	Small, more often large
Metabolism and photosynthesis	Anaerobic or aerobic	Aerobic
Mobility	Immobile or mobile moving with the help of protein flagellates	Immobile and mobile
Cell walls	Characterized by sugars and peptides	Cellulose or chitin, but lacking in animals
Organelles	No membrane-bound organelles	Mitochondria and chloroplasts
Genetic organization	DNA loop in cytoplasm	DNA in chromosomes and bounded by nuclear membrane
Reproduction	By binary fission	By mitosis or meiosis
Cellular organization	Monocellular	Mainly multicellular with differentiation of cells

organisms. The affinity of fungi with animals has been substantiated by the data of present-day biochemistry.

Taking into account the above, it is possible to regard the organic world of the biosphere as consisting of four kingdoms: that of the prenuclear organisms (prokaryotes), animals, fungi and plants. The most ancient organisms in geological history were prokaryotes. Their vital activity was morphologically and biochemically traced back to the formations of the Precambrian period. The main features of genetic interrelationships between prokaryotes, plants, fungi, and animals are given in Fig. 3.

Eukaryotes are mainly represented by plants and animals. Plants are immobile organisms (they do not have their own means of movement). Their cells are covered with a hard cellulose in the form of a coating which protects them and does not allow them to move freely. Hence for the accumulation of nutritious substances plant cells mainly use the process of photosynthesis. Conversely, the cells of animals have an elastic coating. The animals actively move themselves in search of better habitats and food. It should be noted, however, that there exist marine forms of animals (sponges, corals, crinoids) which lead a sessile way of life and use food in the form of microorganisms.

The principal distinction between plants and animals lies in the means of nutrition and movement. It was made apparent as early as the Precambrian period, when the biosphere was inhabited by unicellular organisms. The

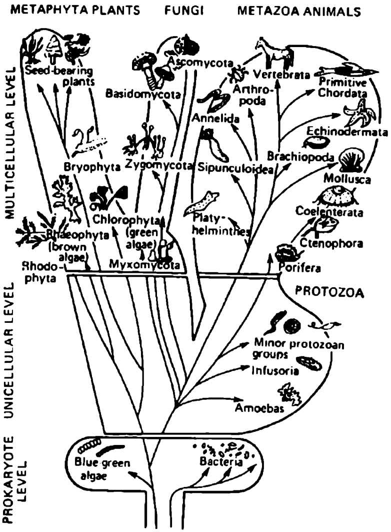


Fig. 3. Genetic interrelationships of various kingdoms of animal organisms. The unicellular prokaryotes led to the formation of more complex unicellular eukaryotes which gave rise to three kingdoms of multicellular organisms: plants, fungi and animals (according to Robert H. Whitteker)

number of animal species is approximately four times greater than those of plant organisms, i.e. the animal kingdom of our planet is more varied than the vegetable kingdom.

According to the number of species insects preponderate among the animals. This is the most numerous class of invertebrates and comprises over one million species. The overall relationship of the number of various species of animals is presented in Fig. 4. It becomes quite obvious that the number of species of insects markedly exceeds the number of species of any class of living organisms. However, in accordance with the data provided by entomologists, the number of specified insects within the confines of biosphere is the same as those that have not yet been taken into account. Since insects reproduce very rapidly, it is quite evident that they represent a powerful biological and geochemical factor. Approximate estimates have revealed that our planet is inhabited by minimum 10^8 billion insects, i.e. there are 250 million representatives of this class per human being on Earth.

The next species in number are the mollusks; but they are considerably fewer than insects. According to the number of species the vertebrates hold the third place, and among them the most developed class is that of mammals which comprise its tenth part. About fifty percent of the vertebrates are accounted for by the fish. Thus, if with the arthropods the most intense formation of species took place on land, and predominantly among the insects, the most favourable possibilities of this kind for the vertebrates found their expression in the aqueous medium.

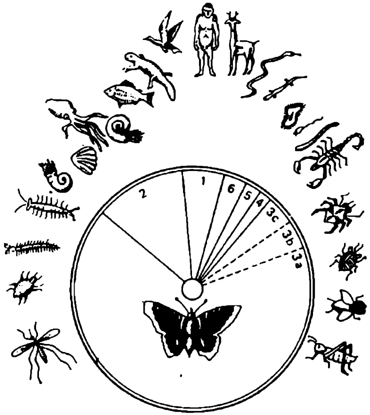


Fig. 4. The numerical relationship of animal species: *1* — chordates; *2* — mollusks; *3* — arthropods (*a* — insects, *b* — spiders, *c* — crustaceans); *4* — worms; *5* — unicellular organisms; *6* — others

Among the plants more than half of the species are made up of angiosperms, which emerged in the recent geological past mainly on the surface of land. Their development was most closely connected with the evolution of insects which functioned as pollinators. Among the mammals the greatest number is accounted for by the rodents. In their development they too were connected with angiosperms.

As far as species are concerned the organic world of land is more varied than that of the aqueous medium. If the number of species of land animals is equal to 93%, the marine animals comprise only 7%. Among the plants we find a similar relationship: 92% are accounted for by the land forms and the marine ones comprise only 8%. It is quite obvious that the exit of organisms to the land opened up wide possibilities for their progressive and accelerated evolution. It must be admitted, however, that this process had a selective character. If we don't take the ancestors of vertebrates into account, we may assume that of the three types of animals there were only six classes that inhabited the land. Meanwhile, 60 classes referring to the other types continued to exist in the sea. However, under these circumstances, the number of species of land organisms was far greater than that of the marine variety.

Within the confines of the Earth's entire biosphere and its components there isn't a single substance that could live in total isolation. The change in the environment can disrupt the equilibrium between itself and the ecological system and sometimes determines substantial changes within this system.

Living organisms are characterized by a marked variety within land and sea. The living population of the sea is distributed at different depths. A part of the ocean's littoral zone from the shore to the depth of 200 m is called the shelf. Depending on the degree of turbidity and the presence of suspended particles the solar light can penetrate into the depths between 80 and 200 m. It is quite natural, then, that in this zone there can exist photosynthesizing plants, predominantly algae, that produce a great amount of nutritive substances which serve as food for marine animals. Further to the middle regions of the ocean there is a continental slope and an abyssal zone which the sunlight does not reach, and where the number of organisms is considerably on the decrease. Depending on the place of habitat and means of movement the living population of the sea is divided into plankton, nekton, and benthos.

The microscopic free-swimming organisms that are suspended in water comprise plankton, which is divided into phytoplankton, consisting of plants, and zooplankton, which includes very small marine animals. The animals that actively move in water form nekton. The largest animals of nekton are the whales, dolphins and sharks. Nekton also includes the so-called bony fishes which feed on the abundant plankton. The living organisms inhabiting the sea floor preponderantly within

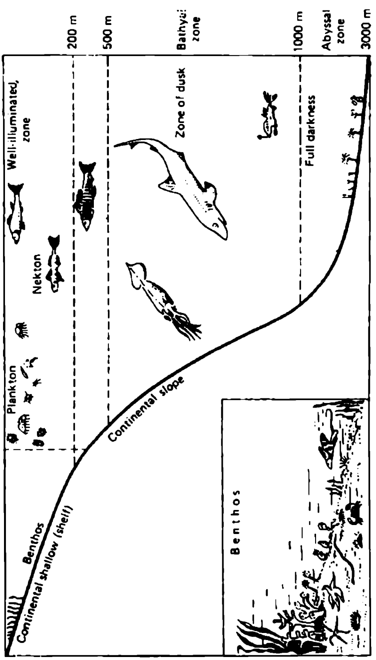


Fig. 5. The distribution of living population in sea

the region of the sublittoral zone, make up what is known as benthos, which is classified into the sedentary (algae, sponges, corals) and mobile (mollusks, crustaceans, echinoderms, etc.) varieties. In the abyssal zone of the dark depths of the ocean there exist some bacteria and several types of saprophytic fungi. The animals in this zone feed at the expense of what is left of plankton organisms that go down from the illuminated zone. According to the current data there are no such depths in which there would be no life at all. Even in the deepest Mariana Trench (measuring 11 022 m) it was possible to discover and photograph crustaceans and other animals. The distribution of marine population is given in Fig. 5.

On the surface of continents various ecological systems do not always lend themselves to a clear-cut distinction, and it is not infrequent that one of them is superimposed upon the other. It is only the zonal and latitudinal character of the distribution of vegetation that has the most expressive form of manifestation. In principle, these zones repeat themselves in mountain systems, where from the foot of the mountain to its peaks there occurs an alteration of plant belts from thermophilic forms to woods of coniferous trees, Alpine Meadows and perennial snow. There are numerous deviations from the general latitudinal character that is typical of the distribution of vegetation. In a large number of cases the distribution of vegetation depends on the changes of climate caused by the proximity of warm sea currents, location, the altitude of the place and other factors. In general, the settling of animals is connected with the plant zones, though it cannot be but mentioned that it is the birds migrating in the mass every season that have the most spacious habitats.

The Antiquity of Life on the Earth

> The development of geology for the past three centuries gives us every right to assert that no deposits have ever been found on our planet in which there were no traces of life. Furthermore, even the indirect data make it impossible for us to assume its absence from the given geological phenomena.
>
> *V.I. Vernadsky*

The antiquity of life on our planet refers to highly complicated problems pertaining to the evolution theory of organisms and is directly connected with the problem of the origin of life itself.

As far back as 1861 one of the outstanding physicists of the nineteenth century the English scientist William Thompson Kelvin on the basis of the theory of heat conductivity estimated that the Earth's age was equal to approximately 24 million years. In his opinion, within such a short period of time the process of the overall biological evolution by means of natural selection could not possibly have taken place. W. Kelvin opposed the views expounded by Charles Darwin. The great naturalist acknowledged that the calculations made by the physicists of those days concerning the age of our planet proved to be a serious hindrance for the development of the theory of evolution. Much later, in connection with the discovery of radioactivity and the use of this phenomenon for the estimation of geological time, it occurred that W. Kelvin's calculations were untenable as well as his criticism of Darwin's principles.

The data provided by radiological methods have most considerably increased the duration of geological time which is required for a complete manifestation of natural selection in the process of biological evolution. The words of J.B. Lamarck have been confirmed. As early as the beginning of the nineteenth century, he wrote, that time has no relevance to Nature and has never presented it with any problems. It has always been amply at Nature's disposal and has served it as a means not restricted by any limits. With its help Nature creates things that are sublime as well as those that are down-to-earth.

The authors of various hypotheses concerning the origin of life on Earth assumed that in the course of a very long period of time the planet was lifeless and on its surface there was taking place an abiogenetic synthesis of organic compounds which resulted in the formation of the living matter. As far back as 1924 in his first publication devoted to the problem of the origin of life Academician A. I. Oparin wrote about a continuous existence of lifeless Earth that emerged from the incandescent gas of solar composition. In 1963 he repeated his thesis, saying that at that time only the inorganic forms of the movement of matter were typical of the Earth. In addition to this, everything that was taking place on its surface was wholly conditioned by the laws of physics and chemistry.

We can find similar concepts with other researchers too. Thus, in 1967 John Bernal wrote that chemical evolution could have continued for the 2 billion years which preceded the organic evolution. In a very interesting monograph 'The Origin of Life by Natural Causes' of the Dutch scientist M. Rutten it was pointed out that the emergence of life should have covered, according to our standards, an enormous span of time, that the development was progressing at so slow a rate that it is practically impossible for us to imagine it.

However, there also existed other concepts about the extraordinary duration of the existence of life on our planet. They were elaborated by such prominent Soviet scientists as V.I. Vernadsky, L.S. Berg, and L.A. Zenkevich. In 1947 L. S. Berg, in particular, wrote: 'In reality, three or four billion years could hardly have been enough for the origin of life on Earth; moreover, for the Earth to give rise to the whole variety of organic world that we see today. Let us not forget that the evolution of only one subtype of animals—the vertebrates—took about half a billion years. How much time then would it have been necessary for the formation of mollusks, arthropods, worms and others? What period of time would nature have required for the production of a group of unicellular organisms that include not only several types, but also animals and plants? How much time would have been needed for a shapeless clump of living matter to acquire the primary forms of a developed organism?'. L. A. Zenkevich considered that the evolution of the organic world should have covered no less than 10 billion years.

In order that the tenability of all these statements could be properly evaluated, it is necessary to get to the bottom of the more recent geological data concerning the actual traces of the vitality of organisms in the remote past of our planet. This requirement is made even more imperative since outstanding achievements have been attained in this branch of science within the past twenty years.

According to the extent to which the history of the earth's crust has been studied in geological and paleontological terms it is divided into two irregular parts. The younger period of time covering the latest 570 billion years has been studied rather well. The American geologist C. Schuchert called it the Phanerozoic eoin (Gk *phanerós*—visible and *zōé*—life). This geological period includes the Cenozoic, Mesozoic, and Paleozoic eras. The second part—the one that is more ancient and prolonged—received the name of Cryptozoic eon (the period of the concealed development of life). It covers an enormous interval of time, which goes back to 4600-570 mln years. In most cases the organisms of the Cryptozoic period did not have a hard skeleton and left only sparse traces of their existence.

Geological and paleontological records are closely interwoven. In the sedimentary masses of different age we can find fossil remains of animals and plants. However, the early stages in the development of Earth are not registered in the stone documents of the geological records since the primary rocks were destroyed by the subsequent geological processes, and the traces of the initial forms of organisms disappeared likewise in the course of the development of the upper layers of the planet. Academician B.S. Sokolov [1979] pointed out that the transition from chemical to biological evolution would never be strictly documented by paleontologists and paleobiochemists, i.e. give the answer to the most difficult question when and how life had emerged. Nevertheless the data from paleontology and other sciences make it possible to approximately evaluate the antiquity of life.

Traces of the existence of organisms that lived in the past can be divided according to morphological, biochemical and isotopic-geochemical features.

Morphological remains are the ones that are most evident. They find their expression in the natural mummification of remnants, petrifications, and imprints. Though natural mummification most fully preserves the organism, it is nevertheless rare and is found to be characteristic of the youngest geological formations.

What is often left after the organisms have perished is their skeletons. However, the soft parts of the body too can become petrified. Sometimes they consist of chitin, but most often they are formed of inorganic substances. In addition to this, various mineral substances that are found in aqueous solutions penetrate into the body of the decayed organism and replace the substances that had initially made up of the organic remains, which proved to be unstable. Besides the remains of animals, the process of fossilization can also be undergone by the remains of plants, when their tissues, and xylem in particular, are replaced by silica. Under different circumstances, when there is a certain lack of oxygen, the stems and stalks are transformed into coal, while leaves become carbonaceous films. Microorganisms are also subjected to the analogous processes of fossilization. But this occurs only in exclusive conditions when their remains are buried and preserved in either finely-dispersed sediments or the colloidal deposits of silica. There are instances when microfossils are well preserved, with a clear-cut image and find their analogs among the present-day microorganisms. At the same time it should be noted that the interpretation of microscopic samples is connected with difficulties that are by far not always of the same kind. Microfossils have been discovered in very old deposits the age of which is up to 3.5 billion years.

Morphological remains make it possible to restore the ancient forms with maximum accuracy and conduct their systematization in the same way as it is done for the contemporary forms of plants and animals.

The biochemical traces of the existence of ancient organisms are represented in the form of the most stable chemical compounds in the sedimentary rocks of the earth's crust. On the whole an organic substance of biological origin is widely distributed in various rocks. Its major part is found to be in a dispersed state. The concentrated organic substance in the form of coals, pyroschists and oils in general comprise a small part in relation to the dispersed substance. If the mineralization of the remains of plants does not take place and their tissues are relatively well preserved, then the process of carbonization occurs. According to some estimates the amounts of dispersed organic matter of biological origin exceeds that of the concentrated variety by approximately 300 times. What enters into the organic substance of the earth's crust in different proportions includes carbohydrates, hydrocarbons, proteins, fats, and amino acids. In their main mass they are soon transformed into a humic substance. In general over 500 organic compounds have been established in rocks.

In the fossils of organic accumulations the amino acids reflect the former presence of protein bodies. Most of the amino acids have only one asymmetrically arranged atom of carbon in the molecule, which leads to the formation of two possible optical isomers: *D* (right) and *L* (left) that rotate the light beam which passes through them. The amino acids of biological origin that are found in terrestrial geological objects are represented by *L*-isomers. Meanwhile, the amino acids synthesized by inorganic means, represent mixtures of optical *D*- and *L*-isomers in equal quantities and hence optically non-active. In general, a large number of organic compounds of rocks of different geological age reveal optical activity, which serves to prove their biological origin. The principal sources of these organic compounds of biological origin were plant remains, as the products of photosynthesis, that had existed before in various zones of ancient water bodies in the form of phytoplankton.

The study of the organic substance of ancient rocks does not enable us to determine what were precisely the types of plants that served as the source of their formation. This particularly concerns the most ancient, or Precambrian deposits. Hence, the biochemical traces of the existence of living organisms on our planet can only in general indicate the presence of life itself in a given geological epoch. In the process of metamorphism of rocks a part of the organic matter is transformed into graphite, which is found in ancient Precambrian rocks—gneisses and schists—in the form of interlayers and inclusions. Sometimes in graphites of this kind we find the remains of organic matter in small quantities. One of the tangible achievements of organic geochemistry of the past two decades has been the fact that carbon compounds of biogenic origin were established in more ancient sedimentary rocks.

A particular place in modern geochemistry is attributed to isotopic methods of research which make it possible to determine the traces of the vital activity of organisms in most ancient metamorphosed rocks of the Cryptozoic period. In the process of vital activity and in the case of the metabolism with the environment the isotopic composition of biophile elements, in particular, such as sulphur and carbon, undergoes alteration. This was predicted by V. I. Vernadsky. Nowadays the fractional character of isotopes in the course of biochemical processes has been established experimentally.

The estimates of the isotopic composition of sulphur from the Early Precambrian formations of the USSR, North America, and South Africa have revealed the fractionation of its isotopes which finds its expression in the fluctuations of the ratio $^{32}S/^{34}S$. The general regularity of the fractionation of the isotopes of sulphur in the biosphere consists in that the content of the lighter isotope ^{32}S is increased in its sulphide forms (associated with the formation of hydrogen sulphide H_2S in water bodies) as compared with its sulphate forms ($CaSO_4$, $BaSO_4$ and others) in which

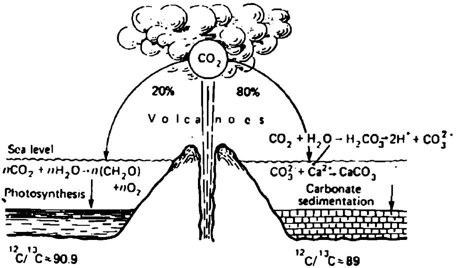


Fig. 6. The main paths of geochemical circulation of carbon in the biosphere

the proportion of the heavy isotope of sulphur ^{34}S is relatively greater. The isotope shift of sulphur between sulphides and sulphates testify to the bacterial sulphate-reduction in ancient water bodies.

What is most important as regards the discovery of the ancient traces of life is the data concerning the isotopic composition of carbon. Within the circulation process of this element in the planet's biosphere, connected with living matter, there takes place the shifting of isotopic ratios $^{12}C/^{13}C$. The main paths of geochemical circulation of carbon are given in Fig. 6. The initial stage of this circulation is characterized by the emission of CO_2 from the pallial depths as a result of volcanic processes. What is further added to it is CO_2 under the thermal decomposition of limestones in conditions of metamorphism. Then CO_2 is distributed between the atmosphere and hydrosphere and migrates along the two paths with the approximate proportion being 4 : 1.

The first path is connected with the formation of a complex carbonate system between the atmosphere and hydrosphere:

$$CO_2 \rightarrow [CO_2] + [H_2CO_3] + [HCO_3]^{-1} + [CO_3]^{2-}$$

At last CO_2 is combined with Ca and Mg in sea water and thus forms limestones that are predominantly in the form of skeletons of marine organisms.

The other path of CO_2 migration in the biosphere is expressed in its absorption by the green plants in the process of photosynthesis with the formation of organic substances and the release of free oxygen. In general terms this can be formulated as follows:

$$nCO_2 + nH_2O \rightarrow n\,(CH_2O) + nO_2$$

The process of photosynthesis leads to the fixation of carbon in an organic substance. One part of it is oxidized with the formation of CO_2 in conditions of the Earth's surface, while the other is buried in the deoxidizing medium.

Along these main paths of geochemical migration there takes place the fractionation of its isotopes. For instance, in marine limestones the content of the heavy isotope of carbon ^{13}C is increased, which is also typical of calcite and aragonite shells of marine organisms. Thus, the isotopic relationship of $^{12}C/^{13}C$ in marine limestones is established within the limits from 88.2 to 89. During the process of photosynthesis, however, the relative content of isotope ^{13}C is reduced since the rate at which the light molecule $^{12}CO_2$ is captured is higher than that of the molecule $^{13}CO_2$. Hence, the ratio $^{12}C/^{13}C$ for plants and their remains is found to be within the range of 90-92. The isotopic composition of the carbon of plants is inherited by the carbon of animals which feed themselves on plants. It is interesting to observe that the isotopic composition of graphite from the ancient Precambrian metamorphic rocks corresponds to the carbon of plants—the products of photosynthesis.

The most ancient rocks, mainly the metamorphic ones, are deposited in the Precambrian shield on practically all the continents of the Earth. The age of their oldest parts which is determined by various radiological methods is estimated to be equal to 3.8-3.5 billion years. To some extent they are associated with the traces of life in the ancient period. The old rocks have been found and studied in North America, Western Greenland, Northern Norway, South Africa, and Western Australia. According to the data of lead-isotope method, the oldest minerals are the detrital zircons the age of which is 4.2-4.1 billion years. However, they are found in the secondary strata of the Archean limestones in Western Australia, and their root source remains unknown.

The most ancient and morphologically properly expressed traces of life in the Precambrian period are considered to be stromatolithes. They represent biotherms that emerged on the floor of the shallow water bodies and that have either a convex or uneven surface as well as complicated lamination. The laminated formations are most often created by the calcium and carbonate as a result of blue-green algae and bacteria activity. Stromatolites were studied most elaborately by the Soviet paleontologist A.G. Vologdin (1896-1971), who described a large number of these forms from the Precambrian sections of the USSR. Stromatolithic structures revealed the presence of microfossils. For this reason there can hardly be any doubt now that stromatolithes are characterized by biogenic origin. The oldest stromatolites were discovered in the Warrawoona series in the section of the Precambrian block of Pilbara Plateau in Western Australia. Their age is 3.5 billion years.

In South Africa, in Central Transvaal, ancient rocks of the Swaziland series become exposed, which includes the systems of the Fig Tree and Onvervacht. In the black schists of the Fig Tree system microscopic analysis made it possible to observe bacterial formations of the size of 0.56 × 0.24 μm, which were called *Eobacterium isolatum* by E. Barghoorn. The spheroidal dark-coloured organic bodies, which in terms of general morphology are compared with some of the contemporary unicellular algae, have been found in the formation of black schists in the very same places.

In Onvervacht system complex organic compounds of fatty acids and isoprene hydrocarbons have also been discovered. Out of the rocks pertaining to this system algal forms have not infrequently been described in terms of morphology. They represent spherical minute bodies whose diameter usually ranges from 6 to 20 μm. The largest of the ones that have been discovered have the diameter of 200 μm. They resemble the analogous formations of the superimposed Fig Tree series in the same region and of the Gunflint suite in the Precambrian North America. The biological origin of the given forms raises no doubts since they are associated with the isoprene hydrocarbons, which are the products of photosynthesis and are widely distributed in the deposits of the younger geological epochs. Data on the isotopic composition have revealed an appropriate coincidence with the data concerning oils, coals and dispersed organisms. This substance is presumably connected with the activity of the primitive bacterium-like autotrophs. The age of Onvervacht suite is estimated at 3.44 billion years.

The determinations of the isotopic composition of sulphur in different mineral associations of the early Precambrian formations of the USSR, South Africa and North America have revealed the fractionation of isotopes caused by the activity of sulphate-reducing bacteria. In weakly metamorphosed ferruginous formations of the Ontario province in Canada the isotopic distribution between sulphates and sulphide mineral forms of sulphur comprise from +20 to $-2^0/_{00}$. This serves to prove the energetic sulphate-reducing activity of bacteria in water bodies where iron was accumulated 2.7 billion years ago. However, the research of the more ancient rocks from the Isua section in Greenland did not show any substantial distribution of the isotopes of sulphur in sulphides and sulphates, the fact which show the absence of bacterial reduction of sulphates. The first isotopic evidences of the reduction of sulphates were established in the Upper Archean of the Aldan shield in Siberia (about 3 billion years ago) and in the banded ferruginous formations of Women River in Canada (approximately 2.8 billion years ago). In the opinion of the West German geochemist M. Schidlowski the sulphate ion SO_4^{2-}, which is absorbed by the first sulphate-reducing organisms, must have emerged as a result of the oxidation of the reduced compounds of sulphur by photosynthesizing sulphur bacteria. Therefore, it is possible to imagine that photosynthesis—a process that releases free oxygen into the biosphere of the planet—chronologically preceded the emergence of the bacterial reduction of sulphur in ancient Precambrian water bodies.

The scientific study of the isotopic composition of carbon as an indicator of the antiquity of photosynthesis, and consequently, the antiquity of the biosphere itself, is of paramount importance. M. Schidlowski and his colleagues conducted numerous estimates of the isotopic composition of the carbon samples of carbonaceous and other rocks of the ancient Isua supracrustal complex. By means of radiological methods the age of rocks belonging to this complex was estimated as 3.8 billion years.

According to the data C_{carb} and C_{org} were present and migrated in the Earth's ancient biosphere in proportion that on the whole is very much the same as that of today. The carbonate carbon and the carbon of organic origin initially possessed isotopic relationships that were close to what is nowadays typical of corresponding sedimentary rocks. Thus, the commonly known biogeochemical cycle of carbon connected with the photosynthesis in the biosphere was essentially stabilized over 3.8 billion years ago.

Since photosynthesis results in the release of free oxygen it is quite natural that the traces of ancient biosphere should reflect the processes of oxidation determined by this element. This can be evidenced by the fact that in the Isua section banded ferruginous quartzites that were widely spread in the Precambrian period have been discovered. They refer to the oxidized facies of iron-ore formations and actually reflect the presence of free oxygen. However, there was not yet enough of the free oxygen proper in the Earth's atmosphere since in the biosphere it was expended in great quantities on the oxidation of a large number of substances, including the volcanic gases (CO, H_2S, S_2, SO_2) and all the forms of divalent iron. In general, the amount of free oxygen in the atmosphere of the early Precambrian period was the result of the confrontation of two opposite trends: biological productivity and inorganic absorption. The presence of an enormous amount of unoxidized substances in the hypergene zone of the Precambrian period led to the progressive absorption of free oxygen together with the oxidation of volcanic gases.

The great antiquity of the Isua geological section had interested many researchers. According to the latest data petrol and naphthene compounds were discovered in the graphitic inclusions of the ancient rocks, with the isotopic relationship of $^{12}C/^{13}C$ corresponding to the carbon of photosynthetic (biological) origin. From the information provided by G. Pflüg we now know that formations of other Precambrian rocks of younger geological age have also been found in the Isua quartzites. However, the biological nature of these formations proper has not yet been proved. Their interior parts are filled with hydroxides of iron.

Thus, in accordance with the data of geochemical research of the most ancient rocks it becomes possible to come to the conclusion that the evolution level of photoautotrophic life was reached 4.55-4 billion years ago.

The study of the rocks in the section of the Isua region enabled the scientists to come up with the assertion that photoautotrophic biosphere existed on our planet not less than 4 billion years ago. But what we know from the data provided by cytology and molecular biology is that photoautotrophic organisms were secondary in the process of the evolution of living matter. In Fig. 7 we have the basic stages in the evolution of matter (the formation of primary cells, and then the photosynthesizing organisms). The autotrophic means of the nutrition of animal organisms had to precede the heterotrophic variety of the same since it was much more simple. The autotrophic organisms which build their body at the expense of inorganic mineral substances are characterized by a later origin. It was the prominent Soviet biologist A. A. Zavarzin (1886-1945) who was the first to point that the contrastive study of energy processes in contemporary organisms made it possible to infer that the oxidizing processes (breathing) had

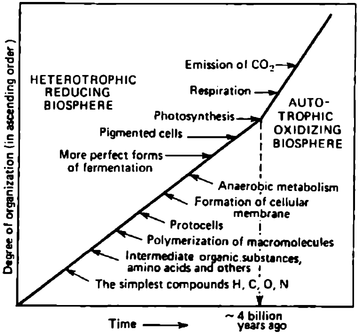


Fig. 7. The main stages in the evolution of matter

a secondary origin. The first processes that relieve energy in the earliest formed substances were the processes connected with the molecular rearrangements, the analogous processes of fermentation. It follows then that at the beginning there had to emerge heterotrophic organisms with intramolecular breathing, or those that did not require any free oxygen.

Most probably only after a complex evolution of a particular activity there appeared substances that used solar radiation for the accumulation of CO_2 and H_2O.

Thus, the organization of the living matter, on the basis of which the contemporary cells originated, had already advanced to a considerable extent before the autotrophic organisms emerged. In general it appears to be an irrefutable fact that the autotrophic nutrition calls for a far more complex organization than the heterotrophic metabolism of substances.

There is some reason to believe that the most ancient life existed in the form of heterotrophic bacteria which received food and energy from the organic material of abiogenic origin that had been formed even earlier. From what has just been said it is not difficult to imagine that the beginning of life as such receded still further, beyond the limits of stone records of the earth's crust, i.e. more than for 4 billion years in the past.

Taking into consideration the above it is quite easy to arrive at the general conclusion that the life on Earth has existed as long as our own planet. This conclusion based on the new scientific material should be regarded as an empirical generalization. It is wholly congruous with the concepts of V.I. Vernadsky who over fifty years ago wrote: 'It has empirically been established that life on Earth existed in the most ancient accessible deposits known to us on our planet. On the other hand nobody of us has ever found in the biosphere rocks which would give us some idea concerning their origin within the time when the living matter was absent. Even such massive rocks as those of the volcanic and plutonic varieties, bear in themselves most evident traces of the existence of living matter in conditions pertinent to their formation.

And as the consequence of this empirical conclusion the American geologists had every right to introduce recently the concept of the Cryptozoic eon, i.e. the most ancient and prolonged period in the geological history of our planet with no overt manifestation of life. Thus, empirically, we have failed to find any indications as to the period when the living matter did not exist on our planet. Life on it has been geologically perennial' [Vernadsky, 1965].

The period of evolution of the largest groups of organisms is given in Fig. 8. In the opinion of the Soviet microbiologist G.A. Zavarzin [1984], the data on the time of the emergence of the most ancient prokaryotes make it possible to consider that life originated in space rather than within the confines of the Earth. Thus, from the present-day state of the art it becomes clear that the problem of the origin of life is also becoming a cosmochemical problem and not only that which can be treated solely in biological and biochemical terms.

In the light of new data there inevitably follows the conclusion concerning the earliest origin of life within the confines of the Solar system. The chemical evolution as a substantial prerequisite for the biological evolution had

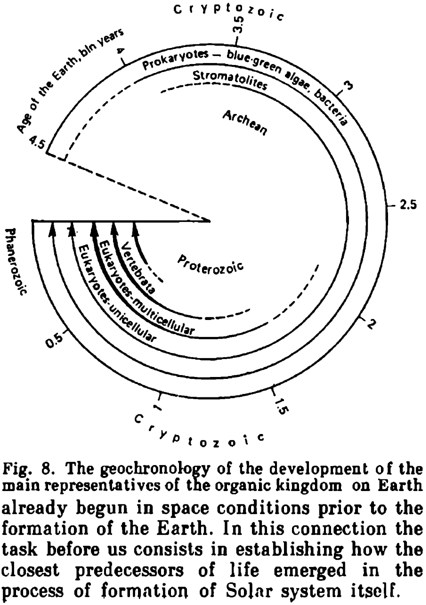


Fig. 8. The geochronology of the development of the main representatives of the organic kingdom on Earth

already begun in space conditions prior to the formation of the Earth. In this connection the task before us consists in establishing how the closest predecessors of life emerged in the process of formation of Solar system itself.

The Organic Compounds in Space

> I cannot but wonder how this incredibly complex mechanism is still functioning at all. Thinking of life one clearly sees our science in the poorest and most primitive light. The properties of living matter are most probably predetermined by the fertilized cell in the same way as the prerequisite of life itself consists in the existence of an atom and, consequently, the mystery of everything that existing can be found in its lowest stage of development.
>
> *A. Einstein*

The interrelationship of the embryos of life and its predecessors—the highly molecular compounds of carbon—presents a scientific task of the first importance. The first experiments of Louis Pasteur, which he carried out in the second half of the nineteenth century, showed that the origin of life, or the simplest living organisms, in the contemporary conditions of the Earth was impossible. To some extent it had led to the emergence of the theory of panspermia* according to which

* Panspermia (from Greek meaning mixture of elements)—the ancient study of the overall propagation in the universe of perennial and consistent embryos of life. Its author is the ancient Greek philosopher Anaxagoras (500-428 BC).

life had never originated on Earth, but was brought to it from space, where it existed in embryonic forms. The most typical proponents of these concepts were H. Helmholtz and S. Arrhenius, though similar ideas were earlier expounded by J. Liebig. According to S. Arrhenius, the particles of living matter—spores or bacteria—that have descended upon the microarticles of cosmic dust are transported from one planet to another by the force of light pressure, thus preserving their vital activity. When the spores reach a planet with appropriate conditions of life, they grow into it and give rise to biological evolution.

In somewhat different forms these concepts are regenerated today. F. Hoyle, for instance, put forward the idea concerning the possibility of the existence of microorganisms in the interstellar space. His idea is that the clouds of cosmic dust are mainly composed of bacteria and spores. It is assumed that in the time interval covering 4.6-3.8 billion years ago, the Earth could have experienced two possible events, viz. either the origin of life on the planet itself or the introduction of microorganisms from outer space. In 1981 F. Hoyle and N. Wiekrámasinghe' expressed their opinion that the latter could have been more probable. According to their estimates, the Earth's upper atmosphere annually receives 10^{18} cosmic spores as the residue of the hard material that is dispersed in the Solar system. Thus, comets may well be regarded as transporters of the embryos of life, which were formed earlier in the interstellar space and only then got into the Oort's cloud.

What should be mentioned here is the extreme irreality of those concepts that cannot be correlated with the well-known experimental data. However, there is no doubt that life is certainly connected with space in terms of atomic composition and energy. This can be seen in Table 6, in which we have the values

TABLE 6. The Composition of the Abundance of Elements in Atomic % (According to Deleemme, 1981)

Element	Cosmic	Interstellar	Volatile fraction of comets	Bacteria	Mammals
H	76.5	55	56	63.0	61.0
O	0.82	30	31	29.0	26.0
C	0.34	13	10	6.4	10.3
N	0.12	1	2.7	1.4	2.4
S	0.0015	0.8	0.3	0.06	0.13
P	0.00002	—	—	0.12	0.13
Ca	0.002	—	—	—	0.23
H/O	14.000	1.8	1.8	2.2	2.3
C/O	0.64	0.43	0.32	0.22	0.40
N/O	0.12	0.03	0.08	0.05	0.09

of the relative distribution of elements in space, in the volatile fraction of comets, bacteria and mammals. Our attention cannot be but drawn to a marked closeness, and in some cases even the equivalence of space substance and the living matter of the Earth. The main elements of living matter are the widely spread elements of space. It should also be added that H, C, N and O—the typically biophile elements—are the ones that are most lavishly spread in nature.

It is not difficult to infer that the living organisms use in the first place the most accessible atoms, which are furthermore capable of forming stable and multiple chemical bonds. It is common knowledge that carbon can give rise to the emergence of long chains, which leads to the origin of innumerable polymers. Sulphur and phosphorus can also form multiple bonds. Sulphur enters into the composition of proteins, while phosphorus forms a constituent part of nucleic acids.

In the appropriate conditions the most widely spread atoms are combined with each other, thus forming molecules, which are found in space clouds by means of currently employed methods of radio astronomy. Most of the known space molecules refer to the organic variety, including the complex ones of 8- and 11-atom type. Thus, as regards the composition the cosmochemistry of the Universe vast possibilities are created for various combinations of carbon with other elements according to laws of chemical bonding.

However, the problem of the formation of molecules in space conditions refers to one of the most complicated ones of cosmochemistry. In the interstellar medium itself, even in its densest parts, the elements are found in the conditions that are remote from thermodynamic equilibrium. Due to the low concentration of matter chemical reactions in the interstellar space are highly improbable.

Hence, an idea was put forward that particles of cosmic dust take part in the formation of interstellar molecules. In the simplest case there can emerge molecules of hydrogen when its atoms come into contact with hard particles. The most widely spread space molecules of CO, can probably originate in the conditions of stellar atmospheres when there is a sufficient density of the matter and then be ejected into outer space.

Nowadays the role of the hard phase in the formation of molecules of organic substances is becoming ever more clear-cut. The most probable models of this process have been elaborated by J. Greenberg [1984]. In the opinion of this scientist the particles of cosmic dust are characterized by a complex structure and consist of the nucleus that is predominantly of the silicate composition, surrounded by a coating of organic substances. In the coating, presumably, there take place various chemical processes that lead to the complication of the structure of the primary substance. The structure of similar dust particles after the first stage of accretion is substantiated by means of an experimental modelling of the mixtures of water, methane, ammonia, and other simple molecules, that are radiated by ultraviolet radiation at the temperature of approximately 10 K. Each dust particle has for its origin the silicate nucleus which emerges in the atmosphere of the cold supernova. Round the nucleus an ice coating is formed. Under the action of ultraviolet radiation some of the molecules of the coating (H_2O, CH_4, NH_3) are dissociated with the result that radicals, or reactive fragment of molecules, are formed. These radicals can recombine and other molecules can be formed. As a result of a continuous radiation, there can emerge a more complex mixture of molecules and radicals (HN_2HCO, HOCO, CH_3OH, CH_3C and others). When the dust particles are destroyed under the influence of cosmic factors, the compounds that were formed on their surface give rise to molecular clouds.

If we concentrate our attention on the huge masses of molecular clouds, then we shall see that it is precisely they that are the main reservoirs of organic matter in space. However, the organic compounds found in them turn out to be relatively simple and as yet remote from those molecular systems, which could provide the necessary impetus for the beginning of life upon any favourable planetary body.

The presence of organic substances in meteorites should most certainly not be unheeded either. This is extremely important for the understanding of the processes related to the origin of highly molecular systems as the predecessors of life. It should also be noted that meteorites together with their parental bodies—asteroids, belong to the Solar system. Then, the age of meteorites, according to the data of nuclear geochronology, is 4.6-4.5 billion years, which coincides, in the main, with the age of the Earth and the Moon. Consequently, meteorites are undoubtedly witnesses of the formation of various chemical compounds, including those of organic nature, in the very early stages of the development of the Solar system.

What was found in meteorites included hydrocarbons, carbohydrates, purines, and amino acids, i.e. those chemical compounds, which enter into the composition of living matter, thus forming its basis. They have also been discovered in carbonaceous chondrites and asteroids of particular structure and composition. Asteroids chiefly move within the belt between Mars and Jupiter. If we go by the data on the cosmochemistry of comets, it would then be possible to assume that the field within which organic substances were formed covered a vast space within the confines of the greater part of the volume of the primary solar nebula. It is quite natural that in elucidating the general problem of the origin of life we have no right to ignore the data on the composition of meteorites. In one way or another this circumstance has been taken into account by different authors of the hypotheses concerning the origin of life.

Thus, we are now quite justified in regarding the known meteorites as the historical documents, or the true witnesses of the early history of the Solar system, also covering the processes pertaining to the formation of organic substances.

Any meteorite represents a hard body, consisting of a number of mineral phases. The most important of them are the silicate (stone), metallic (iron-nickel) and sulphide (troilite) ones. Other phases are also found, though they are of secondary significance as far as their propagation is concerned. In meteorites we can discover various minerals the number of which exceeds 100; but the main rock-forming ones are few (olivine, pyroxene, feldspars, plessite, troilite, and others). In addition to this, meteorites have revealed 20 minerals that are not present in the earth's crust. They include carbides, sulphides and some others the formation of which is connected with the marked reduction conditions. The most essential concentrations are those of carbon, which are associated with organic matter, in carbonaceous chondrites.

What is of particular importance is the information on organic matter in meteorites expounded in the works of G. P. Vdovykin, E. Anders, R. Hayatsu, M. Studier. The first who singled out the organic matter in the composition of meteorites was the famous chemist J. Berzelius, when he analyzed the carbonaceous chondrite of the Alais Mountains in 1834. The results of his analysis were so impressive that he himself considered this substance to be of biological origin. During the ninetieth century chemical analyses have helped to discover in meteorites the presence of hard hydrocarbons, consisting of the compounds of organic substances with sulphur and phosphorus. Carbonaceous chondrites, the greater part of the carbon of which is found in the form of organic compounds, were given a most elaborate and circumstantial treatment. The general content of carbon and some other volatile substances in carbonaceous chondrites is characterized by the following values (in weight %):

	C	S	H_2O
C1	2.7-5.0	5.2-6.7	18-22
C2	1.1-2.8	2.3-3.7	8-17
C3	0.2-0.6	1.8-2.4	0.1-1.5

It follows that the content of carbon (as well as sulphur and water) is the greatest in carbonaceous chondrites of type C1, and minimum in those of C3 type. Thus, at present there can hardly be any doubt that in the parent bodies of carbonaceous chondrites as a result of the processes of their formation themselves there emerged complex organic compounds as a regular outcome of the chemical evolution of the Solar system in its early stages.

The elementary chemical composition of carbonaceous chondrites with the exclusion of volatile substances is very close to that of common chondrites. The principal characteristic features of different types of carbonaceous chondrites consist in the following.

Type C1 is represented by unstable black stones which turn into dust when we rub them

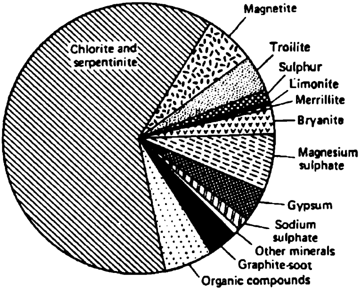


Fig. 9. Mineral composition of carbonaceous chondrite of type C1

Sections in the diagram are proportional to the weight content of minerals

with our hands. The fine-grained mass in them comprises approximately 95%. What is impregnated in them includes chondrules (microchondrules), consisting of olivine and magnetite (the size of which is 1-50 μm). The mineral composition of this type of meteorite is given in Fig. 9. Carbonaceous chondrites of C1 type are found to be most profusely enriched with the organic substances of abiogenetic origin.

Type C2 covers the greyish-black stones that are considerably more dense than those of C1. Into the main fine-grained mass, comprising 60% of the volume, much larger chondrules than the ones of type C1 are impregnated. Growths of primary microchondrules into a single crystal have been found too.

Type C3 represents hard stones of dark-grey, greenish-grey and grey colour. The fine-grained mass in them takes up 35%. Chondrules are fairly large and are properly expressed.

The propagation of a large number of chemical elements in carbonaceous chondrites of type C1 reveals a number of characteristic relationships which bring them closer to the matter of which the Sun consists. In other words, these carbonaceous chondrites represent a solidified solar substance deprived of light gases.

The organic matter found in meteorites is enumerated in Table 7. As can be seen, their list is fairly impressive. Most of these compounds to a certain extent correspond to the universal units of the metabolism of substances that are known in living organisms: amino acids, protein polymers, mono- and polynucleotides, porphyrins, and other compounds. The proximity to the composition of organic complexes of biological origin proved to be so

TABLE 7. Main Organic Compounds Found in the Carbonaceous Chondrites

Hydrocarbons	Other compounds
Saturated hydrocarbons	**Carbolic acids**
n-Alkanes	Fatty acids with unbranching chain
Alkanes with branching chain	Benzolcarboxylic acids
Isoprenoids	
Cycloalkanes	Oxybenzoic acids
Olefine hydrocarbons	
Aromatic hydrocarbons	**Nitrogen compounds**
Alkylbenzoles	Pyrimidines
Naphthalene	Purines
Acenaphthenes	Guanilurea
Acenaphthalenes	Triazoles
Phenanthrenes	Porphyrins
Pyrenes	Amino acids

great that some of the authors even began to consider that in the past the living organisms were found directly in the meteorites themselves. In the sixties of the present century the given question was most lively discussed. However, a thorough analysis of organic compounds from meteorites did not substantiate the presence of any optical activity, which serves to prove their abiogenetic origin.

The comparison of the organic substances of meteoric origin with the products of artificial reactions of the Fischer-Tropsch type and the fossil organic substances of biological origin reveals their marked closeness, in particular as far as the content of some of the hydrocarbons is concerned. For instance, in meteorites hydrocharbon molecules consisting of 16 atoms prevail, which is also found in terrestrial objects and products of laboratory experiments.

Meteorites are the remnants of the larger bodies such as asteroids, the greater part of which is in the asteriod belt at the distance of 2.3-3.3 AU from the Sun. Over the past ten years as a result of the astrophysical observations of asteroids in the visible part of the spectrum and the infrared waves, data have been received which are of primary importance for the establishing of genetic interrelationships between asteroids and meteorites. By contrasting the reflectivity of meteorites and asteroids it became possible to determine that almost all the known classes of meteorites have their analogs among the asteroids that have been studied.

Depending on reflectivity asteroids are subdivided into two large principal groups—the dark variety, or the C-asteroids, and relatively light ones, or the S-asteroids. The first group is characterized by a low albedo—less than 0.05, while over 0.1 is typical of the second group. According to the spectral reflectivity group C is close to carbonaceous chondrites, and group S may well be correlated with ironstone meteorites and common chondrites. The latest photometric measurements have on the whole confirmed the unity of the material of meteorites and asteroids. For this reason all mineral, chemical and structural characteristic features of meteorites, that were received and studied in the laboratories on Earth, can be equally applied to asteroids.

As a result of the research that has been conducted it was established that in different regions of the asteroid belt the composition of asteroids is not the same. Within the confines of the Solar system a highly essential space chemical regularity has been discovered, viz. the composition of asteroids depends on the heliocentric distance. In the interior part of the asteroid belt there are bodies that have very much in common with common chondrites, but as the distance from the Sun increases, within the limits of 2.5-3.3 AU, their number becomes lower, while the number of asteroids of the type of carbonaceous chondrites, which occupy the predominant position in the middle and the marginal parts of the asteroid belt, becomes greater. On the whole, according to contemporary observations, the asteroid belt is characterized by the preponderance of carbonaceous and chondrite bodies.

If most of the asteroids consist of carbonaceous chondrites, then it is quite clear that they comprise a large number of organic substances that determines their dark colour and low reflectivity. Thus, the lowest reflectivity is characteristic of Bamberga asteroid (albedo 0.03). This is a dark and fairly large object in asteroid belt the cross section of which measures approximately 250 km.

Comets have recently attracted to themelves no minor interest. There have been some assumptions that they took part in the origin of life on Earth, or in any case could have made a certain contribution to the composition of the early atmosphere. They could have also brought to the surface of the then emerging planet the first organic molecules. The opinion has been established that comets reflect the primary conditions in the Solar system better than any other objects.

The greater part of comets is situated on the very periphery of the Solar system in the so-called Oort's cloud. They have excessively elongated orbits and are found to be at a distance of hundreds and thousands of times farther away from the Sun than Pluto. Long-periodic comets approach the Sun from far away. On the whole a comet represents a lump of dirty snow. The 'snow' in a comet is made up of ordinary water ice with the admixture of carbon dioxide and other congealed gases of unknown composition. The 'dirt' represents particles of silicate rocks of various size impregnated into the comet ice. It may well be assumed that due to the absence of chemical interactions comets can serve as the untouched specimens of the primary substance, from which the Solar system emerged.

As the distance to the Sun becomes smaller the volatile substance of comets evaporates and is driven away by the light pressure as a result of which a gigantic tail is formed. All the observable comet phenomena are determined by the processes connected with the emission of gas and dust. The ions H^+, OH^-, O^-, and H_2O^+, entering into the composition of comet tails originate mainly in the molecules of water, though, most probably, other compounds of hydrogen may also be present there. The atoms, radicals, molecules and ions can have the following expression: in comets—C, C_2, C_3, CH, CN, CS, CH_3CN, HCN, NH, NH_2, O, OH, H_2, O_2, Na, S and Si; near the Sun—Ca, CO, Cr, Cu, Fe, and V; in the tail—CH^+, CO^+, CO_2^+, CN^+, and N_2^+.

Biophile elements, mainly C, O, N, and H, have been discovered throughout the comets. At present it has been established with no little probability that comet molecules have much in common with those that are essential for pre-biological evolution. They can be represented by the molecules of amino acids, purines, and pyrimidines. As has been pointed out by A. Delsemme [1981], there exist several groups of data showing that the cosmic dust has the nature of chondrite meteorites. Firstly, it consists mainly of silicates and compounds of hydrocarbon. Secondly, the relationships of metals that are evaporated from comets when they move close to the Sun, correspond to the relationships that are typical of chondrites. Thirdly, the dust particles of cosmic origin that presumably reflect the comet substance are very close to the composition of the material of carbonaceous chondrites. And, as is actually the case, the analysis of the samples of cosmic dust reveals that 80% or more of dust particles of the size less than 1 mm consist of a substance that is similar to carbonaceous chondrites. Some scientists have compared the content of hydrocarbon in comets and carbonaceous chondrites and have come to the conclusion that not less than 10% of the substances entering into comets represent organic compounds. The nature of the chemical compounds found in comets shows that it is quite probable that the nucleus responsible for their origin is comparable as far as their complexity is concerned at least with the molecules of interstellar space.

Thus, all the data on cosmochemistry of meteorites, asteroids and comets prove that *the formation of organic compounds in the Solar system in the early stages of its development was a typical and mass phenomenon.* It found its most coherent expression in the space of the future ring of asteroids, but one way or another also covered the other regions of protoplanetary solar nebula, probably including the region from which the Earth originated itself. On reaching a particular stage in the formation of complex organic compounds, occurred, as it were, congealed in most of the bodies of the Solar system, and continued on Earth, thus attaining incredible complexity in the form of living matter.

A Space History of Carbonic Molecules

For a long time the scientists thought that the synthesis of organic compounds as the predecessors of life took place in the conditions of the early period of our Earth and that the lifeless atmosphere of the planet consisted preponderantly of H_2, CH_4, NH_3 with the pairs of H_2O. In this mixture there could have occurred chemical reactions of the synthesis with the formation of organic compounds, which has been indirectly proved by experimental research. The first experiments connected with the receiving of organic substances from hydrogen-ammonia-methane mixture with the electric charges passing through it were carried out in 1953 on the initiative of the American physicist and chemist H. Urey by his pupil S. Miller. Later similar results were received by the Soviet researchers T.E. Pavlovskaya and A.G. Pasynsky when they subjected the same gaseous mixture to the impact of ultraviolet rays. Reactions of this type in the gaseous medium under the activity of ionizing radiation were called the Miller-Urey reactions.

On the whole numerous experimental studies have been conducted in this field. Their results were usually regarded as the substantiation of the idea that the ultraviolet radiation of the Sun and the thunderstorm phenomena in the Earth's primary atmosphere under particular temperatures and pressures had to

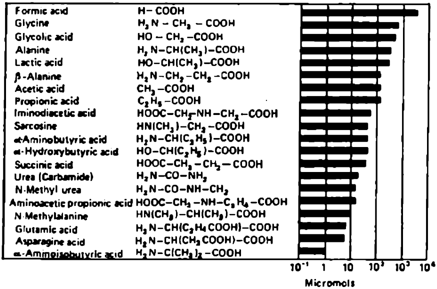


Fig. 10. The emission of products of Miller-Urey reaction from the mixture containing 710 mg of carbon in the form of methane gas

lead to the mass formation of complex carbonic compounds, including proteins (Fig. 10). However, in the light of contemporary data concepts of this kind should be discarded. The Earth belongs to the inner planets of the Solar system and was formed in the thermodynamic conditions, that were distinct from those in which the gigantic outer planets Jupiter and Saturn were formed. In their hydrogen-helium atmospheres they actually contain CH_4, NH_3 and other hydrocarbons. The closest though not identical to the Earth's primary atmosphere is that of lifeless Venus, which consists mainly of CO_2. The abyssal gases of the Earth's primary mantle, that were released during volcanic eruptions and that gave rise to the primary atmosphere of our planet contain predominantly H_2O, CO_2, SO_2, H_2S, and N_2. Gases of similar composition were found in meteorites. Thus, the data on contemporary geochemistry and cosmochemistry do not provide us with any information on the presence of hydrogen, ammonia, and methane in the early planets of the terrestrial group.

The most abundant gas of the Earth's primary atmosphere was represented by CO_2. However, it cannot spontaneously be transformed into thermodynamically less stable organic compounds. The small amount of hydrogen or its rapid loss in conditions of the Earth's early period also markedly decreased the possibility of the synthesis of organic substances in the atmosphere. On the basis of the study of physicochemical equilibria in conditions of space H. Urey came to the conclusion that during the formation of the Earth from the protoplanetary nebula a considerable part of the primary methane of the gas dust cloud escaped since the temperatures in the region where the planets of the terrestrial group were formed increased.

What has been discussed above serves to prove that the principal mass of organic compounds emerged outside the confines of the Earth in the period that preceded its origin. There is nothing unusual or paradoxical in this conclusion; suffice it to say that in the course of the evolution of the matter of the Sun's system the main rock-forming minerals of our planet and organic substances were formed. The same can also be said of the most highly molecular ones that gave rise to the primary forms of life.

Thus, the problem pertaining to the origin of organic substances as well as that of the emergence of life itself is directly connected with the cosmochemistry of the Solar system itself. At present owing to the substantially widespread information on the composition of various bodies of the Solar system we can look much deeper into the chemical history of the matter. These data enable us to make empirical generalizations that are necessary for the understanding of the process involving the formation of the organic substances in the protoplanetary matter.

1. The Earth, planets, and meteorites emerged from the Sun's matter. What substantiates this statement is the affinity of the isotope composition of the chemical elements. The difference in the chemical composition of planets and meteorites is the result of the latest processes connected with the differentiation and fractionation of the primary more

or less homogeneous material of solar composition.

2. According to the data of nuclear geochronology the age of the Earth, Moon, meteorites and, probably, the other planets too is 4.6-4.5 billion years. Meteorites, as the remains of asteroids, are the most ancient stone bodies of the Solar system.

3. The parent bodies of chondrites are the products of reduction-oxidation processes in protoplanetary nebula. They have various degree of oxidation. Enstatite chondrites are the ones that are most reduced since all the iron contained in them is found to be in a metallic state, calcium is represented by oldhamite (CaS), phosphorus—by schreibersite $(Fe, Ni, CO)_3P$, chromium enters into the composition of daubréelite $(FeCr_2S_4)$, while a small part of silicon is partially dissolved in metallic iron. The material of common chondrites is more oxidized, and the minerals that have just been mentioned are found in inconsiderable quantities. Carbonaceous chondrites are the most oxidized of the minerals. All the iron in them is chemically connected with oxygen in silicates and magnetite. Sulphur is present in the composition of sulphates.

4. The planets of the terrestrial group and asteroids are distinguished by a chemical composition, which reflects the conditions of differentiation and the physicochemical processes in the period of their formation. In

the planets close to the Sun there is more metallic iron than in those that are more remote. 3/4 of Mercury consist of a metallic phase; the figure for Venus and Earth is 1/3; for Mars it is 1/4. In the asteroid belt there are bodies that are mainly of the type of carbonaceous chondrites, i.e. those that are oxidized to a maximum degree. Depending on the heliocentric distance the planets of the terrestrial group and asteroids are represented by the bodies with a different degree of oxidation. When the Solar system was formed the oxidation iron (and other substances) occurred less intensely near the Sun and increased in intensity as the distance became greater.

5. The formation of heavy radioactive and other elements was completed immediately before the emergence of the Solar system. In meteorites and some of their mineral fractions traces of extinct radioactive isotopes ^{26}Al, ^{129}I, ^{146}Sm, ^{236}U, ^{244}Pu, and ^{247}Cm were discovered. The origin of the Solar system is related to that of chemical elements. The period between the termination of natural nuclear synthesis and the emergence of solid bodies in the Solar system is estimated at approximately 50-100 mln years. It is precisely within this period during the condensation of solar gas that the small particles and droplets were formed as the products of condensation, which in the future served as the building material for the planet of the terrestrial group and meteoric bodies.

6. The whole Solar system is differentiated. Its bodies change their composition depending on the geocentric distance, which is the reflection of the established particular chemical zonation of protoplanetary nebula in the period of its formation. Thus, if we take into account the main planetary components in the form of the following series: Fe-(O, Si, Mg)-H_2O-CH_4, then, as the distance from the Sun becomes greater, the content of the components in the corresponding bodies increases from left to right. Mercury, which is the closest planet to the Sun, contains predominantly two primary components, in carbonaceous chondrites—asteroids, all the iron is oxidized and there is already a noticeable amount of H_2O. The greater part of the satellites of the gigantic planets is covered with ice (H_2O), while the remote Pluto consists of the outer cover, composed of methane (CH_4).

The given principles founded on the contemporary space-chemical material help us to come to the general conclusion that the origin of the Solar system was first and foremost connected with the physicochemical processes in the broadest sense of the word. These processes depended on the heliocentric distance and the degree of the cooling of matter in a particular zone of nebula.

As a result of the efforts made by a fairly wide circle of researchers the cosmogonic hypotheses were superseded by a new theory, which rests mainly on the data of cosmochemistry and considers the physicochemical processes that take place during the cooling stage of the primary Solar nebula, which have led to the chemical heterogeneity of various bodies of the Solar system.

The formation of the chemical composition of the Earth and planets was determined by a consecutive condensation of elements and their compounds in the order that was reverse to their volatility—from the gaseous system of approximately solar composition: first the refractory elements, then the involatile ones, and finally those that are most volatile and their compounds. The condensation temperatures of elements and their compounds from the gas of solar composition when cooled to below 2000 K were calculated according to the equations of chemical thermodynamics by G. Anderson, J. Larimer, L. Grossman, J. Lewis, etc. Within the wide range of possible pressures the first to emit are the drops of iron at temperature 1500 K and below that, then come the silicates of magnesium(Mg_2SiO_4, $MgSiO_3$), and sulphides (FeS). In the end, at the temperature below 200 K, condensation covers such substances as water (ice) and mercury. The results of these calculations should be taken for the first approximation to the solution of the chemical evolution of protoplanetary nebula. As was actually the case, it was characterized by complex processes of the interaction between all the chemical elements of Mendeleev's table, as well as between the previously emitted condensates and the environment of the gaseous phase.

In its most general form it is possible to imagine that the formation of planets took place in the course of two stages. The first of them was characterized by the congelation and condensation of the the matter of gaseous nebula. In connection with the marked rate of cooling depending on the heliocentric distance the nebula in some of the zones had acquired a different chemical composition. This kind of heterogeneity increased under the influence of the Sun's rays, which drove the light gases into the marginal part of the Solar system, within the region where gigantic planets were formed. The second stage was the process pertinent to the accumulation of condensed particles in protoplanets. It may be assumed that those two stages were not separated by any considerable period of time. Accumulation in certain parts of the protoplanetary nebula had begun at the time when condensation was not yet over.

The question concerning the sequence of accumulation of protoplanetary particles has not yet been made quite clear. A large amount of geochemical and physical data tend rather to be in favour of the heterogeneous accumulation of the planet, when the sequence of accumulation repeated that of condensation. In this case the upper horizons of the primary Earth found themselves composed of the most recent condensates of solar nebula. The central part of the Earth's nucleus was formed during the accumulation of the metallic iron, which was then covered by the condensates in the form of a mixture of metals, silicates and troilite. The last to appear on the surface of the burgeoning Earth was the material, the composition of which was close to carbonaceous chondrites which was enriched with volatile and organic substances.

In the last stages of the congelation of Solar nebula there took place a mass formation of organic compounds in the region where the planets of the terrestrial group originated, the asteroid belt, and probably over a vast space on the whole, including that part of the Universe where comets came into existence.

In connection with the increased propagation of hydrogen in the primary nebula the simplest of its compounds with carbon and nitrogen emerged. Since the most stable form of carbon was CO, the following reactions took place as the cooling of solar nebula was progressing

$$2CO + 2H_2 \rightleftharpoons CH_4 + CO_2$$

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

In some of the regions of protoplanetary nebula, presumably in those parts where the gigantic planets were formed, and into which light molecules were transformed under the pressure of solar radiation there appeared H_2, CH_4, NH_3 and H_2O. In the combination of these components the reactions of the Miller-Urey type could have taken place under the impact of ionizing radiation, which led to the formation of numerous organic compounds. However, the role of solar radiations as an ionizing factor must have been rather insignificant. The dust-contaminated protoplanetary nebula was not transparent to ultraviolet light.

Nevertheless it becomes possible to assert that in the early Solar system there existed powerful sources of radiation, which brought forth photochemical reactions. They include the generally spread dispersed radioactive isotopes that are found in gaseous as well as in hard dust phases of primary nebula. The contemporary radioactivity of the Solar system material is mainly determined by the presence of isotopes ^{232}Th, ^{235}U, ^{238}U, and ^{40}K, the number of which was considerably greater 4.5 billion years ago; for instance, there was 80 times more ^{235}U and 10 times more ^{40}K than there is now. Besides, in the period of the formation of planets and parent meteoric bodies, which emerged in connection with the completion of the processes of nuclear synthesis, markedly radioactive isotopes were present. However, they soon became extinct since the period of their decay was within the range of 1-100 mln years. Some of the extinct radioactive isotopes are given in Table 8.

Taking these circumstances into account, it is not difficult to infer that the natural radio-

TABLE 8. Extinct Radioactive Isotopes

Radioactive isotopes		Half-life, years	Type of decay	Product of decay
Beryllium	^{10}Be	$2.5 \cdot 10^6$	β-decay	^{10}B
Aluminum	^{26}Al	$0.74 \cdot 10^6$	$\overset{+}{\beta}$-decay	^{26}Mg
Manganese	^{53}Mn	$3.7 \cdot 10^6$	$\overset{+}{\beta}$-decay	^{53}Cr
Niobium	^{92}Nb	$3.3 \cdot 10^7$	*e*-capture	^{92}Zr
Palladium	^{107}Pd	$7 \cdot 10^6$	β-decay	^{107}Ag
Iodine	^{129}I	$1.7 \cdot 10^7$	β-decay	^{129}Xe
Samarium	^{146}Sm	$5 \cdot 10^7$	α-decay	^{142}Nd
Lead	^{205}Pb	$5 \cdot 10^7$	*e*-capture	^{205}Tl
Uranium	^{236}U	$2.4 \cdot 10^7$	α-decay	^{232}Th
Neptunium	^{237}Np	$2 \cdot 10^6$	α-decay	^{209}Bi
Plutonium	^{244}Pu	$8.2 \cdot 10^7$	α-decay	
Curium	^{247}Cm	$1.64 \cdot 10^7$	and fis-	
$Z = 114—116$		$n \cdot 10^6$?	sion	

activity as inherited from the more ancient cosmic epoch of the synthesis of nuclides in the form of α-, β-, and γ-radiations could and had to ionize the environment, thus stimulating a large number of chemical reactions, including the synthesis of organic compounds. Hence, the matter itself, the laws of forces, implanted in atoms, including the properties of nuclei and electronic shells, had determined in a historical sequence the optimal situation for the creation of high-molecular organic compounds.

As the emission from the gaseous phase of hard particles was progressing during the cooling of the solar nebula and the reaction of these particles with the residual gaseous medium, there also emerged certain compounds that turned out to be appropriate catalysts of many chemical reactions. The organic compounds found in meteorites were formed mainly by means of chemical reactions between, H, CO and the simplest compounds of N. In these conditions the most probable reactions are of the Fisher-Tropsch type. In general they can be expressed thus:

$$nCO + (2n+1)\,H_2 \rightarrow C_nH_{2n+2} + nH_2O$$

Reactions of this type take place very slowly even in favourable thermodynamic conditions, but are accelerated in the presence of catalysts.

In the last stages of cooling of solar nebula the basic refractory components (metallic iron, silicates, oxides, etc.) had already been condensed in the form of dust particles, and hydration processes of the previously emitted silicates (predominantly olivine) and the formation of organic compounds either simultaneously or later were taking place. At temperatures below 500 K there took place hydration reactions between olivine and water vapours:

$$4\,(Mg,\,Fe)_2\,SiO_4 + 4H_2O + 2CO_2 \rightarrow$$
$$\rightarrow 2\,(Mg,\,Fe)_2\,SiO_4 + (Mg,\,Fe)_6\,(OH)_8\,Si_4O_{10} + \ldots$$

The products of these reactions in the form of hydrated silicates, magnetite, and carbonates actually compose the main mass of chondrites pertaining to type C1 as rock-forming minerals. According to the data provided by different methods, the typical mineral associations of carbonaceous chondrites were formed with the interval of temperatures between 300 and 430 K.

Thus, it becomes possible to conclude that the association of organic matter with low-temperature mineral complexes is a typical phenomenon in the space chemistry of meteorites. In accordance with the structural data organic compounds were synthesized on the surface of mineral grains, which in the later period entered into the composition of carbonaceous chondrites. Under the microscope it has been observed that a large amount of organic matter of meteorites is present in the shape of rounded fluorescent particles the diameter of which measures 1-3 μm. The nucleus of magnetite or hydration silicate are found in the centre of these particles.

The given processes of catalytic synthesis of organic compounds in space conditions are also substantiated by experimental data. Experimental research on the modelling of the reactions of the Fischer-Tropsch type, close to those in space, were carried out by D. Yoshiro, R. Hayatsu, and E. Anders. It was discovered that when CO, H_2, and NH_3 begin to react at temperatures of 150-500° C in the presence of nickel, aluminium and clayey minerals as catalysts, a large number of organic substances, including amino acids,

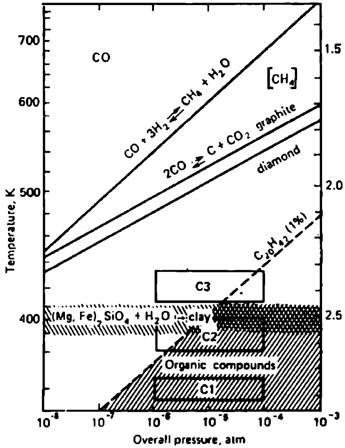


Fig. 11. The chemical condition of carbon in thermodynamic conditions pertinent to the cooling of solar nebula

Hydrated silicates are formed which serve as appropriate catalysts for stimulating the reactions of the chemical synthesis of organic substances. The restricted fields show the formation of carbonaceous chondrites, as well as the region where organic compounds originate (according to Hayatsu, Anders, 1981)

form. Nowadays the research in this field which is carried out quite intensely, substantiates the results that were received earlier. Thermodynamic conditions of the formation of organic compounds in cooling gaseous nebula of solar composition are presented in Fig. 11.

It should be mentioned that the particles of natural catalysts in solar nebula were primarily also characterized by the enhanced radioactivity, which influenced the environment. For this reason it is possible to assume that the synthesis of organic substances took part under the impact of catalysis phenomena as well as under the influence of radioactivity.

Until now there are but few tests on the experimental modelling of the synthesis of organic substances under the direct impact of radiations of radioactive isotopes upon particular gaseous mixtures, the composition of which would be close to the assumed nebula. Investigations in this field have been conducted only by the American scientists S. Palm, M. Calvin, and C. Ponnamperuma. Their research was connected with the radiation of CH_4, NH_3, and H_2O mixture by β-rays. This resulted in that there occurred reactions which led to the formation of aliphatic compounds, adeline and amino acids. However, what presents particular interest are the results of D. Gidley. By exposing primitive gaseous mixtures of β-rays, the researchers established that under the activity of β-radiation the formation of asymmetrical molecules of the organic substances of homogeneous structural type, including amino acids and sugar, takes place. In this connection it cannot be but mentioned that one of the fundamental peculiarities of living matter is the optical molecular asymmetry of the principal components of organisms—proteins and nucleic acids. The composition of proteins comprise only *L*-amino acids. This enables us to assume that the activity of radioactive factors was the decisive factor in the formation of asymmetrical molecules of organic compounds, which proved to be the most favourable for the formation of living matter.

There is some reason to believe that the synthesis of organic substances in ancient space systems could have taken place under particular doses of ionizing radiation. Radioactive radiation of high intensity destroys chemical compounds. Hence, it should be assumed that in conditions of the general decrease of the radiation background in the period of the decay of extinct and extant radioactive isotopes a certain optimum of radioactive impact upon the initial substances was attained, which was favourable for the processes involving the synthesis of organic compounds.

The chemical and isotopic data on carbonaceous chondrites show that immediately prior to the formation of parent bodies of these meteorites the synthesis of organic substances found its expression mainly in catalytic reactions of the Fischer-Tropsch type, with the Miller-Urey reactions functioning in only few cases. In particular, this can be seen when comparing the molecular mass—spectrograms of hydrocarbons that were received as a result of the Fischer-Tropsch type of reactions by artificial means and the hydrocarbons of Murchison meteorite (Fig. 12). What attracts our attention is that the coincidence of particular maximums of the two samples is very good indeed.

All this taken into account, it is not difficult to come to the conclusion that the synthesis of fairly complex organic compounds was a regular stage in the chemical evolution of the solar system just before the planets were formed. The organic substances that had emerged in space conditions entered into the composition of a large number of bodies, though it was only on Earth that the possibility of progressive evolution found its expression. This resulted in the rapid development of self-regulating high-molecular systems, or the ancestors of the first living organisms. In meteorites and their parent bodies chemical evolution was found to be congealed.

The organic substances of space origin got upon the growing Earth in the last stages of its accumulation together with the material of the type of carbonaceous chondrites. It should be noted here that, according to a series of geochemical and isotopic data, the material of the Earth's primary upper mantle had very much in common with that of the type of carbonaceous chondrites as with the source

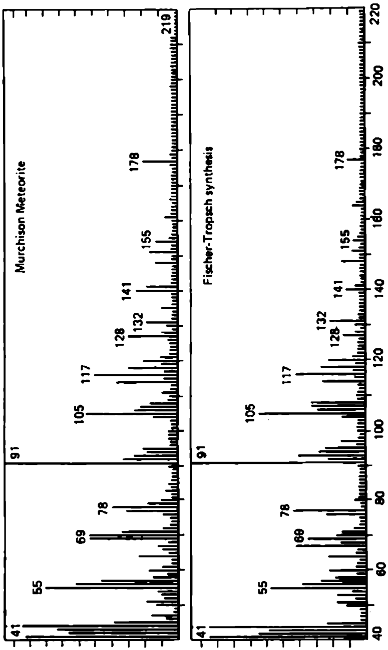


Fig. 12. The comparison of the mass-spectrograms for hydrocarbons of the carbonaceous chondrites and the Fischer-Tropsch reaction products

of water and other volatile substances. There tends to be an ever-increasing amount of data substantiating this conclusion. In the later period during the radiogenic heating of the upper primary mantle gases and vapours were emitted that gave rise to the formation of atmosphere and hydrosphere. In addition to this there also took place an outcrop of organic compounds, which changed in the direction of progressive evolution, remaining in close contact with the solid phases of various degree of fractioning—from colloidal particles of clayey minerals to large stones and lumps as the first weathering products of the newly-born crust of our planet. This hard material was distinguished by enhanced radioactivity in the early stages of the development of the Earth.

However, we don't know how far the chemical evolution of matter progressed in space conditions. Those carbonaceous chondrites which were studied in terms of how much organic content they had and that we have recently received from the asteroid belt, can be regarded only as a probable analog of the material, which created the upper horizons of our planet. However, they can hardly be taken for the one-to-one equivalents of the Earth's primary upper mantle.

Presumably, there are two ways of solving the problem: either the chemical evolution, which began in space conditions, continued on Earth and in a relatively short period of time led to the emergence of primitive living organisms, or the formation of the initial complex DNA molecules, that lie in the foundation of heredity, took place in space conditions, while the complete realization of DNA came into effect in the first water bodies of our planet, that contained dissolved organic substances.

The Origin of Bisophere and the Main Features of Its Development

> Within the whole period of geological history the living material has always been and still remains the constituent part of the biosphere, the source of energy it captures from solar radiations—the substance that is in an active state and has the main impact upon the course and trend of geochemical processes of chemical elements throughout the earth's crust.
>
> *V.I. Vernadsky*

The development of organic compounds as well as the living matter is most closely connected with water. However, the problem of the origin of water on our planet refers to the field of research on the concluding stages of accretion. At that stage the most low-temperature condensates of the solar nebula—the hydrated silicates, organic substances and the water itself in its adsorbed state in hard particles or in form of cosmic ice—concluded the formation of planets of the terrestrial group. These condensates were most comprehensively expressed in the carbonaceous chondrites of type C1. However, on the contemporary level of knowledge it is possible to assume that a certain part of water entered the planet in the last stages of accretion. This process is particularly well manifested in the ice satellites of the outer planets, the covers of which presumably reflect the result of the fallout of large quantities of cosmic snow which had covered the earlier surface of these planetary bodies. On the whole the factors underlying the intrusion of volatile components into the composition of the planets of terrestrial group presents a highly difficult and yet unsolved problem. The same can be said of the problem connected with the presence of organic substances in the composition of the earth and planets of the terrestrial group.

If we assume that in the epoch when the formation of the Earth was reaching the stage of its completion, it received on the whole approximately 1% of the material of the type of carbonaceous chondrites, it is not difficult to calculate that at the beginning of its development our planet acquired $n \cdot 10^{17}$ t of organic matter of abiogenetic origin. The general amount of organic carbon in the earth's crust is estimated to be $3.8 \cdot 10^{15}$ t, which is two orders lower than what is supposed to have been the primary organic carbon in the composition of the upper layers of the newly formed Earth. In addition to this it should be taken into account that the vast quantity of organic matter of the earth's crust in the form of dispersed organic substances, coals and oil emerged later in the course of the photosynthetic activity of organisms which utilized carbon dioxide of either the abyssal pallial origin or that of the primary atmosphere, but not the initial organic matter that emerged on the surface of the Earth in the earliest stages of its development. Thus, the general amount of primary organic matter, which the Earth could have inherited from the protoplanetary nebula, cannot be assessed in quantitative terms at the present level of our knowledge. The exact amount of matter of the carbonaceous chondrite type that accomplished the formation of our planet is still unknown.

On the other hand the data of contemporary cosmochemistry evidence that in the period of its formation our planet generally received an adequate amount of organic compounds so that by means of the polymerization of amino acids, complex hydrocarbons, and other compounds there could appear self-regulating systems essential for the living matter.

In the opinion of a great number of researchers in the early stages of its development life was not connected with any individual living organisms, and found its expression in a common living matter. According to V.I. Vernadsky the origin of life is reduced to that of the biosphere, which from its very inception was a complicated self-regulating system. A great variety of geochemical functions of living matter emerged at least as a result of the fact that any most primitive cell, being in aqueous and marine medium, had the closest possible contact with all the chemical elements of Mendeleev's Table. In the process of their vital activity these primitive organisms naturally selected not all the elements, but primarily those that were favourable to their growth and perfection of a whole series of physiological processes.

In this connection, V.I. Vernadsky wrote: 'The conclusion substantiating the necessity of an excessively varied geochemical function of the representatives of life in the biosphere is the undisputed prerequisite for its emergence. Irrespective of what kind it was, it had to be represented not by a combination of indivisible specimens of one particular type, but by an integral number of species, morphologically belonging to either different, markedly separated classes of organisms, or of certain hypothetical forms of living matter, distinct from species unknown to us. The possibility of a complete accomplishment of all geochemical functions of organisms in the biosphere by unicellular organisms makes it probable that such was the advent of life itself....

Thus, the first appearance of life at the time when the biosphere was being created had to take place not in the form of the emergence of some kind of species of organisms, but in the form of their totality corresponding to the geochemical functions of life. What had to immediately appear was biocoenosises.'

It can be assumed that as the role of catalytic reactions grew, the chemical evolution in space nebula could lead to the formation of DNA molecules. However, the realization of its functions was made possible only within the confines of the Earth where on the basis of the development of living matter the early biosphere was formed as a combination of favourable conditions for life as viewed from the biologically inert systems and the living matter itself. In the other bodies of Solar system the chemical evolution was found to be retarded.

At present there exists a clear-cut subdivision of organisms into autotrophic and heterotrophic varieties according to their means of nutrition. However, in the Earth's early biosphere the relationship between heterotrophic and autotrophic organisms was different. What exactly it was remains unclear. The only thing that can be assumed is that the photosynthesizing autotrophic biosphere, as recorded by the date of isotopic geochemistry, was a secondary formation 4 billion years ago and emerged on the basis of a biosphere of quite another biogeochemical type.

As is actually the case, a detailed study of photosynthesis revealed that it has a complex character. This process could not be initial in the history of living matter. Hence, all the hypotheses concerning the primary origin of autotrophic organisms turned out to be untenable. In the light of contemporary data the concept of the primary nature of the heterotrophic form of the metabolism of substances in primary organisms is now being formed. The primary nature of heterotrophic nutrition can be substantiated by the following statements:

(1) all contemporary organisms have systems that are accommodated to employ ready organic substances as the initial building material for the processes of biosynthesis;

(2) the preponderance of organic species in the Earth's contemporary biosphere can exist only provided there is a constant supply of ready organic substances;

(3) the heterotrophic organisms reveal no traces or any rudimentary remains of those species enzyme complexes and biochemical reactions which are necessary for the autotrophic means of nutrition. The latter conclusion is most essential. Thus, the statement that was previously made serves as proof that the autotrophic photosynthetic life in the biosphere on our planet is of secondary character.

From what has been said above it becomes possible to infer that the primary biosphere of our planet was in the first place restricted by an aqueous medium, and, secondly, was impregnated with heterotrophic organisms which fed themselves on the organic substances dissolved in water, and which emerged earlier predominantly in cosmochemical conditions. This kind of biosphere must have existed most likely within a short period of geological time.

The primary heterotrophic organisms, which possessed the properties of living matter, reproduced at a high rate, and thus naturally exhausted their nutritive basis. Hence, when they reached maximum biomass, they had to either become extinct or employ the autotrophic photosynthetic means of nutrition. This new means of nutrition promoted a speedy settlement of organisms near the surface of the original water bodies. However, the primary surface of the newly formed Earth, deprived of free oxygen, was radiated by the ultraviolet radiation of the Sun. For this reason, G. Gaffron assumed that the primary photochemical mechanisms which took part in the sequential synthesis of organic substances, and later covering the living organisms, initially made use of radiation in the ultraviolet region of spectrum. It was only after the emergence of the ozonic screen in connection with the emergence of free oxygen as a subsidiary product of the same photosynthesis that the autotrophic photosynthesizing process began to use radiation in the visible part of the solar spectrum. According to the prominent Soviet biologist M.M. Kamshilov life had most probably developed as a circulation of substances in close association of heterotrophic and autotrophic organisms. Solar radiation was the principal energy factor of life, and its origin consisted in establishing circular metabolic processes with the use of the photons of light.

The primary heterotrophic microorganisms inhabited in the ancient water bodies for some time only. Then they were set aside by photoautotrophic organisms, which produced free oxygen that had a genuinely deteriorating effect on the heterotrophs. It is possible to assume that in the early ocean there took place a struggle between the primary and secondary organisms. In the water enriched with hydrogen sulphide free oxygen was present in very small quantities. It was expended on chemosynthesis of some organisms and was absorbed by mineral suboxidized substances of the ocean and the primary lithosphere. The struggle for existence went on between the photosynthesizing organisms of plankton in the illuminated part of the sea and the organisms that absorbed oxygen during chemosynthesis and the decomposition of organic remains. This became one of the main reasons which determined the amount of free oxygen in the biosphere. The confrontation ended in the victory of photosynthesizing autotrophic organisms, which had essentially driven the anaerobic microflora into the zone where deep-sea ooze was formed. In general the evolution of oxidizing functions took place under the increase of redox potential.

At present, with some of the geochemical data taken into account, we can successfully restore the composition of primary atmosphere and hydrosphere as the medium for the origin and development of early life. The water and primary gases of the atmosphere refer to the volatile substances of our planet, and it is natural that their history is connected with a unified process of degassing of primary mantle. A number of components which nowadays enter into the composition of sedimentary rocks, hydrosphere and atmosphere are genuine volatile substances. If we compare their quantity in the composition of the whole complex of sedimentary rocks, hydrosphere, and atmosphere with that amount which could have been released in the process of weathering and the reworking of crystalline igneous rocks of the earth's crust, we shall discover a great difference, which W. Rubey suggested to call volatile excess.

The excess of volatile substances is a fairly impressive value and as far as some of the components are concerned it is scores and even hundreds of times greater than the volatile material resulting from the weathering of igneous bedrocks of the lithosphere. In the excess of volatile vapours H_2O is 128 times greater than it could have been produced by the primary earth's crust during its complete intensive disintegration, while the corresponding figures for CO_2 and Cl are 83 and 60 respectively. The composition of volatile excess is the following (in weight %):

H_2O	92.8	Ar	traces
C as CO_2	5.1	Cl_2	1.7
I_2	0.13	F_2	traces
N_2	0.24	H_2	0.07

The composition of volatile excess is very close to that of volcanic gases. The most typical compositions of gases related to abyssal and magmatic origin are given in Table 9.

TABLE 9. The Composition of Gases from Volcanoes, Igneous Rocks, Hot Springs and Excess Volatiles in Atmosphere and Sedimentary Rocks

Gas	Kilau-ea and Mauna Loa	Basalt and dia-base	Obsid-ian, ande-site, and granite	Fuma-roles, hot steam wells, and geysers	Vola-tile excess
H_2O	57.8	69.1	85.6	99.4	92.2
C as CO_2					
CO_2	23.5	16.8	5.7	0.33	5.1
S_2	12.6	3.3	0.7	0.03	0.13
N_2	5.7	2.6	1.7	0.05	0.24
Ar	0.3	Traces	Traces	Traces	Traces
Cl_2	0.1	1.5	1.9	0.12	1.7
F_2	0.04	6.6	4.4	0.03	Traces
H_2	0.04	0.1	0.04	0.05	0.07
Others	—	—	—	—	—
	100.4	100.0	100.4	100.01	100.04

Even if CO_2 did emerge in the active volcanoes at the expense of thermal decomposition of carbonates, in this case too it had been borrowed from the much earlier atmosphere in the process involving the formation of the most ancient carbonaceous sedimentary rocks.

In the spreading order volcanic gases are composed of H_2O, CO_2, and N_2. With this kind of composition of the atmosphere the presence of organic compounds and moreover their emergence is thermodynamically unfavourable; any organic compounds consisting of H, C, N, and O are less stable than the above listed basic components of the primary atmosphere.

At the time the primary atmosphere and ocean were formed the fairly complex organic substances contained in the early mantle were in close contact with the hard particles of silicates, which in the later period could play the role of powerful catalysts in the process pertaining to the development of ever more complex compounds.

Data on volcanic gases most definitely show that in the course of eruption it was molecular nitrogen (N_2) that was emitted, and not ammonia; consequently, ammonia had never been the main component of the Earth's atmosphere.

It has already been mentioned that the period within which the heterotrophic biosphere existed was exceptionally short, for which reason the reserves of organic substances in primary water bodies could not be replenished in the same way as those of the autotrophic organisms. However, we could assume that the remains of heterotrophic organisms did incessantly refill the reserves of nutritious organic substances. Thus, there existed a balance between the active heterotrophic organisms and their decomposed remains.

From what has been just described we can conclude that the source of living matter and water was an integral whole, or, to be more exact, the source of volatiles on Earth and the living matter was one and the same. It was the upper horizons of the mantle that emerged mainly at the expense of the accretion of the primary matter of the type of carbonaceous chondrites. Besides, it is impossible to merely equate the material of the Earth's primary upper mantle with that of carbonaceous chondrites. We can speak here only of close analogs since the composition of individual zones of primary solar nebula depended on the heliocentric distance.

The Earth's primary atmosphere, with which early life was connected in one way or another, can be visualized by comparing it with that of other planets of the terrestrial group, such as Venus or Mars (Table 10). With the emergence of photosynthesis and free oxygen the Earth's primary atmosphere had drastically changed.

The contemporary level of our knowledge enables us to hypothetically accept the statement that as the functioning of catalytic and radiochemical reactions in the concluding stages of cooling was becoming more pronounced, the chemical evolution in the protoplanetary nebula could have led not only to the formation of complex organic compounds, which is now a well-established fact, but also to the emergence of DNA molecules.

One very important fact cannot be but

TABLE 10. The Atmosphere of the Earth and Venus

Component	Earth		Venus
	at present	primary*	
N_2, %	78	1.5	1.8
O_2, %	21	Traces	Traces
Ar, 10^{-4} %	9000	190	200
CO_2, %	0.03	98	98
H_2O, km**	3	3	Traces
Pressure, bars	1	70***	80±3

* Primary variant of the Earth model corresponds to the conditions pertinent to the absence of photosynthesis and carbonates on the Earth.

** The average depth of the World Ocean.

*** For crustal carbon with the abundance $9 \cdot 10^{22}$ g.

mentioned: the biological evolution of the biosphere that had come into existence traversed an irreversible path of ever-growing complexity. In 1893 this drew the attention of the prominent Belgian paleontologist L. Dollo (1857-1931), who formulated the law of irreversibility of evolution. According to this law an organism cannot even partially return to the state which was characteristic of its ancestors. Then, referring to Charles Darwin, he pointed out that the evolutionary transformation of organisms took place as a result of the retention of useful individual variations under the influence of natural selection, caused by the struggle for existence. All types of plants and animals, from the very first days they emerged on Earth, owe their origin to this fundamental law.

The irreversibility of biological evolution naturally presupposes that the very process of the emergence of living matter and the biosphere was taking place in irreversible conditions. What can be considered the most typical irreversible process is radioactivity. Its possible role in the synthesis of organic substances has already been mentioned. Radioactivity is the general and the most fundamental property of a substance, the reflection of processes connected with the building of nuclides just before the Solar system was formed. It was radioactivity that was giving rise to that natural radiation background, against which chemical evolution in space as well as on the early Earth was taking place. As far back as 1926 it was established that under the radiation of methane there took place the polymerization of hydrocarbons with the formation of ever more complex polyatomic molecules.

According to all the data the most favourable conditions for the development of life on our planet were being created in sea water—the natural solution containing all the chemical elements. The radioactivity of the sea water of the early Earth itself was mainly determined by the dissolved isotopes ^{40}K, ^{235}U, and ^{238}U. Taking into consideration the rate of their decay, it is not difficult to estimate that sea water as such was 20-30 times more radioactive than it is now. Additional radioactivity might have been introduced by the rapidly decaying ^{129}I, the smallest quantities of which could have caused various radiation and ionization effects in connection with its marked specific radioactivity. It is also probable that the radioactive isotopes (Table 8) which had soon become extinct played their role too.

The function of radioactivity in the development of life on Earth presents a problem to the solution of which we have only recently started to approach. The impact of radioactivity upon the living organisms was on the decrease in the course of geological time. In addition to this we have to consider the fact that the simply organized algae and bacteria can take considerably greater doses of radiation than the highly-organized forms of animals and plants. This makes it possible to assume that the lower degree of sensitivity to radioactivity of simple forms of life is connected with their emergence in the early epochs of the development of the biosphere, when the radioactivity of environment was higher than it is today.

Among the metals that enter into the composition of organisms and predominantly plants, potassium is the richest and most widespread element. A.I. Perelman suggested that the biophile behaviour of potassium was connected with its radioactivity in the historical aspect. At the dawn of its development the life, which had then not wholly acquired the mechanism of photosynthesis, was in need of sources of energy. By assimilating potassium the primary organisms received not only the substance with the required chemical properties, but also an additional source of free energy. This could have determined more intensive biological assimilation which was retained hereditarily. The absorption of potassium was also transmitted to the more highly organized forms of life, for which radioactivity had already had no minor significance. However, the established physiological role of potassium made its absorption reach very high quantities.

At the time the first organisms came into existence: the main event was the formation of spiral DNA molecules, which given the abundance of organic substances, could have been a relatively quick process. There is some reason to believe, however, that what emerged was not a single organism, but living matter itself. And only much later it was divided into spherical forms that gave rise to organisms.

In the later period the process of complexity was taking place in living matter. There occurred a qualitative change in the evolution of living material connected with the accuracy of reproduction of nucleic acids as a coding process of the synthesis of proteins, which considerably surpassed the other organic compounds by their biocatalytic properties.

In the process of reproduction new organisms occupied the whole space that was useful for life, which became an important condition for the completion of the formation of biosphere in general. V.I. Vernadsky advanced a principle presupposing the constancy of the biomass of living matter and spread it throughout the whole history of our planet. This principle was and still remains a profound scientific generalization. However, it should be emphasized that it has a relative significance. The overwhelming intensity of life which finds its expression in the high rates of the reproduction of smallest organisms, results in a planetary equilibrium between the natural production of living matter and its decomposition. Hence, at present, we would be more justified to speak of an age-long trend towards establishing the constancy of biomass for particular, presumably even considerable, intervals of geological time.

According to the data of molecular biology the most ancient microbes were represented by heterotrophic organisms, that propagated in a medium which was characterized by a large number of organic and mineral nutritive substances. These nutritive substances included at least ribose, desoxyribose, phosphate, purines, and their predecessors—pyrimidines, various 'protein' and 'non-protein' amino acids. In the early stages of the Earth's development phosphates Na, K, and Ca must have been present in adequate quantities, as the weathering products of primary rocks. Moreover, a large number of unknown or unidentified compounds including some of the resin-like long polymers could have been used as food too.

The first organisms were characterized by the process of fermentative transformation of organic substances, or fermentation, in which the acceptors of electrons were other organic substances. The realization of these transformations in the transitory metabolism practically in all the organisms serves as an argument in favour of the antiquity of these processes.

In the Earth's early heterotrophic biosphere there soon emerged organisms that were capable of absorbing carbon dioxide, utilizing the energy of the solar rays. According to L. Margulis the biosynthetic fixation of carbon dioxide, which was so abundant in the Earth's primary atmosphere, was taking place along three particular lines.

First came the most primitive fixation that was typical of a large group of microorganisms which were not sensitive to visible light. The second means emerged with the participation of carboxylase, which is found with anaerobic photosynthetic bacteria. The third fixation CO_2 was being accomplished by means of the taking part of ribulose bisphosphate, carboxylase. It is characteristic of a large number of aerobic organisms and is also typical of most of the photosynthetic organisms and chemoautotrophs. The fixation of atmospheric nitrogen was produced almost at the same time. This anaerobic process accompanied by an expense of energy was found only with prokaryotes.

The photosynthetic pigmentary systems were formed with prokaryotes even before the latter as a result of symbiosis became the plastids of eukaryotes. It becomes possible to assume that the photosynthesis with the emission of free oxygen primarily emerged not with the green plants at all but with the photosynthetic bacteria and blue-green algae that release it.

The development of the Earth's biosphere can be regarded as a subsequent alteration of three stages (Fig. 13). The first stage, or that of the reduction, began as early as in the space conditions and was completed on Earth with the emergence of heterotrophic biosphere. The first stage was characterized by the advent of very small spherical anaerobes (Fig. 13*a*). Only traces of free oxygen were present. The early means of photosynthesis was essentially anaerobic. The fixation of nitrogen was developed since a part of ultraviolet radiation had penetrated through the atmosphere and rapidly disintegrated the ammonia that was present.

The second stage (the weakly oxidizing one) was marked by the emergence of photosynthesis. It continued till the completion of the sedimentation of banded ferruginous formations of the Precambrian period. The aerobic

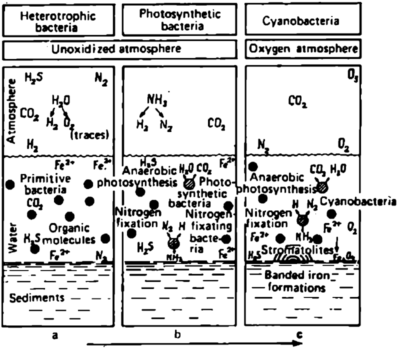


Fig. 13. Organism and environment evolved in counterpoint during the Precambrian

The first living cells (*a*) were presumably small, spherical anaerobes. Only traces of oxygen were present. They survived by fermenting organic molecules formed nonbiologically in the anoxic environment. The role of such ready-made nutrients was diminished, however, when the first photosynthetic organism evolved (*b*). This earliest mode of photosynthesis was entirely anaerobic. Another early development was nitrogen fixation, required in part because ultraviolet radiation that could freely penetrate the atmosphere would have quickly destroyed any ammonia (NH_3) present. In early Precambrian (*c*) aerobic photosynthesis began in the precursors of modern cyanobacteria. Oxygen was generated by these stromatolites—building microorganisms (according to W. Schopf, 1978)

photosynthesis was initiated by the ancestors of cyanobacteria. Oxygen was produced by organisms that were building stromatolites

(Fig. 13*b*). Its accumulation in the atmosphere, however, was low, since it reacted with the iron dissolved in water. Besides, iron oxides continued to settle, thus forming banded ferrigenous formations of the Precambrian type. It was only when the ocean relieved itself of iron and other semi-valent metals that the concentration of oxygen began to grow towards the present-day level.

The third stage was characterized by the development of oxidizing photoautotrophic biosphere. It began with the completion of deposits of banded ferrigenous quartzites about 1800 mln years ago in the epoch of Karelian-Svekofennian orogenesis. This stage in the development of biosphere is characterized by the presence of such amount of free oxygen which was quite sufficient for the emergence and growth of animals, which use it for breathing.

The last two stages in the development of biosphere are registered in the stone records of geological history. The first stage is the one that is most remote and puzzling, and the interpretation of its history is connected with the solution of the main problems of organic space chemistry.

Some organisms of the early Precambrian period, which refer to the blue-green algae and cyanobacteria, have changed but little in the course of geological history. It can be assumed that the simplest organisms possessed a high degree of persistence. Essentially, throughout the whole history of the Earth there have been no reasons for some of the marine microorganisms, in particular the blue-green algae and bacteria, to undergo any marked changes.

THE DEVELOPMENT OF PLANTS

Plants, as the typical representatives of the photoautotrophic organisms of our planet emerged in the course of a very long evolution, the beginning of which goes back to the primitive inhabitants of the illuminated zone of the sea—planktonic and benthonic prokaryotes. By contrasting the paleontological data with those of comparative morphology and physiology of the plants living at present time, it becomes possible to give the following general outline of the chronological sequence of their emergence and growth:

(1) bacteria and blue-green algae (prokaryotes);
(2) cyanic, green, brown, red and other algae (eukaryotes as well as all the subsequent organisms);
(3) mosses and liverworts;
(4) ferns, equiseta (horsetails), lycopods, and pteridosperms (seed ferns);
(5) gymnosperms (including cone-like plants);
(6) angiosperms, or flowering plants.

Bacteria and blue-green algae were discovered in the most ancient preserved deposits of the Precambrian period; much later there appeared algae, and only in the Phanerozoic period we can find a luxuriant growth of higher plants: lycopods, equiseta (horsetails), gymnosperms, and angiosperms.

Within the whole Cryptozoic period in the primary water bodies and in the euphotic zone of the ancient seas there was a predominant development of unicellular organisms—the algae of various type.

With the main representatives of prokaryotes found in the Precambrian period the nutrition was autotrophic, or with the help of photosynthesis. The most favourable conditions for photosynthesis were being created in the illuminated part of the sea at the depth of up to 10 m from surface, which also corresponded to the conditions of shallow-water benthos.

Recent progress in the studies of Precambrian microfossils is due to the accumulation of a large amount of data. But on the whole the interpretation of microscopic preparations presents a difficult task which cannot be accomplished in any one particular way. What lends itself most readily to be discovered and recognized are the trichomic bacteria, which are markedly distinguished from the mineral formations of a similar form. The empirical material on microfossils that has been received enables us to infer that they can be correlated with the now existing cyanobacteria.

Stromatolites, as biogenic constructions of the remote past of our planet were formed at the time of the accumulations of fine sediment of calcium carbonate, which was captured by the photosynthesizing organisms of microbiological associations. The microfossils in stromatolites consist almost exclusively of prokaryotic microorganisms, which refer mainly to blue-green algae—Cyanophyta. In studying the remains of benthonic microorganisms that compose stromatolites, one very important and interesting peculiarity was discovered. Microfossils of different age hardly change their morphology and on the whole evidence the conservative character of prokaryotes. Microfossils referring to prokaryotes had remained practically constant over a fairly long period of time. In any case, what we have before us is a well-established fact that the evolution of prokaryotes took place considerably slower than that of higher organisms.

Thus, in the course of the geological history bacteria-prokaryotes have revealed the highest degree of persistence. Persistent forms include organisms that in the process of evolution remained unaltered. As has been pointed out by G.A. Zavarzin, since the ancient communities of microorganisms reveal marked features of similarity with the contemporary ones that are developed in hydrothermal conditions and in the regions where evaporites are formed, which makes it possible to employ present-day natural and laboratory models to more thoroughly study the geochemical activity of these communities, extrapolating them into the remote Precambrian period.

The first eukaryotes emerged in planktonic associations of the open seas. The end of the exclusive domination of prokaryotes refers to the date of approximately 1.4 billion years ago, though the first eukaryotes had come into existence much earlier. Thus, according to the latest data the appearance of the fossils of organic remains of black schists and carbonaceous formations found near the Lake Superior proves that the emergence of eukaryotic microorganisms took place 1.9 billion years ago.

From the time of 1.4 billion years ago to the present moment the paleontological record of the Precambrian period had considerably been enlarged. This date coincides with the emergence of relatively large forms that refer to the planktonic eukaryotes and that received the name of 'Acritarchum' (which in Greek means the creatures of unknown origin). It should be mentioned that the group of Acritarcha is suggested as an indefinite systematic category which designates microfossils of different origin, though similar as to their outer morphological features. Scientific literature contains descriptions of Acritarchum of the Precambrian and Lower Paleozoic periods. Most of the Acritarcha were presumably unicellular photosynthesizing eukaryotes, or shells of some ancient algae. Some of them could also have had prokaryotic organization.

The planktonic character of Acritarchum is brought out by their cosmopolitan distribution in coetaneous sedimentary deposits. The most ancient Acritarchum of the deposits of the early Riphean period in South Ural was discovered by T.V. Jankauskas.

In the course of geological time the size of Acritarcha was becoming ever greater. According to the data furnished by observations it occurred that the younger the Precambrian microfossils were, the larger their size was. We may assume that a considerable increase in the dimensions of Acritarcha was connected with the growth of the size of the eukaryotic organization of cells. They could have appeared as either independent organisms or, more probably, in the symbiosis with others. According to L. Margulis the eukaryotic cells were brought together on the basis of the already existing prokaryotic ones. However, for the survival of eukaryotes it was necessary that the environment should have been saturated with oxygen, and as a result of this there appeared aerobic metabolism. At first free oxygen, which was emitted during the photosynthesis of cyanophites, was accumulated in limited quantities within the shallow-water places of habitat. The increase of its content in the biosphere caused a reaction on the part of organisms: they started to occupy the places of habitat deprived of oxygen (in particular, the anaerobic forms).

The data pertaining to the Precambrian micropaleontology reveal that in the Middle Precambrian period even before the eukaryotes appeared, cyanophites had comprised a relatively small part of plankton. Eukaryotes were in need of free oxygen and were ever contesting for it with prokaryotes in those regions of the biosphere where free oxygen appeared. According to the available data it is possible to consider that the transition from prokaryotic to eukaryotic flora of the ancient seas was taking place at a low rate and that these two groups of organisms had coexisted for a long period of time. However, the same coexistence, though in quite a different proportion, also takes place today. By the beginning of the Late Riphean period a large number of autotrophic and heterotrophic forms of organisms had already been spread.

In the course of their development the organisms moved in search of nutritive substances towards the deeper and more remote regions of the sea away from the shelves. Paleontological records have registered a marked increase in the variety of large spheroidal forms of eukaryotic Acritarcha in the Late Riphean period 900-700 mln years ago. As far back as about 800 mln years there appeared in the World Ocean representatives of a new class of planktonic organisms—the cubical little bodies with massive shells, or outer crusts, mineralized by calcium carbonate or silica. At the beginning of the Cambrian period in the evolution of plankton there took place substantial changes which found their expression in the emergence of diverse microorganisms with complicated sculptural surface and an improved floatability. They were the ones that gave rise to genuine spine-like Acritarcha.

In the early Riphean period (about 1.3 billion years ago) the emergence of eukaryotes created a highly important prerequisite for the origin of multicellular plants and animals. For the Beltian series of the Precambrian period of the western states in the North America, their description was first given by Ch. Walkott. But to what type of algae they belong (brown, green or red varieties) still remains a question. Thus, the excessively long era of the domination of bacteria and the blue-green algae close to them was superseded by the era of algae, which in the waters of the ancient oceans acquired a considerable variety of forms and colours. Within the Late Riphean period and Vend the multicellular algae became more varied and could be correlated with the brown and red types.

In the opinion of Academician B.S. Sokolov, the multicellular plants and animals appeared practically at the same time. In the Vend deposits we can find various representatives of aqueous plants. The most prominent place is occupied by multicellular algae the thallus of which often overfilled the masses of Vend deposits: argillites, clays, and sandstones. We can often find microplanktonic algae, colonial, spiral and filamentous algae *Voly-*

mella, felt-like and other forms. The phytoplankton is extremely varied indeed.

Within the greater part of the Earth's history the evolution of plants took place in the aqueous medium. It was precisely here that various stages in the development of aqueous vegetation originated. On the whole algae constitute a vast group of lower aqueous plants containing chlorophyll and producing organic substances by means of photosynthesis. The body of algae had not yet been differentiated into roots, leaves and other characteristic parts. They were represented by unicellular, multicellular and colonial forms. The reproduction was asexual, vegetative and sexual. Algae enter into the composition of plankton and benthos. At present they are referred to the subkingdom of Thallophyta plants, the body of which is composed of a relatively homogeneous tissue, or Thallus. The latter consists of a large number of cells, that are similar as far as their type and functions are concerned. In the historical aspect algae underwent the most prolonged stage in the development of green plants and in the general geochemical cycle of the biosphere's matter played the role of a gigantic generator of free oxygen. The emergence and development of algae had an exceptionally irregular character.

The green algae (Chlorophyta) represent a vast and widespread group of predominantly green plants, which is subdivided into five classes. According to their outward appearance they are markedly distinct from one another. The green algae come from the green flagellate organisms. This is evidenced in the transitory forms, Pyramidomonas and Chlamydomonas, mobile unicellular organisms that live in water. Green algae are bred in a reproductive way. Some groups of green algae reached a high degree of development in the Triassic period.

The flagellate algae (Flagellata) are united into a group of microscopic unicellular organisms. Some researchers refer them to the vegetable kindgom, while others regard them as belonging to the animals. As is the case with plants, some flagellates contain chlorophyll. However, in contrast to most of the plants they do not have any individual cell system and are able to digest food with the help of ferments, and also live in darkness in the same way as living organisms. There is some reason to believe that flagellates existed in the Precambian period, though their representatives were undoubtedly found in the Jurassic deposits.

The brown algae (Phaeophyta) are distinguished by the presence of brown pigment the quantity of which is such that it actually conceals chlorophyll and makes the plants acquire a corresponding colour. The brown algae refer to benthos and plankton. The largest algae reach 30 m in length. Almost all of them grow in salt water, for which reason they are called sea grass. Brown algae include the Sargasso variety—the floating planktonic forms with a large number of bubbles. In their fossil state they have been known since the Silurian period.

The red algae (Rhodophyta) have this colour owing to the presence of red pigment. They are predominantly marine plants that are excessively branched. Some of them have a calcareous skeleton. This group is often referred to kullipores. They exist nowadays too, but in their fossil state they have been known since the Lower Cretaceous period. Somipores that are very close to them and have large and wide cells appeared in the Ordovician period.

The chara-shells (Charophyta) represent a very specific and fairly high-organized group of multicellular plants which are characterized by sexual form of reproduction. They are so different from other algae that some botanists refer them to the cormophytic variety in connection with what has now appeared as the differentiation of tissues. Chara-shells are of green colour and now live in fresh water and brackish water bodies. They avoid sea water with a normal degree of salinity, but we may well assume that in the Paleozoic period they dwelt in the sea. Other chara-shells are characterized by sporophydia that are saturated with calcium carbonate. Chara-shells belong to the important rock-forming organisms of the limnetic limestones.

The diatoms (Diatomeae) are typical representatives of plankton. They have an elongated form, and are covered by a shell consisting of silica. The first remains of diatoms were found in the deposits of the Devonian period, though they might be older. On the whole diatoms constitute a relatively young group. Their evolution has been studied more thoroughly than that of the other algae since the siliceous shells and valves of diatoms are preserved in a fossilized state for a very long period of time. Presumably diatoms come from the flagellates that had acquired a yellow colour and that were capable of depositing in their shells small quantities of silica. At present diatoms are widely spread in fresh and sea waters and are sometimes found in humid soils. The remains of diatoms are known to exist in Jurassic deposits, though there is some reason to believe that they had appeared much earlier. The fossil diatomaceous algae have reached us from the early Cretaceous period without any interruption in deposits.

A highly important event which promoted a marked acceleration of evolution of the whole living population of our planet was the migration of plants from water to land. The emergence of plants on the surface of continents can be regarded as a genuine revolution in the history of biosphere. The development of land vegetation created the necessary conditions for the advent of animals on land. However, the mass transition of plants to land had been preceded by a long preparatory period. It can be assumed that the plant life on land appeared very long ago, in any case locally—in the humid climate on the shores of the shallow bays and lagoons, where with the changes of water level there periodically occurred the supply of aqueous vegetation on land. The Soviet naturalist L.S. Berg was the first to suggest that the surface of land did not represent a lifeless desert either in the Cambrian or in the Precambrian period. The prominent Soviet paleontologist L.Sh. Davitashvili also regarded it possible that in the Precambrian period on the continents there might have been some population consisting of low-organized plants and possibly even animals. However, their total mass was infinitesimal.

In order that the plants could live on land they should not have lost water. In this connection we must bear in mind that in the highest plants such as mosses, pteridospermaphytes, holospermatophytes and spermatophytes, which nowadays comprise the main mass of land vegetation, only the roots, their fibres and rhizoids come into contact with water; the rest of their organs, however, are in the atmosphere and evaporate water by their whole surface.

Vegetable life reached its peak of development on the shores of lagoon lakes and swamps. This is where there appeared the type of plant the lower part of which was in water and the upper one in the air, under the direct rays of the Sun. Somewhat later, with the penetration of plants to the unflooded land, their very first representatives developed a root system and received the opportunity using ground waters, which helped them to survive in the arid periods. Thus, the new conditions led to the division of plant cells into tissues and the development of such protective means that their ancestors living in water did not have.

The mass conquest of the continents by plants took place in the Silurian period of Paleozoic era. First and foremost they were the psilophytales—a specific kind of sporophytes which look like lycopods. A certain part of sinuous stalks of psilophytales was covered with hispid leaves. Psilophytaleans were deprived of roots and basically of the leaves too. They consisted of branched stalks the height of which was up to 23 cm and horizontally extended towards the soil of the root stalk. Psilophytales, as the first known plants on land, gave rise to massive green carpets on the humid ground.

The production of the organic matter of the primary vegetative covers on land must have been sparse. The vegetation of the Silurian period undoubtedly came from the sea algae and was itself responsible for the emergence of plants in the subsequent period.

After the conquest of land the development of vegetation led to the formation of numerous and varied forms. The intense division of plant groups began in the Devonian period

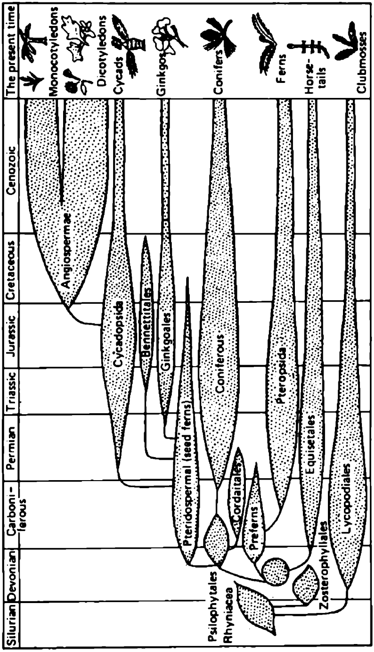


Fig. 14. Development and genetic relationships of various groups of land plants (according to S. Awramik, S. Morris, 1982)

and continued in the following geological time. The general genetic relationship of plants is given in Fig. 14.

Mosses came from algae. Their early stage of development is very much the same as that of some green algae. However, there exists an opinion that the origin of mosses is connected with simpler representatives of brown algae, that had accommodated themselves to the conditions of wet rocks or in the soils as such.

On the surface of the early Paleozoic continents the age of algae gave way to the age of psilophytaleans, which gave rise to the vegetation the appearance and size of which had much in common with the present-day bushes of large mosses. In the Carboniferous period the domination of psilophytaleans was superseded by that of pteridospermaphytes, which formed fairly vast forests on the marshy soils. The development of these plants had an effect on the change in the composition of air. A substantial amount of free oxygen was added and a mass of nutritive substances that was required for the emergence and development of land vertebrate animals was accumulated. At the same time enormous masses of hard coal were concentrated. The Carboniferous period was characterized by an exclusive flourishing of land vegetation. There emerged arborescent lycopods, the height of which reached 30 m, huge equiseta (horsetails), ferns and the first conifers. The Permian period was marked by the continuation of the development of land vegetation, which considerably expanded the places of its habitat.

The period when the pteridospermaphytes dominated was replaced by the time of coniferous plants. The continental surface began to acquire its present-day shape. At the beginning of the Mesozoic era coniferous plants and cycads were spread most broadly, while in the Cretaceous period there appeared the flowering plants. At the very beginning of the early Cretaceous epoch there still existed the Jurassic forms of plants, but later the composition of vegetation underwent marked changes. At the end of early Cretaceous epoch we find a large number of angiosperms. From the very beginning of the late Cretaceous period, however, they set aside the gymnospermous and started playing the preponderant role on land. On the whole in the land flora there took place a gradual change from the Mesozoic vegetation of gymnospermous (conifers, cycads and ginkgoaceous plants) to the vegetation of Cenozoic form. The vegetation of the late Cretaceous period had already been characterized by the presence of a large number of such now existing flowering plants, as beech, willow, birch, plane tree, laurel, and magnolia. This restructuring of vegetation had prepared a favourable nutritive basis for the development of higher land vertebrate animals—mammals and birds. The development of flowering plants was connected with the burgeoning of numerous insects, which played a very important part in pollination.

The advent of a new period in the development of plants did not result in the complete destruction of the ancient vegetative forms. Some organisms of the biosphere had remained. When the flowering plants emerged the bacteria did not only disappear, but continued to exist, having found new sources of nutrition in the soil and in the organic matter of plants and animals. The algae of various groups changed and continued their growth together with the higher plants.

Woods of coniferous trees, which emerged in the Mesozoic period, are now growing alongside the greenwoods. They gave shelter to fern-like plants, since these ancient inhabitants of the nebulous and humid climate of the Carboniferous period avoided open spaces lit by the Sun.

Lastly, it should be mentioned that there was the presence of persistent forms in the composition of contemporary flora. The most persistent of them were the bacteria that had practically remained unaltered since the days of the early Precambrian period. But the highly organized forms of plants also gave rise to genera and species which had changed but little until now.

It is necessary to note that the relatively highly organized multicellular genera of plants are present in the composition of contemporary flora. The late Paleozoic and Mesozoic forms of plants, which had remained unaltered for tens and hundreds of millions of years most certainly belong to the persistent varieties. Thus, at present in the vegetable kingdom

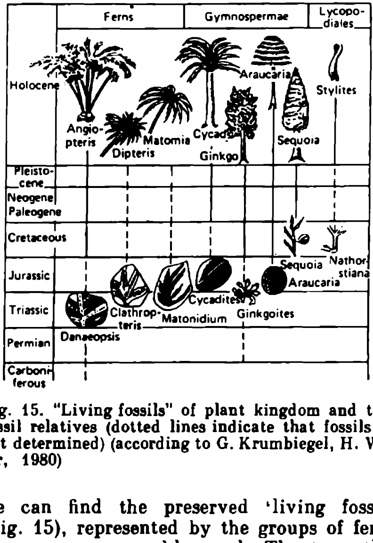


Fig. 15. "Living fossils" of plant kingdom and their fossil relatives (dotted lines indicate that fossils are not determined) (according to G. Krumbiegel, H. Walter, 1980)

we can find the preserved 'living fossils' (Fig. 15), represented by the groups of ferns, gymnospermous and lycopods. The term 'living fossil' was first used by Charles Darwin, who adduced the East-Asian tree of the gymnospermous type Ginkgo biloba as an example. In the kingdom of land plants the living fossils include the widely known fern palms, the ginkgo-tree, araucarians, the mammoth tree, or the giant sequoia.

As was pointed out by the prominent specialist of fossil flora A.N. Krishtofovich, many genera of plants that were the supreme rulers of the ancient forests had also existed for a very long time, particularly in the Paleozoic period; for instance, *Sigillaria*, *Lepidodendron*, and *Calamites* survived for no less than 100-130 mln years. The same figure can be applied to Mesozoic ferns and coniferous *Metasequoia*. The Ginkgo genus covers more than 150 mln years, while the contemporary species of Ginkgo biloba, if we were to include in it the essentially indistinguishable form Ginkgo adiantoides, extended throughout approximately 100 mln years.

The living fossils of the present-day vegetable kingdom can otherwise be called philogenetically conserved types. The paleobotanically properly studied plants which are referred to living fossils may well be regarded as conserved groups. They have practically remained unaltered, and the changes, if any, are but too insignificant in comparison with the cognate forms of the geological past.

Therefore, it is quite natural that the presence of living fossils in the present-day flora raises the problem of their formation in the history of the biosphere. The conservative organizations are present in all major phylogenetic branches and exist in most various conditions: in abyssal and shallow-water zones of the sea, in ancient tropical forests, in open expanses of the steppes and in exclusively all the water bodies. From the evolutionary views the most important condition for the existence of conservative organisms is the presence of habitats with stable conditions. However, the stable conditions of their habitat are not decisive. The presence of only individual forms rather than the whole communities of flora and fauna indicate other factors pertinent to the preservation of living fossils. The study of their geographical distribution evidences that they are correlated with the given territories, in addition to which geographical isolation being a typical feature. Thus, Australia, the islands of Madagascar and New Zealand can be regarded as typical regions where terrestrial living fossils are spread.

In its evolution the plant kingdom created a general form of ancient landscapes, in which the development of animal kingdom took place. Hence, the division of geological time can be made on the basis of the alteration of various plant forms. As early as 1930 the German paleobotanist W. Zimmerman classified the whole geological past into six eras according to the development of vegetable kingdom. He supplied them with alphabetic labels and arranged them in a sequence covering the period from the ancient eras to the younger ones.

A contrastive view of an ordinary scale of geological time constructed chiefly according to paleozoological data against the background of the scale showing the development of plants is given in Table 11.

TABLE 11. The Geochronological Scale and the Main Eras in the Development of Plants

Era	Period	Flora	Plant development era
Cenozoic	Quaternary	Neocenophytic	
	Tertiary	Paleocenophytic	Cenophytic
	Cretaceous	Neomesophytic	
Mesozoic	Jurassic		
	Triassic	Paleomesophytic	Mesophytic
	Permian		
	Carboniferous	Antracolithic	Paleophytic
Paleozoic	Devonian	Psilophytic	
	Silurian		
	Cambrian	Phycomicophytic	Thalassophytic
Proterozoic			

THE DEVELOPMENT OF INVERTEBRATES

The history of invertebrate animals began with the unicellular simplest organisms (Protozoa), which had branched off from the general stem with plants in the Precambrian period. However, the first primitive representatives of the animal kingdom had a soft body for which reason they have preserved very poorly in geological records. The most primitive and simplest of them have common features with the unicellular green algae. In the contemporary epoch the protozoans (radiolarians and globigerines) comprise a considerable part of the plankton of seas and oceans and play an important role in oceanic sedimentation.

All the main types of invertebrate animals emerged in the Precambrian period and gave rise to a highly varied multitude of water and land forms within the Phanerozoic period. The origin of animals from their vegetative ancestors was naturally connected with the transition from the autotrophic to heterotrophic means of nutrition. This transition must have been gradual in the course of a long geological time. In the Precambrian period there took place a development of various algae, which serves as the basic food for marine animals.

At present the animal kingdom, except chordates, includes all the invertebrates, which are classified into the following main types:

Unicellular organisms
  Protozoans (*Protozoa*)
Lower multicellular
  Sponges (*Spongia*)
  Archaeocyatheans
  (*Archaeocyathi*)

Higher multicellular organisms
- Two-layered or radiants (*Radiata*)
- Coelenterates (*Coelenterata*)
- Ctenophorans (*Ctenophora*)

(a) **Protostomes** (*Protostomia*)
- (*Scolecida*)
- Annelids (*Annelida*)
- Arthropods (*Arthropoda*)
- Mollusks (*Mollusca*)
- Bryozoans (*Bryozoa*)
- Brachiopods (*Brachiopoda*)

(b) **Deuterostomatous organisms**
- Echinoderms (*Echinodermata*)
- Pogonophores (*Pogonophora*)

As far as the finds of the most ancient representatives of protozoans, which in the later periods served as the initial forms for all the other animals, paleontological data are scarce and controversial. The unicellular animal organisms in the ancient Precambrian deposits are morphologically not distinct from the vegetative microorganisms. Hence, we should pay attention to the known intermediate forms of organisms between the plants and animals. They include unicellular flagellates (Flagellata), or, more exactly, some of the representatives of this class of protozoans. But within the limits of this class the coloured flagellates are brought into the subclass of phytomastigophorans (Phytomastigina) and the colourless ones constitute the subclass of flagellates (Loomastigina). The flagellates hold a special position in the kingdom of animals and plants. They are characterized by the presence of flagella, or the organs of movement. Their number can be various—from one to several units, and even tens and hundreds. Among the flagellates we find organisms with different types of metabolism, as, for instance, with its autotrophic and heterotrophic varieties, while some representatives of this class share the features of both these means of nutrition.

In this respect the group of Euglena is particularly remarkable (see Fig. 2). Numerous types of the *Euglena* genus are widely spread in contemporary fresh-water basins, and especially in polluted waters. Many types of *Euglena* change the character of their nutrition depending on the environment. Under proper illumination and in the presence of dissolved mineral substances in water the *Euglena* have a typically autotrophic means of nutrition. In their bodies there takes place the process of photosynthesis with the assimilation of various inorganic salts. In the dark in those solutions that contain organic substances *Euglena* become deprived of chlorophyll, lose their colour and assimilate from the solution ready organic substances.

This is how the transition from autotrophic to heterotrophic means of nutrition takes place with the *Euglena*. Often, when developing in polluted waters, in which the organic matter is abundantly dissolved, the *Euglena* avail themselves of autotrophic as well as heterotrophic means of nutrition. If the *Euglena* that became colourless in the conditions of darkness were brought back to light, then within a very short period of time they would acquire their green colour again and would resume their autotrophic nutrition.

Thus, with the relatively primitive unicellular organisms the animal and vegetative types of metabolism are successfully correlated, which evidences the closest genetic link between the two kingdoms of the organic world of our planet.

According to their structure protozoans are excessively varied. Their preponderant number is of such small size that their investigation most necessarily presupposes the use of the microscope. Protozoans are divided into several classes among which we can distinguish the following: rhizopods (Rhizopoda), sporozoans (Sporozoa), and infusorians (Infusoria). The foraminiferas of the class of rhizopods have been found in the fossil state since the lower Cambrian period. Radiolarians represent spheroidal forms with a central capsule and thin radiant pseudopodia. The marine planktonic forms have preserved since the Precambrian period. In particular, in the black siliceous schists of the lower horizons of Adelaide series in Australia Radiolarians have been found which belong to the Spumellaria group; representatives of Nosellaria may also be present there.

The fossils that are close to protozoans are also found in West Africa, within the confines of the Nigerian shield, in the rocks of the so-called Birrimean series. In 1961 the French paleontologists R. Hovas and R. Gotcor found there fossil shells (Protozoa) the diameter of which was 35-800 μm and that had siliceous walls. The researchers suggested that they should be called Birrimarpoldia, since these fossils refer to the earliest of the known foraminifera in geological records (the radiological age of birrimium is estimated at 2 billion years).

In 1963 the Soviet paleontologist M.E. Silber described the forms of radiolarians of the Imandra (Varzuga) suite in the horizontal tuff breccias and lavas in the Kola peninsula.

Thus, all the data concerning the discovery of protozoans testify to their relatively early emergence as representatives of eukaryotes.

One of the landmarks in the development of living matter was the appearance of multicellular organisms. As far as the origin of multicellular organisms is concerned, hypotheses were advanced by such outstanding biologists as E. Hoeckel (1834-1919) and I.I. Mechnikov (1845-1916). The vast majority of researchers consider that the colonial character had been an essential stage in the organization of multicellular organisms. In principle, the colonial growth can easily emerge as a result of an incomplete asexual reproduction, when the cells have been divided but not separated. The colonies of this kind are often formed with colourless and green flagellates, infusorians, solaria, green, blue-green, and diatomaceous algae.

At first the cells entering into the composition of colony were the same. But later, in accordance with the functions they performed, their division began. There took place a differentiation into cells that take food, determine mobility and those that reproduce. Various facts from the field of the anatomy and morphology of protozoans that were analyzed by the Soviet zoologist S.S. Schulman serve as proof that a large number of groups of protozoans have a certain tendency towards the transition from unicellular to multicellular state.

One of the most probable hypotheses about the origin of multicellular state was put forward in 1935 by the prominent Soviet zoologist V.A. Dogel (1882-1955). In his opinion the multicellular state is the result of polymerization. It has been established that the organization level of living beings, the degree of differentiation and integration of their parts are most closely connected with their size. The smallest organisms are represented by viruses. Next in the order of complexity come primitive prokaryotes that are noticeably larger than viruses, but smaller than unicellular eukaryotes. Lastly, the multicellular eukaryotes surpass the unicellular organisms as far as their size is concerned. It then naturally follows that the first living beings in the history of biosphere were of small size, which could be explained by their imperfect organization.

According to S.S. Schulman, the progressive evolution of animals since the moment of the emergence of cellular organisms of the type of eukaryotes has been taking place in the following order: organisms of the oligomerous structure → organisms of polymerous structure → organisms of the oligomerous structure on a new basis. In this case the author has in mind the dialectical law of the negation, when the last stage is characterized by synthesis rather than by negation alone.

On the contemporary level of our knowledge it is possible to assume that in the initial stage of the existence of multicellular organisms the most promising ones could have been only the floating primitive animals, consisting of non-differentiated cells and actively getting food for themselves. At first the necessity of a rapid movement caused the differentiation of cells according to the means of nutrition and the metabolism and then all other progressive changes typical of the subkingdom of multicellular animals. By means of reproduction and variability, which were preserved with the multicellular organisms as something inherited from their ancestors, it is possible that the multicellular organisms themselves even enhanced their ability to take part in the further evolutionary transformations, which can at least be accounted for by the fact that the complication of organization had provided new possibilities for variability.

I.I. Mechnikov assumed that the most probable ancestors of multicellular organisms were the colourless flagellates. One of the substantial reasons that conditioned the emergence of the first multicellular organisms was an increase in the free oxygen content in the biosphere. The other highly important prerequisite was the emergence of eukaryotic cells.

The mass development of multicellular invertebrate animals is found in the Late Precambrian, in the Vendian. The singling out of the Vendian period was substantiated by Academician B.S. Sokolov. In different sections, considerably remote from each other, the fauna of numerous molluscs was found. This type of fauna was initially called Ediacarian after the region of the same name in Southern Australia. It was described in detail by M.F. Glaessner who had studied over 1400 specimens with the imprints and most of other remains and traces of animals. For the interval of 700-600 mln years ago numerous molluscs—marine invertebrates have been most reliably established. Among the finds of the Ediacarian system 70% are made up of coelenterates (Coelenterata). Three fourth of them are represented by other organisms in the form of medusae or isolated colonial organisms of the kind of floating contemporary siphonophores Velella. Typical animals of the Ediacarian fauna are given in Fig. 16. The coelenterates are represented by the colonial forms attached to the sea floor just as the present-day sea feathers. In addition to these animals the

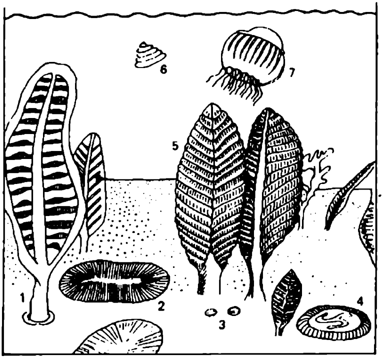


Fig. 16. A reconstruction of the Ediacarian fauna from the late Precambrian of Australia

The animals include (*1*) the sea-pen *Charniodiscus;* (*2*) the worm *Dickinsonia;* (*3*) the tiny arthropod *Praecambridium;* (*4*) the echinoderm *Tribrachidium;* (*5*) the sea-pen *Glaessnerina;* (*6*) the jelly-fishes *Cyclomedusa* and (*7*) *Brachina*. The animals lived in shallow water

composition of Ediacarian fauna included marine worms which had something in common with the modern Polychaeta, the creatures without a shell, and that resemble the arthropods, and the triradiate disc-like organisms of the type of starfish. On the surface of the floor all of them left traces and imprints of their bodies. Some of the organisms were fairly large. For instance, a jelly-fish was found, the diameter of which is 1 m, sea feathers were more than 1 m in length. The leaf-shaped marine worm Dickinsonia had the length of 1 m and was 3 mm wide.

The Vendian period of the Russian platform with its Siberian equivalent of the Yudom series chronologically coincides with the Ediacarian system of Southern Australia. Owing to the research conducted by B.S. Sokolov, it has been established that the Vendian deposits are characterized by a greater variety of fauna of organisms without skeletons than the Ediacarian system. The Vendian fauna of the USSR is represented by tens of species of pelagic and benthonic genera of cnidaria, annelids, arthropods, specific pterodinids, probably mollusks and pogonophores with the first traces of the chitinization of the tube. Among the remains of the Vendian fauna we find a number of cosmopolitan genera and species. The Vendian biological complex is more polymorphous than any of its predecessors.

The most substantial changes in the history of the development of the animal kingdom took place on the threshold of the Vendian and Cambrian periods. According to the apt expression of V.V. Menner and N.A. Schtreis, it is 'the greatest biostratigraphic boundary'.

10—0669

It was characterized by the fact that marine animals began to form hard parts of the body; covers, shells, and the inner skeleton. The early Cambrian fauna had already been drastically different from its Vendian counterpart. And indeed it should be pointed out that in the middle of the Vendian period almost all the invertebrates without skeletons referred to the Phanerozoic types and classes. As early as the Cambrian period separate sessile forms of benthos—Archaeocyathidae—were widely spread. It wasearly considered that Archaeocyathidae were only characteristic of the Cambrian period. However, the researchers began to doubt whether a clearly defined type of animals could have emerged, existed and become wholly extinct within the shortest possible interval of geological time, the more so that the sponges like the Archaeocyathidae and some of the coelenterates, which originated in the Precambrian period, lived far longer. Nowadays it has been also established that the Archaeocyathidae-like forms were lived in the late Precambrian period. They were found and described in the geological sections of Eurasia and Africa. For instance, in the Czech Precambrian period, in the rocks with an unclear stratigraphic position A.G. Vologdin discovered the remains of almost genuine Archaeocyanthidae with double-walled skeleton.

The formation of hard parts of the body with various groups of invertebrates took place in different periods. Thus, with some of the low-organized groups it began as far back as the middle of Vendian period, with others the same process occurred in the Cambrian period, while with higher-organized groups such as mollusks (Nautiloidea, gastropods, and the bivalved varieties), as well as corals—tetracorals, the said formation coincided with the Ordovician period.

The inorganic components of hard formations with contemporary organisms are predominantly represented by anhydrous calcium carbonate (calcite or aragonite), calcium phosphates (apatite) and the silica of various modifications. The organisms of the late Riphean and the beginning of Cambrian period synthesized apatites to a greater extent than the organisms of the younger geological eras. At first calcium carbonates, which were synthesized only by a small number of eukaryotes, had become ordinary products of biomineralization by the middle of the Cambrian period. Later, on the basis of biogenic calcium carbonates, there appeared vast biological communities of which coral reefs are the ones that are best known.

Silica was initially deposited only in the form of sponges. Later it began to be widely used by solaria, radiolarians, diatomaceous algae and some of the green plants.

The primary assimilation of calcium by the organisms was connected with their physiological functions, and only in the later periods it started to deposit phosphate and carbonate ions, dissolved in sea water, thus forming hard parts of the body. However, the factors underlying the structure of the hard parts of the body in organisms have not yet been made quite clear. The reasons of this process have not been discovered, which presumably had been of ecological character. The hard skeleton had to serve as the foundation of organism and promote the growth of its size. Moreover, the hard skeleton, for instance, in the case with marine sponges helped them to occupy a greater space and consequently absorb more food. With the other animals the skeleton increased their firmness serving as a solid construction. The shells of the previously soft-bodied animals protected them from physical injuries. They began to serve as a protective means from the carnivores which appeared later. As a result of the formation of skeletons in the Cambrian period there emerged new means of habitat in the region of marine shallow waters. The sponges acquired the possibility to filtrate bacteria, trilobites could dig themselves into the bottomset beds, and mollusks began to crawl along the surface of the sea floor. With the help of skeletons brachiopods, bryozoans, and echinoderms could rise vertically from the water, and keep themselves practically over its surface, which made it possible for them to more effectively filtrate water containing microorganisms and thus receive the necessary nutrition. Without the hard parts of the body this particular way of life would have been impossible, or at any rate much less productive. According to the American scientist G. Hutchinson the emergence of skeletons that were able to be fossilized at the beginning of the Phanerozoic period, mainly reflects the appearance of predacity. Until then the biosphere had on the whole been a peaceful realm, in which the protective shells were not required.

The phylogenetic bonds of a number of most important types of invertebrates according to the data provided by paleontology and comparative anatomy are given in Fig. 17. We can hardly doubt the tenability of the adequately substantiated statement concerning the origin of sponges and coelenterates from unicellular animals, lower worms—from coelenterates and nemertines—from lower worms. The origin of arthropods from annelids (marine annulids—polychaetes) also seems to have been quite probable.

There is much less information on the emergence of other groups of animals. Besides, what should be taken into account is that Figure 17 is based on the idea pertinent to the monophyletic origin of animals, which can be regarded as wholly acceptable for the evolution of relatively young taxonomical units. However, the polyphyletic origin of species is quite possible for the ancient forms the roots of which go back into the Precambrian period.

In what follows we have a brief account of the development of the main types of invertebrates in the Phanerozoic period.

The sponges (Porifera or Spongia) are predominantly marine animals that live within the confines of the shelf. All the sponges (sessile

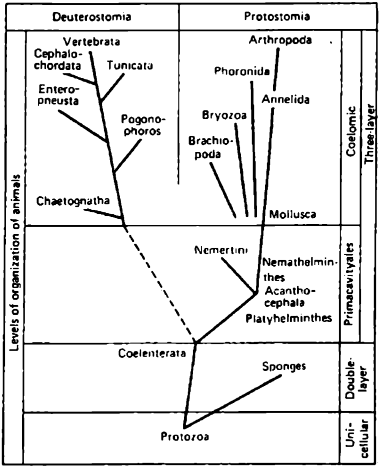


Fig. 17. The scheme of family tree of the invertebrates

benthonic organisms) represent the primitive type of mammals. Their tissues, designed for particular functions, are differentiated more poorly than those of the other multicellular animals. The sponges can be of cubical, spherical, and arbitrary form with tiny pores through which water penetrates with nutritious substances. No minor importance for the systematization of sponges is attributed to the forms of spikes of their skeletons, which are called spicules. According to the morphology of sponges we can assume that they had originated from Choanoflagellata and flagellates. The reproduction of sponges is characterized by sexual as well as asexual means.

The origin of sponges goes back to the late Precambrian period. A.G. Vologdin and N.A. Drozdova described the spicules of sponges from the Gonam suite in Siberia, the age of which is 1500 mln years.

In the Cambrian seas there already existed a fairly rich fauna of sponges, which was represented by practically all the classes and orders that have survived until now. The extinct orders of light-rayed and other orders of sponges are found in the Paleozoic deposits. The sponges had reached the peak of their development in the Jurassic and Cretaceous periods. Some of the genera and species of cretaceous sponges have survived until the present day. The first fresh-water sponges must have appeared in the Cretaceous period.

The coelenterates (Coelenterata) refer to Radiata, which are characterized by a radial and axial symmetry. The coelenterates are the lowest organized multicellular animals among the Radiata. They live predominantly in an aqueous medium and considerably less often in fresh-water basins. The group of coelenterates which is attached to the floor is referred to the polyps; the shellfishes that float freely belong to jellyfish.

Polyps have a cylindrical or ampullaceous form. Jellyfishes look very much like a bell or an umbrella. They swim with their mouth down. They can be of different size. The largest of them (Cyanea arctica) have an umbrella with the diameter of up to 2 m. Their tentacles extend to about 30 m. The body of coelenterate organism most often represents little sack the walls of which consist of an outer layer, or an exoderm, and the inner one, or endoderm. Inside the sack-like body there is the digestive cavity with the only aperture that is called the mouth. This cavity functions for the consumption of food as well as the evacuation of waste matter. The coelenterates have a simple digestive system. The undigested food in the form of the remains of microplankton and various slag formations are expelled from the mouth. The animals do not have any blood system. The nervous system consists of individual nerve cells that form an irregular network. A large number of attached coelenterates have an inner or outer skeleton, which is either organic or mineral—calcareous.

Most of the coelenterates are dioecious organisms. But alongside sexual reproduction they are also copiously characterized by the asexual means, which usually finds its expression in gemmation. Sometimes in different stages of its life circle one and the same type of coelenterates has now the structure of a polyp and now of a jellyfish. In accordance with the characteristic features of their structure coelenterates are divided into three classes.

Nowadays coral polyps form the most highly-organized group. They are exclusively represented by marine single and colonial forms, which lead an attached way of life. They have no succession of generations and the medusal stage of development. The genuine corals (*Anthozoa*—living flowers) fall into three subclasses: alcyonarias (alcyonarian coral polyps), tabulate corals, and zoontarias.

The coelenterates must have originated from the free-swimming multicellular organisms, which had already possessed a cellular organization. When these organisms began to lead a sessile way of life, there appeared coelenterate hydroid polyps, which later gave rise to free-swimming jellyfish and coral polyps.

The first finds of coelenterates were made in the sections of the upper Precambrian. The oldest of them is the imprint of a large jellyfish with the diameter of 18 cm, which was discovered in the sand level of the Nankoweap series of the Grand Canyon (the State of Arizona, USA). The imprint was preserved on the surface of a thin-layered and fine-grained clayoy sandstone cemented by silica. In the opinion of the American geologists, the Grand Canyon series is correlated with the Belt series, the age of which is within the limits of 1400-1000 mln years.

The coelenterates are the most ancient of the genuine multicellular animals. Many of them (70 %) were found in the Ediacarian deposits of South Australia (see Fig. 16). In the deposits of the Cambrian system jellyfish and tabulate corals, or tabulates were discovered. The Ordovician period was characterized by the origin of more complicated forms—chaetitides and tetracorals (Rugosa). At the end of the Permian period there occurred a mass extinction of these ancient corals. Scleractinia and eight-rayed corals (octocorals) appeared at the beginning of the Mesozoic period. These two groups of coral polyps are extant now too.

The worms (Vermes). At one time they were classified as various bilateral and symmetrical animals with the mouth at one end and the anal opening at the other. Nowadays it has been established that a vast group of worms under the general name of Vermes is divided into three types. Among them we can mention the type of flatworms (Plathelminthes), round worms (Nemathelminthes), nemertines (Nemertini), and annelids (Annelida). Since most of the worms are deprived of hard parts of the body they are poorly preserved in fossil state. Only in very rare cases worms reach us in the form of petrified bodies or leave traces of creeping in the fine-grained rocks.

The most ancient worms were found in the deposits of Ediacar (Vendian period). By their structure the annelids approach the type of arthropods. The ancient annelids were probably the ancestors of arthropods.

The arthropods (Arthropoda). The origin of arthropods may well be referred to the beginning of the late Precambrian period, though the Phanerozoic period was characterized by the formation of innumerable variety of forms that superseded the number of species of all other types of the animal kingdom. Insects and vertebrates are the two kinds of animals the domination of which has been established on land by now. The number of insects in the composition of sea and fresh-water fauna is infinitesimal. They have accommodated themselves for the second time to the aqueous element that is alien to them. As was pointed out by V.I. Vernadsky, if we compare the mass of people with that of insects, the latter will presumably be preponderant among the forms of terrestrial life. This brings us to the conclusion that the insects are the original inhabitants on land and their evolution was taking place on the surface of continents in an ordinary nitrogen-oxygenous atmosphere.

Since, but with few exceptions, all types of insects live on land it is quite natural to assume that in the first place the formation of such an enormous number of species called for a fairly long geological time, covering the Precambrian period; secondly, that insects were the first animals, which inhabited the land. Hence, in the Precambrian period (probably in the middle of it) there was already a favourable environment for it. The main factor, however, was the presence of free oxygen that was necessary for breathing. As far as nutrition is concerned we can do no more than merely suppose. For instance, we can assume that in the littoral parts of the sea basins there dwelt the algae that from time to time found themselves on land and thus provided food for the terrestrial insects and their ancestors. Until now no traces of insects in fossil state in the Precambrian deposits have been found. However, this fact can hardly be regarded as substantial since fossilized insects are generally found much more seldom than the other representatives of the same groups of aqueous arthropods. This is made abundantly clear by the presence of an exceptionally delicate chitinous cover, brittleness of their bodies and the way of life of most of the insects. Even in the Phanerozoic period fossilized insects are found in very rare cases. The primary wingless insects (of the order of Collembola) were first found in the deposits of the upper Devonian period. But the insects from the deposits of Carboniferous system were highly varied and required properly developed wings and the dimensions that were the largest in the history of the world of insects. These data undoubtedly prove that the most ancient insects had appeared much earlier.

In geological sections we also know the remains of some other classes of arthropods. The ancient representatives of arthropods included trilobites, xiphosurans, scorpions, and merostomes. The last reached the greatest length of up to 1 m in the Silurian seas. The most ancient scorpions were found in the deposits of the Silurian system.

The **mollusks** (Mollusca) are soft-bodied animals, representing an isolated group of invertebrates, which in the Phanerozoic period gave rise to an enormous number of forms that were superseded only by the arthropods. The body of mollusks consists of the head, unsegmented middle part of the body and foot. All mollusks refer to the symmetrically secondary-branded animals. Most of them are characterized by a hard mineral shell, often covering the whole body of the animal. Though at present it is customary to single out from 8 to 10 classes of mollusks, the greatest significance in geological history was attributed to only three of them, viz. the cephalopods (Cephalopoda), the gastropods (Gastropoda), and the bivalved (Bivalvia). All of them played a highly important role in establishing the stratification of Phanerozoic period. Most of the mollusks are aqueous animals and only some of the representatives of the class of gastropods came out on to land and acquired the lungs. The isolation of mollusks from other primitive organisms in the process of evolution must have taken place as early as the Precambrian period.

The cephalopods, which began to spread widely in the early Ordovician period, led a nomadic way of life and fed on living and dead small organisms. Later some of them, having become carnivorous, thus came to be the first predators in the history of animal kingdom. Presumably, in the early Paleozoic period there existed cephalopods with no skeletons, and which had something in common with the present-day octopuses and squids. The cephalopods were the first animals that could swim freely in the open water bodies at various depths. Their number considerably increased in the seas of the Ordovician period. The length of some of these animals was 10 m. Within the whole period of their existence the cephalopods lived in the water that was constantly saline. The fossil cephalopods produced an exclusively large number of various forms. However, at present only few of their types have preserved. They include octopuses, squids, cuttlefish, and some rare nautiloids. The Phanerozoic period was particularly characterized by the propagation of nautiloids, ammonites, and belemnites.

Some of the cephalopods emerged in the early Cambrian period. As early as the Ordovician period the nautiloids had already dwelt predominantly on the sea floor and in the shallow-water parts of the neritic zone. The first forms of nautiloids had a markedly flattened shell and must have crept along the sea floor. In the course of the whole Ordovician period the fauna of nautiloids consisted chiefly of the forms with a straight shell. At the same time the spiral-like shell comprised approximately 15% of all the cephalopods. However, later the relationships were most drastically changed. In the Devonian period together with the straight and slightly curved forms there existed many spirally rolled ones. Then, in the late Paleozoic period the nautiloids with a straight shell became considerably less in number, while those with a spiral shell gained more ground. The spiral shell was much more compact and less cumbersome than the straight one and proved to be more convenient for the free movement of the animal. Nautiloids with a spirally twisted shell were characterized by a rapid evolution, and accommodated themselves to active swimming. But they swam relatively little, and not high above the sea floor, upon which they could descend from any position. Various and rich in their forms early Paleozoic nautiloids began to gradually degenerate in the Devonian period, and with the beginning of the early Carboniferous period their extinction was already in its initial stage.

In the Silurian period the spirally rounded nautiloids gave rise to ammonites, and in the Devonian period their cognate forms—goniatites—had already comprised a large group of sea organisms. They were more mobile than their ancestors, the nautiloids. During the Devonian, Carboniferous, Permian and the whole of Mesozoic periods various groups of ammonites underwent evolution. Their domination continued until the late Cretaceous period and ended with the formation of gigantic forms discovered in the upper Cretaceous deposits. Thus, one of the upper Cretaceous ammonites in Westphalia (FRG) reached 2.5 m in diameter. Ammonites had existed from the beginning of the Devonian to the end of Cretaceous periods over which period about 1500 types succeeded each other.

In the Paleogene there occurred a rapid extinction of belemnites. What brought it about has not yet been made quite clear. According to the most widespread opinion the mass extinction of large groups of cephalopods was connected with the appearance of new active and highly organized opponents in the seas. They could have been the bony fishes, which had abundantly increased in the middle of the Cretaceous period as well as such water mammals as the cetaceans, which took the place of the sea reptiles of the Mesozoic period. With the emergence of these predators not only the ammonites, but also the belemnites had disappeared. The two groups of cephalopods, which were mobile in the conditions of the Mesozoic seas, found themselves awkward and clumsy as compared with the new predators. That is why in the struggle for existence only the strongest and the most agile cephalopods—the type of octopuses and squids with the markedly reduced calcareous skeleton have survived.

The changes in the structure of the shells of ammonites, which originated in the final stages of their history, make it possible to assume that at that time they had to struggle against more mobile predators that could fracture the shells. This war ended with the defeat of ammonites.

However, the mass extinction of ammonites at the end of the Mesozoic era could have been caused by other factors too. Some researchers think that the suppression of ammonites by bony fishes could not have been the main reason of their extinction since ammonites served as food for numerous predatory sea reptiles, including gigantic mososaurs, ichthyosaurs, plesiosaurs, and marine crocodiles. Nevertheless under these conditions the slow-moving nautiloids survived, while ammonites perished. In the opinion of the Soviet scientist K. Nesis the disappearance of the vast majority of calcareous planktonic organisms was the most prominent event in the Mesozoic era. This also resulted in the extinction of heterotrophic ammonites upon which they nourished.

Thus, the general factor conditioning the extinction of ammonites was the competitive struggle against the bony fishes, while what actually brought it about was an unexpected degeneration of calcareous plankton—foraminifers and coccolithophorids. But what lay behind the sudden disappearance of calcareous plankton has not yet been made quite clear.

The other classes of mollusks—gastropods and bivalves—have survived until now and have yielded a great variety of living forms including those that dwell in fresh waters. The most widespread class had proved to be the gastropods with a large amount of even now existing species. The representatives of the class of Gastropoda mollusks live in seas, in brackish and fresh-water basins, in rivers and lakes, while a certain group of them came out onto the land and accommodated to a new way of life. A large number of fossil Gastropoda mollusks were found in the deposits of the Phanerozoic period, though they had reached the highest degree of abundance and variety in the Cenozoic period.

The Echinoderms (Echinodermata).. This type covers the invertebrates which have a radial pentaclinal or less often bilateral (with some of the early Paleozoic groups) symmetry of their soft body. They are characterized by an inner calcareous skeleton built of plates that bear spicules, which gave this type the name of echinoderms. What is typical of them is the ambulacral, or water-vascular system that provides them with water, oxygen, and food. All the echinoderms are inhabitants of the seas, the salinity of which is either normal or nearly so. They are reproduced by sexual means. The echinoderms are divided into two subtypes: Pelmatozoa and Eleuterozoa.

The Pelmatozoa comprise all the groups of sedentary echinoderms of the benthos. They can also be represented by the non-sedentary forms though they are still derived from the sedentary echinoderms—only the sea lilies (crinoids) have preserved in the sea fauna. In the geological past there existed some other classes of echinoderms which led a sedentary way of life. They included cystoids (Cystoidea), thecoids (Thecoidea), Carpoidea, and blastoids (Blastoidea).

In the evolution of the echinoderms the sedentary forms were the first ones to appear. A fairly large number of the representatives of echinoderms were found in the deposits of the Ordovician period. Thecoids have been discovered from the lower Cambrian to the lower Carboniferous periods. Blastoids are known to have existed from the Ordovician up to the Permian period inclusively, and in their development yielded forms that passed from the sedentary way of life to the free, benthonic one. The sea lilies have the most varied forms. There is some reason to believe that they might have originated from the cystoideans in the Cambrian and even in the Precambrian time.

The Ordovician period revealed the remains of echinoderms, which according to their anatomical structure do not lend themselves to be attributed to any of the well-known and generally recognized classes. The sedentary forms of echinoderms dwelt at different depths of the sea floor—from 20 to 5300 m. The greater number of sea lilies at present live at the depths of 4-5 000 m, and only some of them are found in shallow seas. In the Paleozoic and Mesozoic periods the sea lilies found their habitat in the shallow-water littoral regions of the sea, with some of them acquiring the free way of life. In different epochs there appeared the non-sedentary forms. They are discovered in the Ordovician, Devonian, Carboniferous periods and in the deposits of the Cretaceous system. However, the non-sedentary forms remained benthonic animals. The factors conditioning the development of free forms are connected with the fact that in particular conditions the ability to move provides the organism with substantial advantages over the forms that stay at one place, or there where the animal in the state of larva acquired its initial sedentary position.

The subtype of non-sedentary echinoderms is further subdivided into three classes: sea-urchins (Echinoidea), starfishes (Asterozoa), and holothuria or sea cucumbers (Holothurioidea). As distinct from the sedentary variety, the free-living non-sedentary (detached) echinoderms comprise the greater part of the present-day sea fauna. The origin of the detached forms of echinoderms goes back to the early Paleozoic period. In the Paleozoic period itself the mobile echinoderms gave rise to a great number of various forms of ancient urchins, which became extinct at the end of the Paleozoic period. All the free-floating echinoderms are to a great extent predators, as well as the devourers of the corpses of various organisms.

Until now it has been established that this type of echinoderms refers to the most highly organized group of invertebrates—the deuterosmatous organisms. At first they were predominantly bisymmetrical, mainly sedentary animals. Later, their free-swimming detached forms were singled out.

Among the mobile forms those that are the closest to each other are starfishes and ophiuroids. The former have been known since the Cambrian period, while the origin of the latter may well be associated with the Silurian period. It is assumed that they were derived from the early Cambrian primitive Edrioasteroids (ancient starfishes). Most probably the sea urchins had genetic ties with the latter. However, the zoologists associate the most ancient urchins with cystoideans, while the others are referred to edrioasteroids. Among the now existing urchins the order of the elastic ones, the greater number of whose forms has become extinct, are regarded as the primitive variety.

In the process of the development of animal kingdom under conditions of general progressive movement there exist ramifications of certain groups, the evolution of which seems to stop for tens, or even hundreds of millions of years. Some aspects of the persistence of plants and microorganisms have already been discussed. The invertebrates that may be referred to the so-called persistent forms are presented in Fig. 18.

The brachiopod Lingula is usually adduced as a classic example. It emerged in the Ordovician period and existed throughout the whole

Phanerozoic period without undergoing any changes. Exactly the same life-span was shared by the bivalved mollusks Pilina and Nucula.

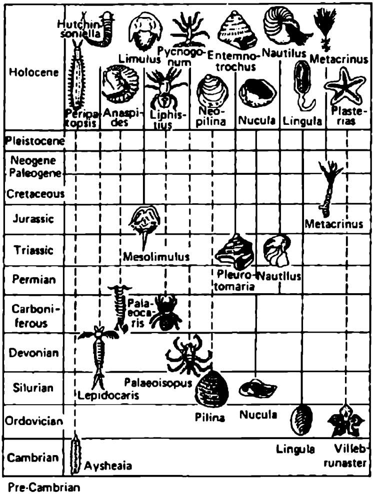


Fig. 18. Persistence forms of the invertebrates

From the cephalopods the living fossil is Nautilus—'the pearly little vessel'. The representatives of this genus—the tetrabranchiates with the shell divided into chambers. It protects the soft parts of the animal's body, and owing to the presence of air chambers regulates the subaqueous floatation. The now existing Nautilus lives mostly in the calm waters at the depths from 40 to 700 m in the southwestern part of the Pacific Ocean. The predecessors of nautilus existed from the early Paleozoic and the Mesozoic periods inclusive. The conservative animals include the xiphosurans (Limulus) which have much in common with scorpions and spiders.

THE DEVELOPMENT OF VERTEBRATES

The term 'vertebrates' (Vertebrata) was introduced into science by the eminent French naturalist Jean Baptiste Lamarck. The vertebrates, as a subtype of animals, appeared in the biosphere later than all others. Their evolution, beginning with the first primitive ancestors and ending with the primates and Man, covered the Phanerozoic period. This is the most highly organized, comprehensive and varied group of animals of the class of chordates (Chordata). With the representatives of this type the axial skeleton is the chord—an elastic rod extending from the tail part of the animal's body to its head. In the embryonic state the chord is characteristic of all the vertebrates, while with the adult animals it is replaced by the alternation of chondral or bony vertebrae. The central nervous system consists of the brain and spinal marrow. The brain has a highly complicated structure and is situated in the cranium (osseous or cartilaginous), which is shared by absolutely all the vertebrates. Most of these animals have two pairs of limbs, which, depending on the habitat and the character of movement, change their forms (fins, flippers, feet, and wings).

The vertebrates are classified into fishes (Pisces), amphibians (Amphibia), reptiles (Reptilia), birds (Aves), and mammals (Mammalia).

The origin of vertebrates has been studied more fully than that of other animals. According to the data provided by paleontology, comparative anatomy, and embryology, the evolution of lowest vertebrates initially took place in water and resulted in the emergence of the most varied cyclostomes and fishes, which had accommodated themselves to the conditions of their habitat. Most probably the first fishes came from the small soft-bodied chordates, which had the chord and gills and which lived at the expense of the filtration of particles from sea water. The marked stage in the evolution of vertebrates was their coming out onto the land. The ancestors of land vertebrates were crossopterygians, while the most ancient representatives of land animals were the amphibians (Fig. 19).

Fishes refer to the most primitive vertebrates. The agnathous (Agnatha) of the fish-shaped are singled out into an independent super-

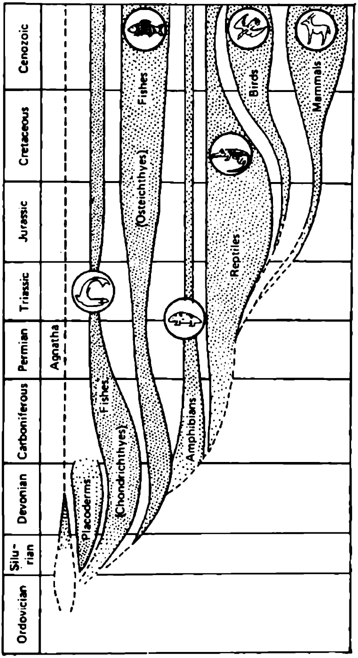


Fig. 19. Family tree of the vertebrates

The thickness of branches indicate the abundance or the small number of the corresponding groups class. The greater part of them included cyclostomes (Cyclostomata), which do not have jaws. Nowadays they are represented by lampreys and hagfishes, which lead a parasitic way of life. In the fossil state the cyclostomes have been known since the early Ordovician period. They were of small size, and in the foremost part of their body there was a large flat head shield, consisting of several osseous plates. They had eyes on either side, which was connected with the benthonic way of life of these animals, when they found food on the sea floor. In the process of their development from the late Silurian to the early Devonian periods the agnathous yielded a great variety of forms and got quite used to the new conditions of life. Some of their species acquired the forms that were convenient for swimming in the open sea. They nourished by means of drawing in the sediments with their tube-like mouth, as well as by swallowing the floating plankton from the surface. Some jawless ichthyoids looked like the present-day sommas that live in the fresh water basins. The fossil remains of cyclostomes evidence that they accommodated themselves to the life in fresh water long time ago. In the early Devonian period the jawless vertebrates led a varied way of life, but they had to feed on very small organisms of plankton, or the fine deposits of sea floor. It is paradoxical that the highest level in the development of primitive cyclostomes in the Devonian period coincided with the growth of fish with articulate-like jaws. At the end of the Devonian period they ousted the cyclostomes, which did not have any osseous skeleton.

Fishes proper (Pisces) have either an osseous or cartilaginous skeleton. Sharks and sturgeons have retained the unsegmented chord. The number of vertebrae with different fishes is markedly diverse—from 16 (moonfish) to 400 (the New Zealand belt-fish). Most fishes are characterized by an elongated fusiform. The skull of the teleost consists of a large number of bones; the brain is properly developed, particularly in the case of dipnoans. The size of fishes varies within the wide range—from the small chub, 1 cm long, and living on the Philippine Islands, to the gigantic whale shark, which can be as long as 15 m. The fishes are subdivided into three classes: placoderms (Placodermi), cartilaginous fishes (Chondrichthyes) and bony fishes (Osteichthyes).

The first class is represented only by the fossil Paleozoic forms; the second class unites not only a large number of Paleozoic forms, but also the sharks and batoids that we can find to be existant; the third class covers the most progressive group which was singled out as far back as the Paleozoic period, but has reached a great variety in the present epoch.

The placoderms bring together the most primitive forms of gnathic, or real, fishes. Their body was covered with plates forming a specific armour, which outwardly had much in common with the analogous armour of the cyclostome ostracodermal forms. That was why earlier a certain part of cyclostomes and some of the gnathic forms were brought into one group under the name of 'Placodermi'. Their typical representative was Coccosteus, the length of which was about 50 cm. As far as the general shape of the body was concerned, it was an ordinary fish, though its lower part was flat, which is characteristic of benthonic forms. It had a rather long tapering tail at the end.

Another representative of placoderms is dinichthys. It had a powerful gnathic system with sharp protrusions and edges, which indicated its predatory character. The most important part in the development of placoderms coincided with the Devonian time of Paleozoic period. In the past there existed two groups of placoderms: the arthrodira and the antiarcha. The earliest arthrodira were small, somewhat flattened fishes with weak jaws. In the course of the Devonian period they rapidly developed into swimming predators of a fairly large size. During the evolution the shell was becoming relatively shorter and the greater part of the body could participate in the movement. The gnathic mechanism was also being perfected.

The antiarcha were covered with a much wider shell that covered almost all the surface of their bodies. Their form was somewhat flat. The eyes were small and were situated in the upper part of the head shield. However, the antiarcha had strong-limbed fins, that looked like hands, adapted to the movement along the sea floor. One of the characteristic features of antiarcha was that they had lungs, which enabled them to breathe.

Placoderms do not reveal any genetic ties with any of the groups of contemporary fishes. They became extinct at the end of the Devonian period, thus giving place to more perfect fishes.

Cartilaginous fishes comprise the now existing sharks and batoids. They have the skeleton of primitive structure consisting of vertebrae. The earliest of species had a set of developed outer protective formations, which disappeared with the later forms. The cartilaginous fishes are a fairly ancient group. The first of them appeared in the Silurian period. In the later years their number grew, and at the beginning of the Carboniferous period their numerous forms developed. However, at the end of the Paleozoic period the number of forms was markedly reduced, and nowadays the cartilaginous fishes already account for an inconsiderable part of the whole fauna of fishes in the natural water bodies. Batoids have proved to be a more current branch of sharks.

Bony fishes originated in the early Devonian period and initially dwelt in fresh-water bodies. At the end of the Paleozoic period they became the dominating group of fresh-water vertebrates and inhabited the seas. The gene-

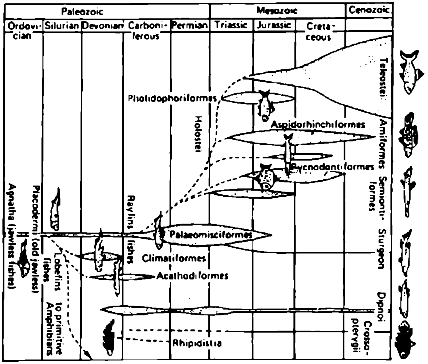


Fig. 20. Evolution of fishes began in the Cambrian period with the appearance of jawless species that had evolved from a pair of gill slits, and fins became paired. One major line of jawed fishes, the ray fins, was ancestral to most of the fish species now living. The other line, the lobe fins did not lead eventually to the earliest amphibians, the ancestors of all form-footed vertebrates. In largely part the ability of the early amphibians to venture onto the land was due to the evolution of multicellular plants that sustained them, giving rise later to animals that lived entirely on land (according to Valentine, 1978)

alogy and geochronology of bony fishes are given in Fig. 20. In the fauna of contemporary water bodies most fishes can be referred to the class of bony ones. They are classified into three subclasses: actinopterygians, or the ray-finned fish, dipnoans, and crossopterygians. They have all been discovered in fossil state at the beginning of the Devonian period, and probably originated from the acanthodians. Most of the contemporary bony fishes have a swimming bladder that regulates the depth of swimming. The dipnoans dwelt in fresh waters and, judging by the structure of their body, had always been slow swimmers. They adapted themselves to the life in periodically desiccating rivers and shallow-water lakes. The lungs helped them to survive in the arid season and then to gain more strength during the period of rains, when it was possible to breathe in water with the help of gills. In this connection the dipnoans had survived in conditions that were intolerable for other fishes. In the present epoch there exist only three types of dipnoans, that live in the rivers of South Africa, Australia, and South America.

The crossopterygians had adapted themselves to the active way of life, and occupied the large rivers and lakes long time ago. They represent the most numerous group that is dominating in the seas even now. Some of them (Rhipidistia), which lived in fresh waters, gave rise to the amphibians in the late Devonian period. Under these conditions the amphibians were better adapted predators than their ancestors, which were ousted by them from their habitats. In the Carboniferous and Permian periods Rhipidistia, that had preserved, increased in size and could live in large-sized rivers and lakes.

Nowadays the amphibians constitute the smallest class of vertebrates. They hold a special place among the other vertebrates since they are the first most simply organized quadrupeds inhabiting the land.

The amphibians breathe with their lungs; they have two cycles of blood circulation, a three-chamber heart, and venous as well as arterial blood. Their body temperature depends on that of the environment which restricts the possibility of their movement, orientation, and propagation on land. The amphibians can depart far from the natural water bodies. However, in the process of reproduction they became inseparably connected with water. The eggs of amphibians as land animals do not have any shells protecting them from desiccation and cannot actually exist outside the water medium. In connection with the aqueous means of parturition and habitat the amphibians develop a larva that lives in water. Later the larva undergoes the process of evolution through a number of transitory forms (ichthyoids, tadpoles, etc.) and become transformed into an animal living on land. At present the amphibians are represented by three orders: the urodelans, apodes, and anurans.

Coming out onto the land in the process of evolution, the animals radically altered the structure of their body and the most predominant organs. The sea water that gave life to vertebrates contained a large quantity of various dissolved nutritive substances, which were not present in atmospheric conditions. The first living organisms that found themselves on land were confronted with problems connected with the means of providing food for themselves. Since upon many of the geographical latitudes the air was insufficiently humid, the life in conditions of land and air was replete with numerous hazards, particularly for reproduction inasmuch as the reproductive cells are especially susceptible to desiccation.

The relationship of free oxygen and carbon dioxide in the atmospheric air is different from what it is in sea water. For this reason land animals require mechanisms regulating the breathing process. The refraction of light beams in air medium is lower than in the aqueous surroundings, which, in its turn, influenced the structure of eyes. The different rate at which the sound propagates in water and air brought about changes of the hearing apparatus with the animals. Lastly, there occurred marked alterations in the gravitational conditions under which the organisms existed. In the air the organisms have a greater weight than in water. Consequently, the exit of organisms from water to land called for an improved physical support, which could not but exert its impact on the development and stability of skeleton. Thus, the transition of vertebrates to the land and its conquest are connected with a number of changes of their body for the adaptation to quite new conditions.

The first representatives of amphibians had strong bones and their bodies, which were of moderate size, were covered with scales. Presumably, their skin practically did not take part in the breathing process. Instead of it rapid breathing was performed by the lungs, which had changed their volume with the increase of the chest. The amphibians had a long and powerful tail, which was crowned with a fin and four limbs that were situated on either side of the body. There is some reason to believe that both the body and the tail functioned most actively in swimming, in addition to which the limbs themselves also participated, though to a lesser extent. The ancient amphibians spent much time in water. In the aqueous medium the primary amphibians with their sharp teeth, and eyes situated in the upper part of their head, as well as the streamline form of the body, resembled small crocodiles.

According to paleontological data, the amphibians emerged in the early Devonian period. The genealogy of amphibians on the scale of geological time is presented in Fig. 21. The ancestors of amphibians were the crossopterygians, which had lungs and paired fins that could give rise to pentadactyle limbs. This conclusion is substantiated by a remarkable similarity between the bones that covered the skull of crossopterygians and the skull bones of Paleozoic amphibians. The amphibians and crossopterygians had upper as

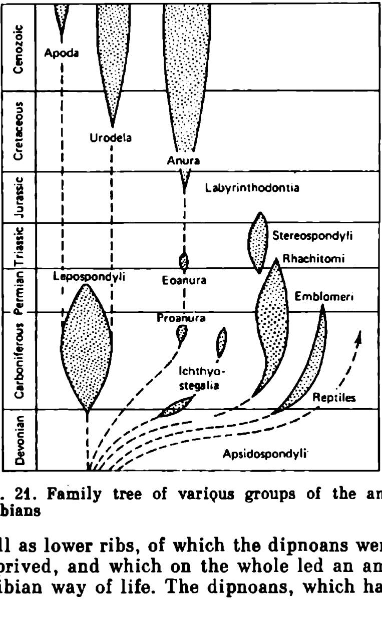


Fig. 21. Family tree of various groups of the amphibians

well as lower ribs, of which the dipnoans were deprived, and which on the whole led an amphibian way of life. The dipnoans, which had lungs, were in many respects different from the amphibians, and hence could not have been their direct ancestors.

In the Devonian period there took place a crustal uplift, and vast parts of land were covered with vegetation. The amphibians reached the peak of their variety and multitude in the Carboniferous and Permian periods when a humid and warm climate reigned over the great expanses of the Earth.

The fossil Paleozoic amphibians predominantly refer to the groups of stegocephalians. An important characteristic feature of these animals was their strong shell of skin bones, which covered the whole skull. On the whole, the stegocephalians differed from the present-day amphibians in a number of primitive features that had been inherited from the crossopterygians. In particular, those features included the osseous shell. The pelvis had not yet been connected with the vertebra, and the shoulder girdle retained its bond with the skull. The front limbs were provided with five fingers.

What crowned the development of ancient amphibians was the end of the Paleozoic era, when stegocephalians reached a large number and variety and did not yet have any enemies among the more highly organized land vertebrates. The data furnished by the paleontology and anatomy of amphibians made it possible to divide them into two subclasses: Apsidospondyli and Lepospondyli.

The first subclass covers the super-order of labyrinthodonts and the super-order of saltatorians (Salientia), which includes various contemporary amphibians.

The labyrinthodonts were found exclusively in fossil state and represented the stegocephalians, which had a 'labyrinthodontal' type of teeth, which they had inherited from their ancestors—the crossopterygians. In their cross-section the teeth reveal an unusually complicated pattern of ramified enamel loops that on the whole provide the picture of a labyrinth. The group of labyrinthodonts included almost all the large amphibians of the Carboniferous, Permian, and Triassic periods. During the time of their existence the amphibians underwent substantial changes. The earlier forms were of moderate size and had a fish-like form of their body; later, they gained in weight, and their body became shorter, thicker, and ended with a little thick tail. The largest representatives of these animals were the mastodonsauruses that lived in the Triassic period. Their skull reached 1 m in length. Outwardly they resembled gigantic frogs. Their main food was fish. The mastodonsauruses were predominantly aqueous animals, that seldom left the water in which they lived.

The second subclass, Lepospondyli, covers three orders of Stegocephalians of the Carboniferous period. It was represented by small amphibians that were well adapted to the life in aqueous medium. A large number of them had for the second time lost their limbs and were transformed into serpent-like forms. It is assumed that from this subclass of amphibians there further emerged the contemporary orders of urodelans and apodals.

The Triassic period was characterized by the coeval existence of large amphibians and primitive reptiles. The struggle for existence between them ended in the victory of the reptiles, which in the Mesozoic period occupied all the regions of habitat on the surface of our planet: the air, land and water.

In their biological organization the reptiles had the most obvious advantage over the amphibians. They were considerably better adapted to the life on land. Essentially, in the history of the development of vertebrates they were the first animals on land that had an oviparous means of reproduction. They breathed only with the lungs, and their skin was covered with scales or scutellum. The development of even those reptiles that live in water is not connected with the aqueous medium. The fibrous and conchoidal shell of their eggs most markedly prevents them from desiccation. As compared with the amphibians the reptiles have a more perfect system of blood circulation. What took place was the further division of the arterial and venous blood flows. Most of the reptiles have a three-chamber heart, though ventricle is divided by an incomplete wall into two halves: the right one for the venous blood and the left part for the arterial blood. In spite of the progressive development of the covers, the organs regulating the circulation of blood and breathing, the reptiles had on the whole not been able to provide for themselves the warm-bloodness of the organism and the temperature of their body, as with the amphibians, depends on the temperature of the environment. Those reptiles that are extant are classified according to the four groups: the squamose, turtles, crocodiles, and rhynchocephalians. Their food is highly varied. Among them we can find insectivores, ichthyophagous, carnivores, herbivorous. In the history of the animal world reptiles have traversed a long path of development. The first finds of reptiles are known in the Carboniferous deposits. They refer to the order of cotylosaurs from the subclass of anapsids. After they have appeared in the Carboniferous period they developed considerably in the Permian time. Cotylosaurs were massive animals that moved on thick pentadactyle limbs. Their size fluctuated from several tens of centimetres to some metres.

The genealogy of various groups of reptiles is given in Fig. 22. The most primitive form of all the fossil reptiles was the Seymouria— a small animal (from 0.5 m in length), which had preserved a number of features pertinent to amphibians. It practically had no neck, and its teeth had a primitive structure, while the bones of the skull were similar to the skull

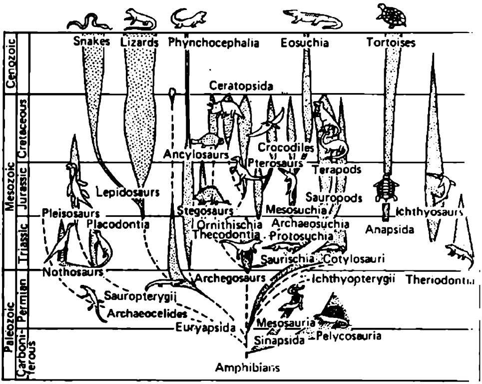


Fig. 22. Reptiles evolved from a primitive amphibian stock, which became free from ties to the water by evolving an egg that could develop in a terrestrial setting. Diversifying rapidly, the reptiles eventually came to dominate life on the land. The pelycosaurs and the therapsids belonged to two most successful reptile groups, the therapsids gradually becoming the more diversified. In the Triassic period the dinosaurs evolved in the reptile group and began their 150 million years' dominance of the terrestrial environment. In this chart and in the other accompanying charts, tracing the evolution of animal and plant groups, the width of a line or a band indicates relative size of that group in the corresponding geological period

cover of stegocephalians in great detail. A thorough study of this kind of reptiles and their remains found on the territory of the USSR made it possible to single out the batrachosaurs which held an intermediate position between the amphibians and the cotylosaurs. According to the available paleontological data as well as those of comparative anatomy it is possible to infer that cotylosaurs were a group, which gave rise to all other basic groups of reptiles.

The cotylosaurs were responsible for the origin of the more mobile forms of reptiles. In addition to this their limbs were becoming longer, and the skeleton grew ever more light. The reduction of skull shell went along two basic ways: at first one temporal fossa was formed, which was delimited from below by a zygomatic arch, then there appeared two temporal fossae and two corresponding zygomatic arches. Given these features of the skull all reptiles can be divided into three groups: (1) anapsids—with an intact skull shell (cotylosaurs and turtles); (2) synapsids—with one zygomatic arch (therapsids, plesiosaurs and, presumably, ichthyosaurs); (3) diapsids—with two arches. They include all other reptiles. The last group is the most numerous one and is further divided into subclasses and a host of orders.

According to the structure of the skull the group of anapsids had particularly much in common with the stegocephalians. Out of this most ancient branch of reptiles only turtles have survived until now.

The group of synapsids separated from the cotylosaurs and led to the formation of ichthyopterygia and synaptosaurs. Typical representatives of ichthyopterygia were the ichthyosauruses, which returned into the water medium and acquired a similarity with fishes and dolphins. They had a smooth skin and numerous sharp teeth, that were adapted to use fish for food. Their size varied from 1 to 15 m.

The representatives of synaptosaurs were the plesiosaurs which were the sea reptiles that were morphologically cognate to the contemporary fissipeds. They had a wide thickened body, two pairs of strong limbs, that changed into swimming flippers, a long neck with a small head and a short tail. Their size fluctuates within a wide range: some species were only 0.5 m long; however, there were also giants measuring 15 m. They had strong muscles, which set their flippers into motion, that served them only for purposes of rowing and could not keep up the animal's body when it was out of water. The factor underlying the transition of synapsids from terrestrial to aqueous forms have not yet been made quite clear.

The group of diapsids. It brings together the most numerous and varied reptiles and is divided into two subclasses—lepidosaurs and archosaurs. As far back as the early Permian period lepidosaurs, known as the most primitive forms, were singled out. They gave rise to rhynchocephalians, squamates—lizards. What is now known of rhynchocephalians is *Catteria*. At the beginning of the Cretaceous period mososaurs separated themselves from the squamates. They were marine reptiles, which had a snake-like body of 15 m in length and two pairs of limbs in the form of flippers. At the end of the Cretaceous period snakes formed a new branch from lizards.

The primitive order of *Eosuchia* had presumably been responsible for the origin of a large branch of archosaurs, which was later divided into three groups: crocodiles, dinosaurs and pterodactyls.

Dinosaurs represented the most numerous and varied group of reptiles. Their size markedly fluctuated—from small animals of the size of cat and even smaller to real giants, that were as long as almost 30 m and whose weight was between 40 and 50 t. There was nothing like dinosaurs on land. The mass of the largest contemporary mammals—the elephants, comprises only 1/5 of the mass of a large dinosaur, and crocodiles—the closest relatives of dinosaurs weigh only about 1 t. Dinosaurs were light and massive, mobile and clumsy, predatory and herbivorous, with no scales and covered with bony armour with various protuberances. They were divided mainly according to the structure of their pelvis, and thus formed two large groups of saurischians and ornithischians. They had different means of movement. In these two groups dinosaurs are found to be either bipeds or quadrupeds. They appeared in the middle Triassic period.

The saurischian dinosaurs were represented by therapods and sauropods. Therapods referred chiefly to the carnivorous predatory animals, while sauropods were predominantly herbivorous. The early therapods became adapted to run fast along the open sites. Some of the therapods had the appearance of ostriches. They had a long neck and a small head with weak jaws, could run fast on their long legs, and were omnivorous. Together with the fast-running small therapods there also existed large animals that were immensely strong. They were the bipeds that supported themselves on the pelvic limbs and had small pectoral limbs. They included the tyrannosaur, ceratosaur, and allosaurus. Tyrannosaur weighed more than the largest elephant; it was as long as 10 m and 6 m high. The tyrannosaurs had a thick skull and sharp teeth. The pectoral limbs were considerably diminished and served only for the capture of food. The animals jumped on pelvic limbs, supporting themselves on their tail. The huge therapods must have fed on the animals from the group of saurischians and ornithischians.

The Jurassic and Cretaceous periods were characterized by the development of sauropods. They were the largest animals on Earth. They had massive skeletons, but with most of the forms the pelvic limbs were longer and stronger than the pectoral limbs. This was conditioned by that the pelvic limbs had to support the massive pelvis, the greater part of the heavy vertebra and the long tail. The pectoral limbs, however, were the basis for only the chest, and the relatively light neck and head.

The large representatives of saurischian dinosaurs included the brontosaurus, diplodocus, and brachiosaurus. Brontosaurus reached over 20 m in length, and had the weight of nearly 30 t. Diplodocus was much lighter, but surpassed brontosaurus in length (26 m). The clumsy brachiosaurus was more compact; its mass comprised about 50 t. Given the structure of the body and the masses of these dinosaurs, it is possible to assume that all of them, as is the case with the contemporary hippopotamuses, spent most of their time in water. They had weak teeth that were fit only for the consumption of soft acquatic vegetation, while with the diplodocuses their nostrils and eyes were shifted upwards, which helped them to see and hear, by taking out of the water only a part of the head.

The ornithischian dinosaurs had a pelvic girdle that looked very much the same as that of birds. They were of medium size and were characterized by various forms. Most of them moved on four feet. The animals were herbivorous, which found its expression in the structure of their teeth. They had a well-developed armour, which was sometimes covered with different kind of warts in the form of horns, spines, etc. The main development of the ornithischian dinosaurs coincided with the Jurassic and Cretaceous periods. Their typical representatives were iguanodonts, stegosauruses, and triceratops.

The iguanodonts moved on hind legs and were 5-9 m high. They had no armour, and the first toe of the pectoral limbs had the form of a spine that could serve as a reliable means of protection from the predators. The stegosauruses had a very small head and their back had two rows of triangular plates, with several sharp spines situated on their tail. Their length comprised 5-6 m.

In the late Cretaceous period there appeared the triceratops (cerapsides)—the dinosaurs with corneous warts on the skull, which functioned as a protective means against the predators. Triceratops looked like a rhinoceros. The big horn was situated at the end of the muzzle, on the nose, and there was a pair of horns above the eyes. By their size the triceratops surpassed the largest rhinoceroses that are known to us today.

Pterosaurs were the first flying vertebrate animals. Their pectoral limbs represented genuine wings. This group also includes the icarosaur whose ribs stretched far aside. When the ribs were completely straightened, the skin that covered their body could easily become wings. The flying lizards were no greater than the present-day squirrel. Most probably they were not less varied than the large flying forms that emerged in the Jurassic and Cretaceous periods. It is assumed that the icarosaurs were better adapted to the control over the bearing surfaces, and in addition to this they preserved the developed limbs that helped them to properly walk on land, crawl and feel various objects.

The real pterosaurs, or pterodactyls, had a number of common features with the birds. For instance, crossed thoracic vertebrae, a large chest with the keel, a complex sacrum, hollow bones, a skull with no seams, and large eyes. They fed mostly on fish and lived in littoral rocks. All the pterosauria had a light body, the bones were hollow, the head was elongated, and the jaws had sometimes many teeth. The pterosauria were of different size—from the size of a sparrow to the giants, the wings of which could spread to 7 m. They were represented by various forms. Among them there was the primitive group of rhamphorynchus, which had a long tail for the regulation of the flight as well as the highly organized group of pterodactyls proper that had a rudimentary tail. The gigantic flying lizards, the pteranodons, were the largest flying animals on Earth. When its wings were spread to 7 m, the animal weighed 16 kg. A great part of the wing and a light structure of the body prove that pteranodons mostly glided and could spread their wings only when there was a necessity to do so.

A special group of sinapsids singled out from the Permian cotylosaurs. They had developed jaws, powerful muscles and a progressive differentiation of dental system—heterodontition. This brought them closer to the highest class of vertebrate animals—the mammals.

At the end of the Cretaceous period there occurred a mass extinction of Mesozoic reptiles. Different hypotheses were put forward to explain this phenomenon, even space factors were mentioned. It would be out of place to present here any critical review of all these concepts, though one of such approaches to the solution of the problem should be touched upon. In the course of the whole Mesozoic era most of the reptiles acquired a relatively high degree of specialization in different habitats, which on the whole were fairly stable. At the end of the Mesozoic period the orogenic processes were markedly increased (the epoch of Lamarian orogenesis), which had a negative effect upon the conditions in which the reptiles lived. Moreover, no minor role was played by the struggle for existence with the other, more highly organized animals—birds and mammals. Owing to the warm-bloodness and highly developed brain they found themselves better adapted to new conditions and ousted the less developed reptiles. At the same time it should be pointed out that the problem of mass extinction of Mesozoic reptiles has by far not yet been solved.

Birds represent a class of vertebrates of a higher degree of organization than the reptiles. The surface of their body is covered with feathers, and the pectoral limbs are turned into wings. In the bird's organism there takes place an intense metabolism with the temperature of the body remaining high and constant. Their heart is four-chamber, and the arterial and venous types of blood are separated. The brain is properly developed. The same concerns the sense organs, particularly those of sight and hearing. Birds hold the first place among the land vertebrates as far as the velocity of flight and the ability to overcome enormous distances. The reproduction of birds of different sexes is achieved with the help of eggs. However, as compared with reptiles, birds lay fewer eggs. The complexity of biological phenomena connected with reproduction, and particularly the cares of the young are concerned, markedly distinguish the birds from reptiles.

Many anatomical data show a similarity between birds and reptiles. As was figuratively expressed by T. Huxley birds are the reptiles that had taken wings. This statement is appropriately substantiated by the transitory fossil form that was discovered in the zolengothenian clayey schists of the upper Jurassic era in Middle Europe. This form received the name of archaeopteryx. The first find of archaeopteryx dates back to 1859 and was interpreted as a representative of pterosaurs. The next and more successful find was made in 1861. The animal had feathers, and there was every reason to refer it to the protoalated type. The archaeopteryx was a bird according to the character of plumage. Given some other features it represented a transitory form from the reptiles to the birds. Presumably, archaeopteryx originated from small dinosaurs of the group of therapods. It cannot be disregarded that they were homoiothermal (warm-blooded). The development of feathers served as a thermal isolation for the whole body. The archaeopteryx was still on Earth, but could already jump up for its prey with the help of wings.

Life in the trees was one of the important conditions in the evolution of birds.

The remains of birds in the form of bones and skeleton are very poorly preserved under geological conditions. This accounts for the fact that in the evolution of birds there still remains a great gap covering fifty million years after the archaeopteryx. The preserved fossil remains of some of the sea birds are found in the depósits of the upper Cretaceous period. Birds became of more various kind only after the Cretaceous period, when the dinosaurs became extinct and the birds had ample opportunity to continue their development for a long time. For some time the primary birds and pterodactyls existed together and waged a competitive struggle against each other. Agile and homoiethermal birds became strong enemies of the mammals in the struggle for the domination on land.

In the upper Cretaceous deposits of North America the remains of two types of birds—ichthyornis and hesperornis—were discovered. The ichthyornis had vertebrae that had much in common with those of reptiles and fishes. These birds were of the size of a pigeon; their jaws were still provided with sharp teeth, and the wings had the same structure as those of the contemporary birds. The hesperornis represented a form that was adapted to the aqueous way of life and reached 1.5 m in length. It was an aqueous bird, its long jaws had teeth that were curved back and were adapted for the capture of small fish. The remains of hesperornis were found in the very same layers, as the bones of the gigantic pteranodont, which was the contemporary of this peculiar wingless bird.

At the beginning of Paleogene the birds became on the whole fairly varied; there appeared the nonflying or the running ones. They included the diatreme—a gigantic nonflying bird that was over 2 m in height and had a large sharp rostrum and powerful clawed paws. The southern continents were to a great extent inhabited by large nonflying birds. In Neogene in South America there lived the Phororakos, a very large nonflying carnivorous bird the height of which measured 2 m. The size of its head was compatible with the head of the present-day horse. The Moa of New Zealand represented a gigantic ostrich up to 5 m high. The aepyornis (*Aepyornis*) was a huge nonflying bird that had only recently dwelt in Madagascar.

The penguins had rather early adapted themselves to acqueous medium and becoming good swimmers, in addition to which they acquired a streamline form, could camouflage and were protected from the cold by their feathers and fat. They inhabited the small oceanic islands and the Antarctica, where there were no land predators, which could jeopardize the life of penguins. The Cenozoic fossil remains show that penguins were as high as 2 m.

Nowadays the birds have spread along the whole surface of our planet; they live under various conditions, and react to any unfavourable changes in the environment by leading a nomadic way of life and migrating.

The end in the development of vertebrate animals came with the class of mammals. In the course of a relatively short period of time they reached a high stage in their development. This found its expression in the transformation of the corneous cover of mammals' body into a hair one serving to protect the organism from the loss of heat; in the perfection of their skull; in the development of the respiration organs, blood circulation, brain, and particularly the cerebral hemispheres; as well as in the viviparity and the lactic means of feeding their young.

The ancestors of mammals were probably the animal-like reptiles (Theriodontia), which emerged in the Permian period. Within the Mesozoic era the mammals were omnivorous or predominantly insectivorous. The small forms were predominant. These animals reached the highest point of their development in the Cenozoic era; they became larger and more varied morphologically. During the whole evolution of animals we can trace one of their highly significant features, connected with the development of brain. As far back as 1851 the prominent American geologist, mineralogist and biologist James Dwight Dana pointed out that in the course of geological time the nervous system of animals and especially their brain continuously changed and developed. What took place was the process of cephalization of vertebrates, which manifested itself most clearly in comparison with various taxonomic groups.

We know that initially the living creatures did not have any nervous system at all and the cephalization process had a number of stages. In the first stage, over 500 mln years ago, the living organisms formed specialized nerve cells that transmitted excitation and regulated the processes of movement and nutrition. In nerve cells the impulse was transmitted at higher rate than in others.

The second stage of cephalization consisted in the restructuring of the network of nerve cells into neurons. This system was becoming more perfect, and the excitation in it was transmitted at the rate of 4-15 cm/s. For purposes of comparison, it is worth mentioning that the transition rate of the nerve impulse with the leech is 40 cm/s, the crustaceans—120 cm/s, and the scolopendra—250 cm/s. Individual concentrations of nerve cells form ganglions, which begin the cephalization proper in the narrow sense of this word.

The cephalopods were the first to experience the earlier stages in the perfection of nervous system. The appearance in them of tentacles and developed eyes was connected with the centralization of nervous system. In the brain of cephalopods there took place the specialization of some of its parts, which regulated the particular organs of their body; the hands, eyes, and ink bags. Meanwhile, the cephalopods showed an increased rate of the transmission of nerve impulses, which reached 25 m/s.

The nervous system of insects was highly specific—it was markedly dependent on the corresponding communities. Their brain consisted of two hemispheres, each of which governed its own half of the body. The chitinous cover restricted the size of their body, and when it increased, the mobility of the animal slackened. At the same time the passive tracheal respiration did not provide the mass concentration of cells with a sufficient amount of oxygen. Given these conditions, the insects were of small size.

Cephalization had its most coherent expression in the case of vertebrates. The degrees of cephalization of animals, according to R.K. Balandin, are presented in Fig. 23. Cephalization was most markedly developed with reptiles. The nervous system was divided into brain and spinal cord. The rate at which the nerve impulses are transmitted depended on the temperature of the body; when it grew, its velocity became greater. In the opinion of paleontologists the brain of gigantic saurians was not larger than that of a kitten, while the spinal cord coped with the control of the body.

The highest degree of cephalization was characteristic of warm-blooded mammals. Their nervous system functioned at the constant temperature of +31 ... +40 °C. The nerve cells had acquired a special cover, which accelerated the passing of nerve impulse. But the most important phenomenon was the increase in volume of the brain. In the series of mammals from the ancient to modern varieties the absolute and the relative volume of the brain has increased; the same can be said of the number of neurons and the area of all the parts of the brain. The warm-blooded mammals underwent a qualitative change of their whole nervous system and the brain, which allowed them to have no minor advantage in the struggle for existence against other classes of vertebrate animals.

The most intense cephalization manifested itself in the development of hominids. During the last two billion years their brain was increasing in volume with the rate 50 cm^3 for

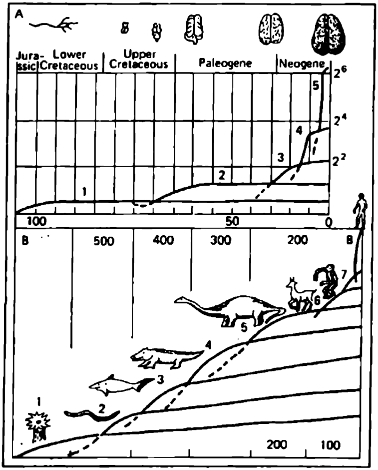


Fig. 23. Stages of cephalization of the animals (R. Balandin, 1979):

A—relation of brain to spinal cord: *1*—tortoises; *2*—ungulates; *3*—cats; *4*—apes; *5*—man; *B*—number of neurons of brain; *1*—coelenterates; *2*—worms; *3*—fishes; *4*—amphibians; *5*—reptiles; *6*—mammals; *7*—apes; *8*—man Logarithmic scale is given on a vertical line and age in mln years—on a horizontal line

the period of 100 thousand years and its general volume rose three times at this time (T. Bielicki, 1987).

Thus, the growth of cephalization in the course of the geological history of animals is an undisputed fact and can be taken as a rule which V.I. Vernadsky called the Dana principle. 'In the chronological expression of geological periods—V.I. Vernadsky wrote as far back as 1902—we can continuously trace this phenomenon from the brain of mollusks, crustaceans and fishes to the human brain. There has not been a single case, when there would be all interruption, and there has never been a period when the complexity and functioning potential of the central nervous system would be lost and there would appear a geological period, or a geological system with a central nervous system that would be inferior to the one of the preceding period.'

The succession of generations of a whole series of groups of animals had a much more rapid space closer to our epoch, but was much slower in the more remote times. This regularity in the acceleration of evolution became obvious long ago and was regarded as a manifestation of the particular properties of the living matter in our planet's biosphere.

The acceleration of the rate of development of the organic world from the ancient times to the current epoch was also noted by one of the founders of evolutional paleontology V.O. Kovalevsky. In the letter to his brother of December 27, 1871, he wrote: 'The fact that life is in a state of acceleration is interesting indeed, so to speak; the period from the Laurentian to Silurian epochs was much longer than from the Silurian epoch to the present time; each successive great epoch of the Earth is shorter than the one preceding it, and this short period of time was sufficient for the emergence and extinction of a large number of various forms as compared with the epoch that came before it; beginning with the Tertiary epoch life has been marching on at an incredible speed; since Eocene onwards large types and whole families had appeared and disappeared with the new one coming in their place. The change that had taken place was enormous, though the time it covered must have been relatively short: then followed the advent of Man, who took possession of the world and everything proceeded at a more rapid rate.'

With the 1874-75 publications of E. Hoeckel, serving as the starting point, F. Engels regarded the acceleration pertinent to the rate at which the organic world developed within the geological time as a natural-historical regularity. F. Engels wrote that in respect to the whole history of the development of organisms it was necessary to accept the law of acceleration proportional to the square of the distance in time from the initial point.

Together with the main types of animal kingdom that were progressing in their development conservative representatives of vertebrate animals were also found. The latter had changed but little in the course of geological history. However, cases of the persistency of organisms are considerably less restricted than those typical of the invertebrates. Among the vertebrate animals this can be exemplified by *Latimeria*—a contemporary crossopterygian that inhabits the depths of 150-800 m and that was first caught in 1938. The land 'living fossils' include the lizard *Sphenodon punctatus*, the ancient frog *Leiopelma* and the little ostrich kiwi-kiwi in New Zealand.

The whole fauna of marsupials in Australia seems to be essentially unique, since one would look in vain to find these animals on the other continents of the world.

THE DEVELOPMENT OF MAMMALS

As has already been mentioned, mammals represent the highest class of vertebrates, which, according to its organization, crowns the whole system of animal kingdom. The most substantial features of the general organization of mammals consist in the following.

(1) They have a perfect system of controlling heat, which helps them to maintain a relatively constant temperature of the body. Thus, the permanent inner medium of the organism is created. These properties have a decisive role in the distribution of mammals in diverse physiographic conditions.

(2) They are viviparous and feed their young with milk, which serves to keep the animals alive in their infancy and provide the possibi-

lity for reproduction in absolutely different conditions.

(3) Mammals are characterized by a highly developed nervous system, which enables them to have complex and perfect forms of the adaptation of organisms to environment and a whole system of interaction of different organs of their body. The process of cephalization with them found its most coherent expression.

All these properties determine the total propagation of mammals in the biosphere, where they inhabit all the types of living environment: the air and land, aqueous, and soil-and-ground varieties. Mammals are actually spread throughout the whole world. They are not found only on the Antarctic continent, though seals and whales do come out on its coast.

The closest ancestors of mammals were the ancient Paleozoic reptiles, which had preserved some structural features of amphibians, e.g. cutaneous glands, the arrangement of joints in the limbs. Paleontologists assume that this kind of ancestral group was a subclass of therapsids (Therapsida). One of its orders—the theridonts (Theriodontia) is the one that is closest to mammals. The fossil remains of these animals had teeth differentiated into the same groups as those that were typical of the mammals, i.e. incisors, fangs, and molars, and were situated in the alveoli. There was also the secondary bony palate—a highly cha-

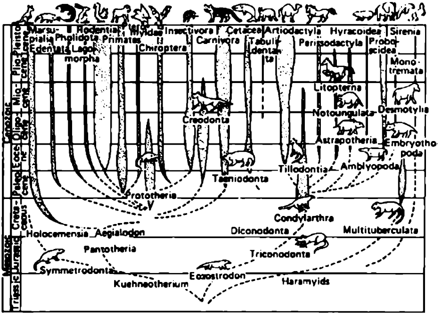


Fig. 24. The evolution of mammals originated in a group of predatory therapsids. The first mammals were quite small: some mammals survived certain types of land animals that appeared at the end of Cretaceous period and weighed less than 20 pounds. Several groups of mammals survived the dinosaurs, and during the Cenozoic era a group of mammals are widely varied. The first primates appeared at the time when the dinosaurs were still dominating: those primates were small, tree-dwelling creatures with the habits probably resembling those of squirrels. The mammals that eventually had a direction to man began to conduct life on the ground, at first only as foragers but later as highly successful hunters

racteristic feature of the mammals. Family ties of individual groups of mammals are shown in Fig. 24.

The small sizes of ancient mammals reveal that their ancestors must have been primitive and minor theridonts, for instance, the ictidosaur of the upper Triassic period in South Africa. It was an animal as large as a rat, the skeleton of which had very much in common with that of mammals, only that their lower jaw consisted of several bones.

According to paleontological data the theridonts had existed only until the upper Triassic period. The actual paleontological finds of ancient mammals correspond to Jurassic deposits. They are represented by highly specialized animals, for which reason their origin could have coincided with the earlier period, or Triassic age. From its end to Neogene there existed the so-called multituberculates—small animals the size of a mole, and only some of them were as large as a marmot. They had no fangs, though their incisors were very well developed. The multituberculates represented specialized forms of plant-eating animals. Possibly their very early forms gave rise to monotremes. At any rate, the structure of their teeth was very much the same as that of the embryo of a duckhill.

The placental mammals, presumably as the marsupial ones, descended from the panthotheres (the order of bunodonts) at the beginning of the Cretaceous period. The earliest forms that referred to the insectivores, had been known from the late Cretaceous deposits of Mongolia. In the Cretaceous period the placental mammals were divided. The cetaceans and rodents produced lateral branches. The insectivores were the ancestors of a large number of mammals. Bats, edentates, primates, and others owe their origin to them. The predatory ungulates formed a single stem, which, in the course of some time, separated into two distinct branches, the predators and the ungulates. The ancient predators, or creodonts were responsible for the emergence of pinnipeds; the perissodactyls, artiodactyls, and, presumably, the proboscideans owe their descent to the ungulates. In the second half of the Cenozoic period the placental mammals became the domineering group of animals on the planet.

The marsupial mammals emerged at the beginning of the Cretaceous period. Their remains were found in the deposits of the upper Cretaceous period in North America and the Paleocene of Eurasia. It follows, then, that the native land of marsupials could have been the Northern Hemisphere. However, in the Neogene they were ousted by the more highly developed placentál mammals, and at present the marsupials have preserved only in Australia, New Guinea and South America.

According to paleontological data the higher placental mammals descended from the trituberculates at the beginning of the Cretaceous period. They formed 31 orders, of which 17 have survived until now and 14 have become totally extinct. The placental mammals had been developing together with the marsupial ones.

The most ancient order of mammals were the insectivores, the remains of which were found in the deposits of the upper Cretaceous period. Those little animals led partly a terrestrial and partly an arboreal way of life. The adaptation of a number of arboreal insectivores to gliding and then to flights resulted in the formation of such flying forms as the order of chiropterans. The gradual transition to the feeding on larger animals and an increase in size were a marked prerequisite for the formation of the order of ancient predators or creodonts, which took place at the beginning of the Paleozoic period. However, later, when the herbivorous forms acquired a greater mobility, creodonts were ousted by more developed predators—the direct ancestors of the contemporary order of Carnivora. As far back as the Oligocene, there lived the ancestral groups of vivetras, mustelids, dogs, and cats, while in the Neogene—we find saber-toothed cats with huge curved fangs.

As early as the beginning of Neogene the predators were divided into two unequal groups: the greater group included land predators, while the smaller one consisted of pinnipeds. The latter became the inhabitants of marine and fresh water basins, and fed mostly on fish.

The creodonts, which turned to vegetative food at the very beginning of Paleogene, gave rise to the first ungulates, or condylarths. At first they were relatively small (the size from a mustelid to a wolf) omnivorous animals with moderately long fangs, tubercular-molar teeth and pentadactyle limbs, in which the middle toe was the one that was most developed. The condylarths gave origin to the two branches of contemporary ungulates—the perissodactyls and the artiodactyls.

In the Eocene there appeared the proboscideans, the origin of which has not yet been ascertained. Not much can be said of the origin of the cetaceans either. There is some reason to believe that the descent of rodents, edentates, aardvarks and primates goes back to the ancient insectivores.

The evolution of mammals covered the whole of Cenozoic era. It was the time when phanerogams was spread on land and served as a vital fodder supply for the settlement and development of mammals on different continents. In a large number of cases the animals were obliged to adapt themselves to new ecological conditions. In addition to this the ancestral forms disappeared, while their descendants became more highly developed and were actually transformed into new species. The division of continents in Cenozoic era led to the emergence of relatively isolated zoogeographical-regions, which had retained the relics of ancient fauna. In the epoch when the marsupials domineered the Australian continent had completely been separated. Somewhat later South America split itself from North America and preserved the relics of the fauna typical of the beginning of Cenozoic era. By that time South America had completely lost the possibility of any animal exchange with other continents. At the beginning of Paleogene South America was inhabited by a large number of mammals, which 40-30 mln years ago developed independently without being influenced by the newcomers.

At first the domineering role in South America belonged to the marsupials. They were the carnivores the size of which was not greater than that of opossums. In the later period the marsupials became larger and stronger. In the Miocene there appeared strong and agile animals. Afterwards they became even larger and reached the size of a saber-toothed tiger.

The placental mammals that inhabited South America did not surpass the marsupials in the time that followed. The fauna of placentals was represented by highly varied forms. There were many ungulate tetrapods the size of which ranged from a rabbit to a rhinoceros, which had the incisors for the gnawing of wood plants. The thoatherium with its head and long front teeth adapted to the trituration of vegetative food, as well as with its straight vertebra and monodactyle thin legs, looked very much like a horse.

The ancestors of armadillos, sloths, and anteaters were known in the early Paleogone deposits of South America. In the process of evolution they developed gigantic forms. Glyptodont—the armadillo of Pllistocene—reached almost 1.6 m in length. It had a thick armoured, as it were, cap on its head, as well as an armour that covered the body. All this had naturally required a thick skeleton. In South America there existed gigantic land sloths. Some of them were of the size of an elephant. The gigantic anteaters adapted themselves to feed on thermites; they used to destroy their habitats with their strong clawed front paws.

The established ecosystem of relative balance between marsupials and placentals underwent some extremely marked changes in the later Pliocene. Then the Central America isthmus had emerged and for the first time in 40 mln years the animals could move freely between North and South America. The more highly developed North American mammals doomed most of the indigenous 'South Americans' to extinction, in particular the ungulates and the large marsupials. And only an inconsiderable part of South American mammals managed to penetrate into North America. They included the opossums and armadillos. The gigantic land sloths reached even Alaska.

In North America and Eurasia there took place the evolution of such large animals as ungulates and elephants. The evolution of horses has been studied most thoroughly. Its basic stages took place in North America. The ancestors of horses are considered to be the

Hyracotherium and the *Eohippus*, the size of which was that of a small dog. The remains of this ancestor date back to Paleocene. However, *Hyracotherium* could also have been a remote ancestor of other perissodactyls, e.g. tapirs and rhinoceroses.

Hiracotheriums moved very quickly in space and fed mostly on the leaves of shrubs. In the Eocene and Oligocene the size of horses increased, their legs lengthened, and became tridactyle, while the teeth became adapted to the incision and grinding of leaves. At the beginning of Neogene there appeared vast expanses covered with grass. This resulted in that all the herbivorous animals dwelling in open plains received an agreeable source of nutrition. These conditions were most favourable for horses, the teeth of which were exactly adapted to the grinding of vegetative food. Thus, the horses which had hitherto been animals plucking the leaves of shrubs now became grazing animals. However, in the Miocene, some horses had still inhabited the undergrowth territory, and retained the tridactyle limbs. The animals reached the size of our present-day pony. The further development of horses found its expression in the formation of hipparion fauna, which had widely spread over the vast spaces of North America and Eurasia. The hipparions represented small horses, the tridactyle limbs of which were characterized by a marked decrease of the lateral toes and a clearly expressed hoof. The hipparions gave rise to the origin of the ancestors of real horses of the contemporary genus *Eguus*.

The Hyracotheriums produced the ancestors of other perissodactyls—titanotheres and rhinoceroses. The evolution of rhinoceroses proceeded in a highly complicated way; this resulted in that there appeared extremely varied and, at times, whimsical forms. The ancestors of rhinoceroses were massive animals with short legs. They fed on leaves and young sprouts. There also existed small rhinoceroses with long legs. However, they became extinct in the Oligocene, which was perhaps due to their having been defeated by horses in the concurrent struggle. Many rhinoceroses looked like the present-day hippopotamuses. Among the rhinoceroses there were large animals. The baluchithere rhinoceros was the largest land mammal of all those that had ever inhabited the Earth. Its height was 5-6 m. Owing to it the animal could feed on the leaves and young sprouts of very high trees. The baluchithere variety lived in the late Oligocene and early Eocene in Central Asia.

The history covering the development of elephants is rather complicated. The concluding stage of their growth began with the Neogene period. Their late Cenozoic ancestors changed the means of masticating food. The jaws moved only in one direction—to the front and back along one and the same line. This change in the chewing functions brought about an alteration of the morphological peculiarities of the head.

Among the mammals the order of primates formed an individual group. According to paleontological data their ancestors had been known since the Cretaceous period. The most ancient primates looked like the contemporary lemurs and tarsioids.

About 80 mln years ago the ancient arboreal primates appeared. In the Paleogene (67-25 mln years ago) the old primates were divided into their lower variety and the anthropoid apes, while as far back as 12-8 mln years there appeared in India and Africa the Ramapithecus—the most ancient of the known primates, which had some similar features shared by the humans. In the Pliocene (approximately 5 mln years ago) there emerged in Africa the closest ancestor of Man—the australopithecus, the biped walking creature that could use the first tools. The australopithecus existed 5-1 mln years ago. The time pertinent to the transition of a certain part of australopithecus to labour refers to about 2.6 mln years ago, which can be substantiated by the unique findings of the remains of the ancestors of Man in East Africa. The epoch of early Paleolith was marked by the advent of Man. Since the evolution of primates had an extraordinary significance in the biosphere it calls for a greater disquisition.

The Evolution of Primates and Man

The primates belong to the most highly organized order of mammals. They have a developed nervous system and an adequately large brain. Their vision is binocular, while colour vision is typical of apes and humans. The vast majority of primates in the past and nowadays are arboreal forms. They lived among the trees and fed chiefly on their fruits, and only few of them began to lead a terrestrial way of life in the later period (gorillas and baboons). The primates are divided into two suborders: the prosimians and anthropoid apes.

Apes had presumably descended from the lemur-like ancestors in the Paleogene. The higher primates are classified into three large groups, the apes of the New World, the apes of the Old World, and the hominids, including large apes and Man.

The concluding and most significant event in the evolution of primates was the advent of Man. Within the confines of the biosphere it determined the development of a new cover—

the anthroposphere—the sphere of active influence of civilization on the environment. In due course the anthroposphere has to transfer itself into the noosphere—the sphere of human mind, the concept of which was comprehensively expounded by V.I. Vernadsky.

In the nineteenth century the data on the ancestors of Man were not interrogated, and the first question that arose concerned the antiquity of man as such. The outstanding English geologist Ch. Lyell in his book *The Geological Evidence of the Antiquity of Man* (1863) adduced substantial evidence in favour of the fact that the labour tools of ancient Man could indicate the degree of his antiquity. The age of these crudely worked stones was estimated by the conditions of their bedding at a considerable depth together with the fossil animals.

Charles Darwin considered that Man had appeared as a result of the evolution of the animal kingdom. His copious work *Origin of Species by Means of Selection* came out in 1871. However, at that time the ancestors of man had actually not yet been known, with the exception of one finding; in 1856 in the Neanderthal valley in Germany the skull, a part of collar bone and the limb remains of a fossilized human were discovered. Later the supposed creature was called Neanderthal man.

In 1891-1893 Dr. Eugene Dubois, a Dutch military physician, when excavating in Java, found the cranium, a thigh bone and the molar teeth of a fossil creature more ancient than the Neanderthaler. The finding received the name of Pithecanthropus (Pithecanthropus erectus).

In 1918 40 kilometres southeast of Peking Dr. J.G. Andersson, a geologist from Sweden, discovered fragments of reworked quartz together with the bones of animals and the teeth of man. In the later period as a result of persistent and selfless quests undertaken by Prof. Davidson Black, a Canadian anatomist, the remains of not less than 38 species of the primitive man were assembled. The age of the find was estimated at 400-350 thousand years. The discovery itself was called the Sinanthropus (Pithecanthropus pecinensis).

In 1924 Professor P. Dartu of Johannesburg University made a study of the fossil skull from Taung, a small locality in South Africa. He gave the fossil the name of Australopithecus—a southern ape. The assumption was expressed that the finding could have been the missing link between the apes and Man. Later, the remains of australopithecus were also discovered in the other parts of Africa. On the basis of studying the remains of australopithecus it became possible to come to the conclusion that they could walk straight, produce tools from the bones of animals and hunt. The age of these findings was initially estimated at one million years.

According to the structure of their skull the australopithecus held an intermediate position between the gorilla and the chimpanzee, but by a number of features it was closer to man, whom it resembled more than the contemporary anthropoid apes. Its teeth and jaws were fairly heavy as regards the skull, which shows that it had mainly fed on vegetative food, though at times it could also eat meat. The volume of brain comprised about 450 cm^3, which was more than that of large apes. Presumably, its height reached 1.2 m.

The further numerous findings of fossil primates in Africa enabled the scientists to establish that the most ancient simian men, who manufactured crude primitive tools and hunted the large animals, were singled out of the vertebrates, not one million but over 2.6 mln years ago.

The quests of the remains of ancient hominides in the Olduvai Gorge between the Kilimanjaro mountains and Lake Victoria were initiated in 1931 by the British anthropologist Dr. Louis S.B. Leakey together with the German geologist H. Reck. Presently in this gorge a skull was found. It proved to be smaller than the skull of a gorilla and that of a modern man, though its appearance was manlike and its walk was erect. L. Leakey called it Zinjanthropus, which meant an East-African man. Later the potassium-argon method helped to establish that the age of the skull was unexpectedly very great—1.75 mln years! Soon other findings were made, which received the name *Homo habilis*, i.e. man who could handle things, since stone tools were discovered together with the remains.

In 1972 on the eastern bank of the Lake Rudolf, a skull was found which reminded of the modern man more than a Pithecanthropus, to say nothing of the Australopithecus. The tufaceous material alternating with the sedimentary deposits where the remains were buried was allowed to determine their age with the help of the potassium-argon method. It was 3.18-2.61 mln years ago.

Thus, according to current data the primitive man was not the Javanese Pithecanthropus, nor the Sinanthropus, but the East-African *Homo habilis*. The ancestors lived together with Australopithecus. It is probable that with *Homo habilis* there concurrently existed various species of fossil hominids. However, the Australopithecuses and their cognate forms had become extinct, and a man continued to live and develop. Meanwhile, in the light of new data it is possible to infer that the initial provenance of man was Africa. The ideas pertaining to the African origin of man were expressed long time ago, but at present they have been adequately substantiated.

Over the past decade the research into the evolution of primates and man has been considerably advanced. There are three factors that can explain it in the main: firstly, there has been a marked increase in the amount of data concerning the fossil remains of the ancestors of man; secondly, new quantitative methods of investigation on the molecular level have extensively been employed; and thirdly—the fact that the evolution of man is a considerably more complex process than what it appeared to be even 20-30 years ago. On the whole, in spite of the copious material on the evolution of man, many of its aspects still remain but poorly elucidated.

The data of molecular biology rendered no minor assistance in the restoration of the family tree of primates. As a result of the further excavation in Africa, on the territory of Kenya and Uganda, about 1000 fossil primates as old as 22-17 mln years have been found. They belong to hominid branches after their separation from the apes of the Old World. New data have revealed that the human branch separated from the stem of African anthropoids less than 10 mln years ago.

At present most of the paleontologists and anthropologists came to the unanimous opinion as regards the marked closeness of man's ancestors to the African anthropoids and concerning a considerable remoteness from the Asian forms. The common ancestor of hominids, chimpanzee and gorilla was twice younger than the ancestor of all the large hominids. The separation of large anthropoids from the ancestral stem must have taken place from the branch of anthropoid apes approximately 8-7 mln years ago. At the same time it has been established that the late Miocene hominids were quite varied, which complicated the structuring of evolutionary trees.

The best known *Proconsul africanus* was the proconsul which represented a nonspecialized primitive form of anthropoid ape that was arboreal and fed on fruits. According to its structure this animal did not look like any of the apes. Its feet, elbow and shoulder joints were the same as those of a chimpanzee, the carpus was not different from that of monkeys, and the lumbar vertebrae were the same as the ones characteristic of a gibbon.

At the end of the early Miocene (about 17 mln years ago) Africa and Eurasia became connected through land. This gave rise to the migration of primates and the exchange of land fauna. The steppe herbivorous were not numerous, and those that flourished were the browsing wood forms.

The hominids of Eurasia were divided into two large groups—Dryomorphs and Ramamorphs. The former included the primates with the features of hominids found mostly in Europe. Ramamorphs were predominantly spread in Asia. Their names were derived from the genus *Ramapithecus*—the remains of which were discovered as far back as 1932. The fossil remains related to Ramapithecuses were found in Pakistan. Their age was estimated at minimum 12 mln years. The separation of African and Asian hominids must have taken place about 16 mln years ago.

The first hominids emerged approximately

4-3.75 mln years ago in Tanzania and Ethiopia. Within the interval of 2.5-2 mln years ago there took place the adaptation of African hominids, while by the end of this period three

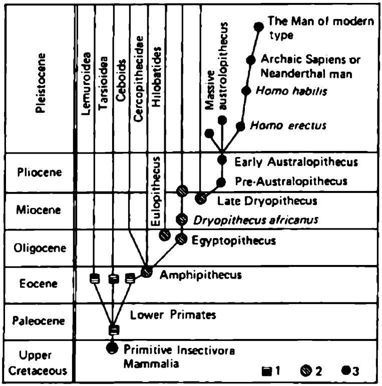


Fig. 25. Evolution of Primates (according to N. Chrisanfova, P. Mazhuga, 1985):

1—lower primates (Prosimii); *2*—higher primates (Simians); *3*—line of man (Hominids)

or perhaps even more species of hominids had existed. About, 1.75 mln years ago *Homo habilis* disappeared to be succeeded by *Homo erectus*. It was widely spread in Africa nearly

1.6 mln years ago. Approximately 1 mln years ago the representatives of this species were found in Eastern and Southeast Asia. They had existed till about 0.3 mln years ago.

Homo erectus had a larger brain (about 800 cm^3), than *Homo habilis*. According to archeological data, it produced large symmetrically cultivated stone tools, bench chisels, and some of these representatives could probably even make use of fire. The archaic form *Homo erectus* gave rise to a continuous line of development up to the current form of *Homo sapiens*. This is the line on which the Neanderthal man was. However, with the transition to present-day *Homo sapiens* the massiveness of the skeleton, face and dental system that was characteristic of Neanderthalers has been lost. The general diagram of the evolution of primates is given in Fig. 25.

Conclusion

> The Earth's creatures are the product of a complex space process and a regular part of a rigid space mechanism, in which, as we know, nothing is haphazard.
>
> *V.I. Vernadsky*

The process of the origin of life in the course of a long irreversible development of natural systems belongs to the great mysteries of Nature. At present we are only approaching its solution. There can be no doubt that the emergence and organization of living matter are connected with the properties of the atoms entering into its composition, and primarily with the properties of carbon. Thus, what brought about the origin of life consisted in those particular processes in space evolution of the substance of the Solar system, or more precisely, in the nuclear synthesis (nucleosynthesis), which preceded the appearance of this system. It was exactly the nuclear synthesis that had led to the formation of the atoms of biophile elements H, C, N, and O in the relationship which proved to be favourable for the formation of complex organic compounds—the direct predecessors of life. When the primary gaseous nebula, that was genetically associated with the early Sun, was being cooled, there appeared organic compounds. They emerged mainly in the last stages of congelation, which was registered in the space rocks of the further periods—meteorites and particularly the carbonaceous chondrites.

The search of traces of ancient life made it clear to us that virtually it had no beginning at all. In the rocks of the early Precambrian period of Greenland, South Africa and Western Australia indisputable geochemical and micropaleontological evidence was found testifying to the existence of ancient biosphere with the predominance of photosynthesizing autotrophic organisms. The early biosphere with the heterotrophic organisms and markedly reducing conditions that is assumed by many scientists existed for a relatively short period of time. In the stone records of the earth's crust we practically do not find its traces.

In the course of geological time the evolution of living organisms yielded an innumerable variety of species. The emergence of photosynthesis took place about 4 billion years ago and possibly even prior to that date. Photosynthesis in the biosphere was initially carried out by blue-green algae and their ancestors. The emergence of photosynthesis had led to the origin of free oxygen and enabled most of the living substances to improve their energy exchange by superstructuring on top of the former anaerobic exchange new systems of oxygen breathing. The biosphere had acquired a powerful oxygen potential, which determined the general character of geochemical processes, the migration of chemical elements, and the forms of their location. In the Cryptozoic-Precambrian periods life had been developing in marine conditions at a rather slow pace on the whole.

In the Cambrian period there appeared higher vertebrate animals, which built their skeleton from calcium carbonate. The formation of biogenic limestones from their remains was on the increase. The development of skeleton with the vertebrates resulted in the growing of fluorine and phosphorus migration. The coming out of plants onto the land in the Devonian period determined a marked change in the development of the biosphere in general. It rendered enormous possibilities for the further comprehensive development of animals as well as plants. At first there appeared ferns, horsetails, and seed ferns, which enhanced the migration of carbon dioxide. The development of land vegetation and the formation of soils created the prerequisites for the influx of animals to the surface of continents. As a result of the evolution of vegetable kingdom there appeared in the Mesozoic period forests of coniferous and flowering plants full of life.

At the end of the Mesozoic and in the Cenozoic periods the migration of biophile elements in connection with the emergence of birds proceeded on a wider scale. Thus, the living matter covered the lower part of the atmosphere, or the troposphere. Birds as well as the other flying organisms, began to play a prominent part in the metabolism between land and sea. In the given case the function of birds had proved to be reverse to that of rivers—viz. in the transportation of a substance from the aqueous medium to land, since a large number of their aquatic representatives fed on fish.

Lastly, the most prominent changes in the Earth's biosphere came with the coming and development of man. In the depths of the biosphere there first appeared the anthroposphere, the beginning of which was set by the settlement of primitive man over the whole surface of continents. The man began to be relatively independent of climate. However, in the course of the development of productive forces and civilization, the anthroposphere, expressing the spontaneous activity of human society, must transfer into noosphere—the new cover of the Earth, the region of conscious activity of the human race.

The term 'noosphere' was suggested in 1927 by the French scientists E. Le Roy (1870-1954) and T. de Chadrin (1881-1955) who were influenced by V.I. Vernadsky's lectures at the Sorbonne University in France. The concept of noosphere was treated most extensively in T. de Chadrin's book *The Phenomenon of Man*. The latest edition of this work in the Russian translation was published in 1987. In it the author determines the noosphere as a 'new cover', 'the reasoning stratum', which originated at the end of the Tertiary period and has been expanding over the kingdom of plants and animals—outside the biosphere and above it. A more profound understanding of noosphere was elaborated by V.I. Vernadsky in the last years of his life in the article 'Some Words on the Noosphere' (1944). He wrote, that humanity, taken as a whole, becomes a powerful geological force. And now man, with his intellect and labour, is posed with the problem of restructring the biosphere in the interests of freely thinking humanity, as an integral whole. This new state of the biosphere which we are approaching without noticing it is exactly what noosphere is. According to V.I. Vernadsky, the noosphere is the biosphere that is rationally controlled by man.

The noosphere extends beyond the limits of the Earth's biosphere in connection with the development of cosmonautics. What is actually taking place is the conquest of the near-Sun space with unpredictable possibilities. The creation of artificial biospheres of the terrestrial type on some of the planets does not present a whimsical idea any longer. Life, which originated within the process of space evolution is on its way back to outer space.

Bibliography

Awramik, S.M., Morris, S.C., Scott, A.C. The Origin and Early Evolution of Life. Fossils and Evolution. In: *Cambridge Encyclopedia of Earth Sciences.* Cambridge University Press, Cambridge, 1982.

Balandin, R.K. Time—Earth—Brain. Vyssheishya Shkola, Minsk, 1979.

Bazilevich, N.I., Rodin, L.E., Rozov, N.N. What Is the Weight of Living Matter on Our Planet? *Priroda*, No. 1, 1971.

Berg, L.S. Speculation on the Origin of the Fresh-water and Sea-water Flora and Fauna. Bulletin MOIP, section: biology, 52, No. 5, 1947.

Bielicki, T. Evolucja mozgu hominidow. *Kosmos*, 36, No. 3, 1987.

Brooks, J. Organic Matter in Meteorites and Precambrian Rocks: Clues About the Origin and Development of Living Systems. *Phil. Trans. of Roy. Soc. London A.* 303, No. 1480, 1981.

Chrisanfva, E.N. and Mazhuga, P.M. Essays on Evolution of the Man. Naukova Dumka, Kiev, 1985.

Ciochon, R.L., Savage, D.E., Tint Thaw, Maw Ba. Anthropoid in Asia? New Discovery of Amphipithecus from Eocene of Burma. *Science*, 229, No. 4715, 1985.

Cloud, P. Biosphere. *Scientific American*, No. 11, 1983.

Cloud, P. Cryptozoic Biosphere: Its Diversity and Geological Significance. The 27th International

Geological Congress. Section C. 05, 5, Nauka, Moscow, 1984.

Darwin, Ch. Origin of Species by Means of Natural Selection. Murray, London, 1859.

Delsemme, A.H. Are Comets Connected to the Origin of Life? Comets and the Origin of Life. Dordrecht: Reidel, 1981.

Dickerson, R.E. Chemical Evolution and the Origin of Life. *Scientific American*, 239, No. 3, 1978.

Dose, K. Hypotheses on the Appearance of Life on the Earth (Review), "Adv. Space Research", 6, No. 12, 1986.

Fox, S.W., Dose, K. Molecular Evolution and the Origin of Life. W.H., Freeman and Company, San Francisco, 1972.

Geballe, T.R. Organic Chemicals in Comets. *Nature*, 329, No. 6140, 1987.

Gidley, D.W., Rich, A., Van-House, J., Litzewitz, P.W. β-decay and the Origin of Biological Chirality: Experimental Results. *Nature*, 297, No. 5868, 1982.

Greenberg, J.M. Interstellar Dust: Structure and Evolution. *Scientific American*, No. 8, 1984.

Groves, D., Dunlop, J., Boick, R. An Early Habitat of Life. *Scientific American*, 245, No. 4, 1981.

Grossman, L. Condensation in the Primitive Solar Nebula. *Geochim. et Cosmochim. Acta*, 36, No. 5, 1972.

Hayatsu, R., Matsuoka, S., Scott, R.G., Studier, M.H. Anders, E. Origin of Organic Matter in the Early Solar System. Organic Polymer in Carbonaceous Chondrites. *Geochim. et Cosmochim. Acta*, 41, No. 9, 1977.

Kamshilov, M.M. Evolution of the Biosphere. Mir Publishers, Moscow, 1976.

Klaus, D. Probiotische Evolution and der Ursprung des Lebens. *Chem. unserer Zeit*, 21, No. 36, 1987.

Krumbiegel, G., Walter, H. Fossilien. VEB Deutscher Verlag für Grundstoffindustrie, Leipzig, 1977.

Lewis, J.S. Prine, R.G. Planets and Their Atmospheres: *Origin and Evolution*. Academic Press, Orlando-Florida, 1983.
Lyell, C. The Geological Evidence of the Antiquity of Man. London, 1863.
Margulis, L. Simbiosis in Cell Evolution. San Francisco, 1981, 320 p.
Nagy, B. Carbonaceous Meteorites. Elsvier, New York, 1975.
Nesis, K. What Was Happened with Ammonites? *Nauka i Zhizn*, No. 6, 1985.
Oparin, A.I. The Origin of Life on the Earth. Pergamon Press, London, 1959.
Oparin, A.L. Chemical Origin of Life (transl. by A. Synge). Charles C. Thomas, Springfield, 1964.
Owen, T. Life as a Planetary Phenomena. *Earth Orient. Appl. Space Technol.* 4, No. 1, 1984.
Perelman, A.I. Geochemistry of the Biosphere. Nauka, Moscow, 1973.
Prinn, R.G., Fegley, B. Ir. The Atmospheres of Venus, Earth and Mars: a Critical Comparison. *Ann. Rev. Earth and Planets.* Palo Alto, Calif. 15, 1987.
Ronov, A.B. The Sedimentary Shell of the Earth. Nauka, Moscow, 1980.
Rudenko, A.P. Evolutionary Chemistry—Historical Approach to the Problem of the Origin of Life. *Journal of Mendeleev Chemical Society*, 20, No. 4, 1980.
Runnegar, B. Molecular Paleontology. *Paleontology*, 29, No. 1, 1986.
Rutten, M.G. The Origin of Life by Natural Causes. Elsvier Publishing Company. Amsterdam, London, New York, 1971.
Scbidlowski, M. Application of Stable Carbon Isotopes to Early Biochemical Evolution on Earth. *Ann. Rev. Earth* and *Planet Sci.*, 15, 1987.
Schopf, J.W. The Evolution of the Earliest Cells. *Scientific American*, 239, No. 3, 1978.
Sokolov, B.S. The Organic World of the Earth on the Way to the Phanerozoic Differentiation.

Vestnik USSR Acad. Sci. Publ. No. 1, 1976.
Sokolov, B.S. Paleontology of Precambrian and Early Cambrian. Nauka, Leningrad, 1979.
Tsytsin, F.A. Cosmic Factors of the Origin and Development of the Life on the Earth and the Intellect in the Universe. *Journal of Mendeleev Chemical Society*, 25, No. 4, 1980.
Valentine, J.W. The Evolution of Multicellular Plants and Animals. *Scientific American*, 239, 1978.
Vdovykin, G.P. The Organic Substance in Meteorites. *Uspekhi Sovremennoi Biologii*, 8, No. 1, 1979.
Vernadsky, V.I. Biogeochemical Essays. USSR Acad. Sci. Publ., 1940.
Vernadsky, V.I. Chemical Structure of Biosphere of the Earth and Its Environment. Nauka, Moscow, 1965.
Vidal, G. The Oldest of Eukaryotic Cells. *Scientific American*, No. 4, 1984.
Voitkevich, G.V., Cholodkov, Yu.I. The Old Traces of Life on the Earth. Rostov University Publ., Rostov-on-Don, 1976.
Voitkevich, G.V. Die stoffliche Geschichte der Erde. VEB Deutscher Verlag für Grundstoffindustrie, Leipzig, 1986.
Voitkevich, G.V., Bessonov, O.A. Chemical Evolution of the Earth. Nedra, Moscow, 1986.
Voitkevich, G.V. Problems of Cosmochemistry. Rostov University Publ., Rostov-on-Don, 1987.
Voitkevich, G.V. Origin and Chemical Evolution of the Earth. Mir Publishers, Moscow, 1988.
Wickramasinghe, N.C., Wallis, M.K., Al-Mufi, S., Hoyle, F., Wickramasinghe, D.T. The Organic Nature of Cometary Grains. *Earth, Moon and Planets*, 40, No. 1, 1988.
Zavarsin, G.A. Bacteria and Composition of the Atmosphere. Nauka, Moscow, 1984.

SCIENCE FOR EVERYONE

The book though included in popular science series presents a vast panorama of geological events ranging from prehistoric times to the present period, and covers practically all the landmarks in the history of evolution. Various stages in the development of plants, animals, and man form a concatenation of scientifically valid discoveries with the disquisition of which the readers will become acquainted.

The author of this book is Prof. George Voitkevich, head of the department of geochemistry and geophysics at Rostov-on-Don State University. His multilateral scientific activity within the domain of the Earth sciences is well known in his own country as well as elsewhere. His *Fundamentals of Geochemistry* is at present the standard manual for Soviet universities, some of his books have been translated into European and Oriental languages.

ИЗДАТЕЛЬСТВО МИР

ISBN 5-03-001521-3