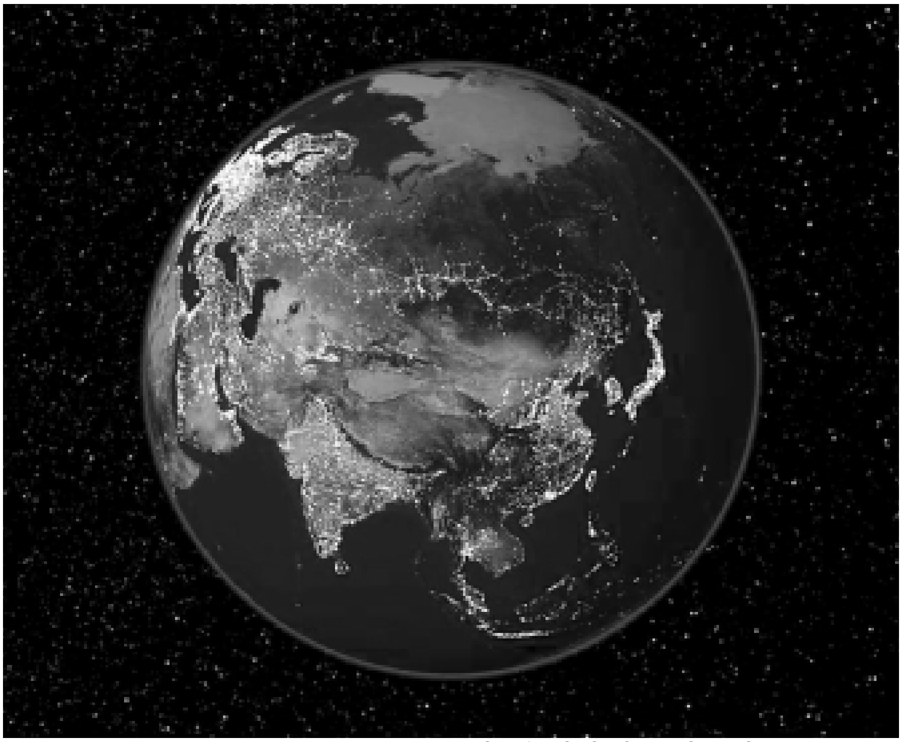
On Some Fundamental Problems of Biogeochemistry

In Connection with the Work of the Laboratory of Biogeochemistry of the Academy of Sciences of the USSR[1]

by V.I. Vernadsky

Member of the Academy of Sciences of the USSR



Data: AVHRR, NDVI, Seawifs, MODIS, NCEP, DMSP and Sky2000 star catalog; Texture: Reto Stockli; Visualization: Marit Jentoft-Nilsen

The Earth at night: A satellite view of the electrical lights created by man's activity in the biosphere.

I

Biogeochemistry, which is a part of geochemistry and has peculiar methods and peculiar problems of its own, may be finally reduced to a precise quantitative mathematical expression of the living nature in its indissoluble connection with the external medium, in which the living nature exists. A living organism thus acquires an aspect different from the one it has in biology; it is expressed in numbers of atomic or weight composition, in physical, quantitatively expressed, manifestations of the space it occupies, in numeral energetical expressions of the work it does in the space of life upon our planet.

Life in the biogeochemical aspect is the living matter of the biosphere, that is, the total of all the living organisms present in the biosphere at a given moment. Thus the living organism itself, expressed in numbers, is a new independent expression of the same phenomenon, which the biologist views in a vivid physiological and morphological expression of the innumerable forms of life. Between these precise and scientific expressions of life relations might be and should be sought for.

Biogeochemistry is, as shown by its very name, a scientific study of the phenomena of life in the aspect of atoms.

Hence, it seems to me that in the phenomena of life we may approach in a new way a number of fundamental problems of life, on one hand, and on the other, relate the biological phenomena. with the branches of science dealing with atoms; i.e. with that field of science, which distinguishes our epoch from the preceding ones. It is in this fundamental distinction of biogeochemistry from the other biological sciences that lies its importance and its interest for the biologist.

At present, we may quite definitely state that biogechemistry penetrates as far as atomic properties, and is not restricted only to the properties of chemical elements, since we may study the different reaction of life to different atoms of the same chemical elements, the different relation of life to the isotopes of the element. It was already evident at the first attack on biogeochemical phenomena that the problem could be advanced as a feasible one in this aspect. This was done by the author on the basis of an empiric generalization of scientific facts at the Academy of Sciences in 1926, ten years ago, and the problem was at once included in the plan of our Laboratory. At present, the problem may be treated with greater precision and assurance, since for hydrogen and potassium the distinction between their isotopes in biogeochemical processes may be considered as settled.

T.B. Pyatibratova, Tambov State Technical University

Vladimir I. Vernadsky (1863-1945)

Until recently the isotopes in the Earth's crust were distinguished by their effect only in radiochemical processes: In this way the problem was treated for potassium by the physiologists Zwardemaaker in Holland, and Stoklasa in Czechoslovakia. The new investigations carried out by Brewer in Washington in 1936 have shown that radiochemical processes have nothing to do with this, since both isotopes of potassium, with the atomic weights of 39 and 41—the ratio between the amounts of the latter varying in accordance with life processes—are not radioactive.

The problem we advanced in 1926 has never since left the field of vision of the Laboratory, but the circumstances prevented its development in the proper way. In 1931, the investigations of V.G. Khlopin and M.A. Khlopina-Pasvik showed for pea grains that within the range of *chemical* determination of the atomic weight, the atomic weight of potassium in the pea remains unchanged; they recognized, however, that this does not settle the question, since the variations may be of a lesser order, than the one detectable by their method.

Still earlier, at the same Laboratory, an attempt had been made to use more sensitive methods, but the construction of Dempster's apparatus, started nine years ago, proved to be beyond the possibilities of the Laboratory. After we had moved to Moscow, our position changed for the better, and the discovery of Brewer, who used an improved mass-spectrograph of Dempster, found us already engaged in the construction of the same mass-spectrograph and of another one, of J.J. Thomson's system, and of an apparatus for the determination of isotopes by a superfine spectrography of atoms. I hope that we shall be able next year to elucidate the problem.

At the same time, by courtesy of my son G.W. Vernadsky, professor at Yale University, New Haven, we have now obtained the necessary material for verifying Brewer's numbers, the material from those gigantic *Macrocystis* algae of the Pacific Ocean, upon which Brewer worked. From this material we extract potassium, which should be changed by the life process.

I hope to be able to report of the results of this work in the current academic year.

We are faced with a general problem. Is the change of the chemical element with a different atomic weight by the life process restricted to some few chemical elements, such as hydrogen and potassium, or is this a phenomenon common to all the organisms and all the chemical elements? Don't we have in this biogenic change of the atomic weight one of the numerous manifestations of a sharp material and energetic distinction of the living matter and the inert, which are observed in all of the biogeochemical problems? I shall return to this question later on.

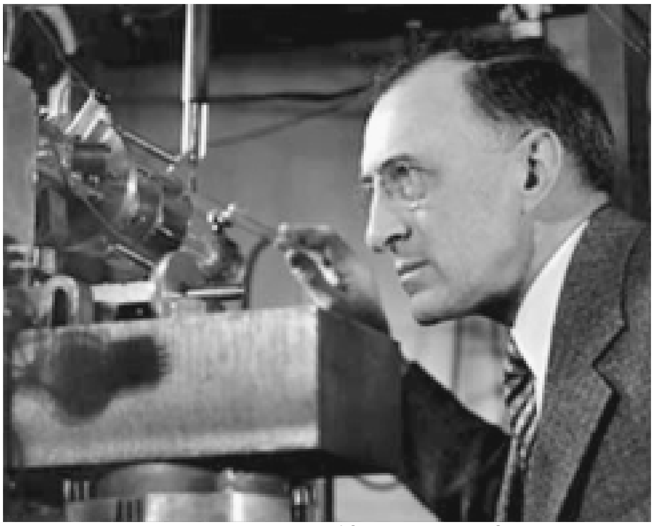
This question may be solved only experimentally.

Likewise, only experiment may show the part played by life in the variations of the atomic weight of the chemical elements, which are only just beginning to be observed in the geochemical processes in the Earth's crust and which up to now have been neglected.

This study cannot be only our object, since the change of the atomic weight is not connected only with life. It is a subject of geochemical investigation. The Laboratory restricts itself to the study of the biogenic change of the atomic weight; H, K, Mg, Fe, Zn await their turn in the investigation.

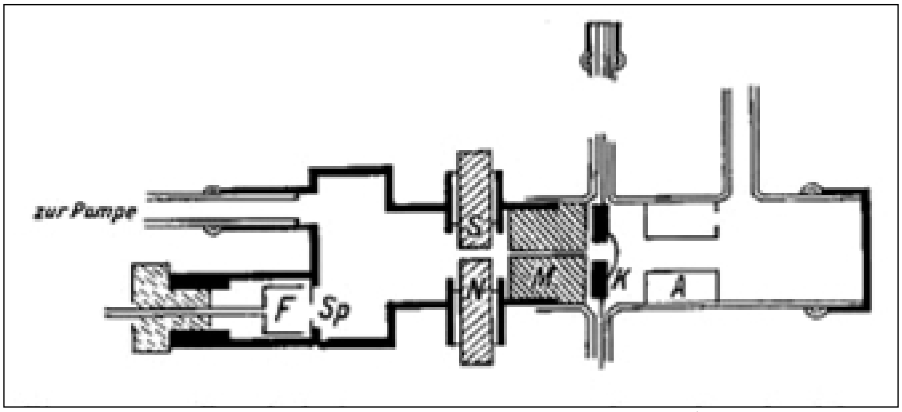
We cannot, however, overlook the other physiological side of the problem, when it is possible to advance it; that is, the question of the mechanism of the action of the organisms upon the isotopic mixtures of elements. We cannot treat this subject ourselves. But since with respect to potassium, the Laboratory will have at its disposal biogenic potassium with a different atomic weight, it is necessary to undertake the study of its vital properties.

It is most important to elucidate the physiological side of the phenomenon both for plants and for animals. With respect to plants and microbes we hope to receive assistance from the laboratories of D.N. Prianishnikov. Negotiations are conducted with the laboratory of A.V. Palladin, at the Ukrainian Academy of Sciences in Kiev, concerning a joint investigation of the problem as far as animals are concerned. The material of the potassium biogenically changed should be fully utilized.



Arthur J. Dempster (1886-1950) developed the mass spectrometer, which he used to discover many isotopes, including U-235. In this schematic of his spectrometer, ions are detected by means of a Faraday cup F behind a slit Sp. The poles of the magnet, S and N, are also the electric deflection plates, and M is ion shielding.

University of Chicago, AIP Emilio Segre Visual Archives



Karl Wien, *Brazilian Journal of Physics,* Vol. 39, Number 2.

II

A great part of our work is connected with a study not of the atoms themselves but of chemical elements, of isotopic mixtures. In purely chemical processes, all the isotopes of the same element are manifested in a similar way. Hence, while we remain within the field of purely chemical processes, the chemical element may be identified with the atom, as it is the case in the periodical system of elements. On this the whole chemistry is based.

Proceeding from this general statement, it has been possible to show by the work of our Laboratory that the atomic composition of organisms, plants, and animals is as characteristic a feature as their morphological form or physiological structure or as their appearance and internal structure. It should be noted that the elementary chemical composition of living organisms of the same species taken at different times, in different years, at different places, for instance in Kiev or in Leningrad, varies less than a natural isomorphous mixture of minerals, easily expressed by stoichiometric formulas. The composition of different species of *Lemnae* or *Insects* is more constant than the composition of orthoclases or epidotes from different localities. For organisms there is a narrow range within which the composition varies, but there are no stoichiometric simple ratios for them. An organism does not show a passive attitude towards the chemical medium; it actively creates atomic composition, it tends to choose, consciously or unconsciously, the chemical elements necessary for life, but as life presents a field of dynamic equilibria, it reflects—both in its composition and in its form—the different physico-chemical properties of the medium. These variations, however, do not change their average, little varying, expression.

A species established by biologists may be characterized in weight or in atomic composition as precisely, as by its morphological features, also within a definite range of variations it may characterize a homogenous living substance—the totality of organisms of the same species, race, jordanons—as it is characterized by morphological features. In the average numbers, the amounts of atoms, of chemical elements, composing a living organism, are as constant and as characteristic for it as its form, size, weight, etc. It is possible that in the numerical relations of living beings thus expressed, the same harmonious combinations will be found, which are so distinctly manifested in the vividness of the living nature. They should be probably manifested in harmonious relations of numbers in these natural bodies—in living organisms, as numerical relations are harmoniously manifested quantitatively in the natural bodies of the inert nature—in crystals and

Ministry of Agriculture and Lands, British Columbia, Canada

A small piece of the massive kelp, Macrocystis, *which was being studied by A.K. Brewer and others in the 1930s for evidence of isotopic fractionation of potassium. Mass spectrometry technology had not yet advanced enough to show it convincingly.*

minerals. The elucidation of this problem is a task of the nearest future.

The greater part of the personnel of the Laboratory is engaged in the study of the problem of the elementary chemical composition of living matter. I have already made reports at the Academy dealing with this side of the work of the Laboratory carried on under the supervision of A.P. Vinogradov. In the 6th volume of the *Transactions* of our Laboratory, now prepared for press, new numbers will be published, which are the result of an eight-year-long work. It may be assumed that in all the cases so far investigated we find a confirmation of the fundamental principle of biogeochemistry, namely, that numerical biogeochemical features are specific, racial, and generic characteristics of the living organisms. As yet it has been possible to establish it precisely for many species of plants and insects. But it is already clear that this is a general phenomenon. The relations are not so simple as one could have presumed. Many questions evidently arise that require biological criticism. I shall not, however, dwell upon this work for the present, for I think that the recognition of its biological importance for wide circles of naturalists is now beyond any possible doubt. It is but necessary to extend and develop in greater detail the work of the Laboratory.

We have first embraced by the precise methods 18 chemical elements; now we are able to make a quantitatively precise study of over 60, and we must comprise all of the 92, if not more, for it becomes still clearer and clearer that in the biosphere the living matter embraces and controls all or nearly all of the chemical elements. All of them are necessary for life, and not one of them comes to the organism by chance. There are no special elements peculiar to life. There are predominant elements. When taken as a whole, life comprises the total system of Earth elements, probably leaving aside but few of them, as, e.g., thorium, but probably comprising all of them in the different isotopes. Life is a planetary phenomenon and predominantly determines the chemistry, the migration of chemical elements of the upper shell of the Earth—the biosphere; it determines the migration of all the chemical elements. A quantitative investigation of such a migration is the fundamental task of the Laboratory.

III

It is to this planetary nature of life, in so far we lay it at the base of the scientific work of the Laboratory, that I intend to call your attention for as short a time as possible.

The following general statements based on the great totality of scientific facts exactly established should be taken as starting points:

(1) For life the field of life—the biosphere—is not a structureless casual Earth's surface—the face of the planet upon which life originated, according to E. Suess, or the cosmic medium of life according to Cl. Bernard. The biosphere is not only the face of the Earth and not a cosmic medium. This Earth's shell has a strictly definite composition and structure, determining, and controlling all the phenomena that take place within it, the life phenomena included; it is morphologically distinct but closely related to the general structure of the planet.

A number of most characteristic and important geological phenomena establish such a character of the biosphere with certainty. Its chemical composition, as well as all the other features of its structure, is not casual and is most intimately related to the structure and time of the planet and determines the form of life observed.

The biosphere is not an amorphous nature, a structureless part of the space-time, in which biological phenomena are studied and established independently of it; it has a definite structure changing in time according to definite laws. This is to be taken into consideration in all the scientific deductions, in the logic of natural science in the first place; and this is not done. The "nature" of the naturalist is only the biosphere. It is something very definite and delimitated.

If this structure is called a mechanism, it would be a special, very peculiar mechanism, a continuously changing equilibrium—a dynamic equilibrium—never reaching a state strictly identical in the past and in the future. At every moment of the past and of the future time the equilibrium is different but closely resembling. It contains so many components, so many parameters, so many independent variables, that no strict and precise return of some state in its previous form is possible. An idea of it may be given by comparing it to the dynamic equilibrium of the living organism itself. In this sense it is more convenient to speak of the *organized state,* rather than of the *mechanism* of the biosphere.

The biosphere may be precisely expressed quantitatively in atoms—like the living organisms; it has definite boundaries, which seem to be determined by the absence of conditions for the stable existence of the liquid phase of water. It extends upwards to the boundaries of the stratosphere, to within about 20 km from the level of the geoid, where water in all forms is practically and probably altogether absent, and downwards to 3-4 km below the land where the liquid phase of the water ceases to exist, and its gaseous phase begins to predominate. Here the anaerobe life begins to be prevalent. Under the ocean bottom it does not seem to extend down to a considerable depth. But here our knowledge is so meager that new exact facts must be awaited. The latent forms of life—in a disseminated inert state—extend far beyond the biosphere both upwards and downwards.

The chemical composition of the biosphere is sharply distinct from that of the Earth's crust, but it is not known to us with any degree of sufficient precision.

The "clarks" of the biosphere are different from those of the Earth's crust. Their precise determination is necessary for many problems having both a scientific and a purely practical importance and reaching far beyond the scope of problems treated in our Laboratory. For their determination, cooperation with other scientific institutions is necessary. At present we advance as a general task for the cooperation of a number of scientific institutions of our country, the development of a table of clarks (means percents of chemical elements) of the biosphere during the nearest few years.

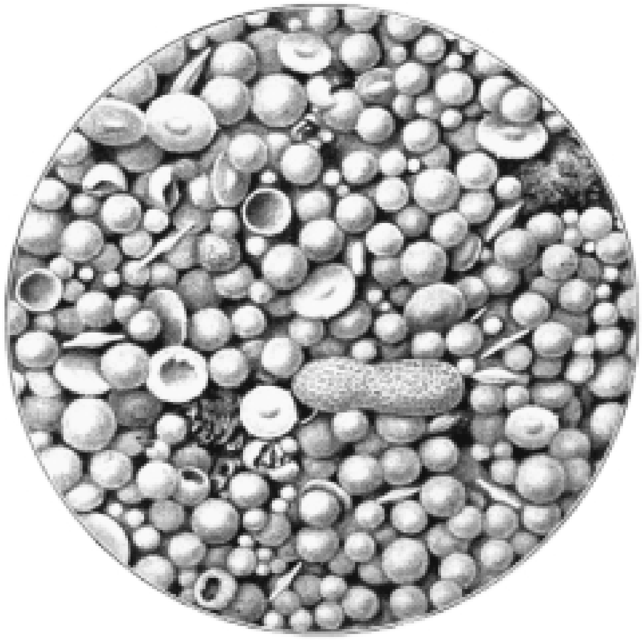
The table of clarks of the biosphere must form a solid base for the whole work of our Laboratory. It is no less indispensable for a scientifically correct treatment of the applied geology and mineralogy.

The Laboratory has started negotiations, concerning a cooperative solution of the problem (undertaking itself a part of the work) with Lomonosov, Petrographical and Soil Institutes of the Academy of Sciences, with the Oceanographic Institute, the Institute of Fishing, the chief Geophysical Observatory, and the Radium Institute. I hope that in the near future the first conference will be held at the Academy.

(2) Life is continuously and immutably connected with the biosphere. It is inseparable from the latter materially and energetically. The living organisms are connected with the biosphere through their nutrition, breathing, reproduction, metabolism. This connection may be precisely and fully expressed quantitatively by the migration of atoms from the biosphere to the living organism and back again—the biogenic migration of atoms. The more energetic the biogenic migration of the atoms, the more intense is life. It is nearly dying out or hardly flickering in the latent phases of life, the importance of which in the organized state of the biosphere has not as yet been evaluated, but should not be overlooked.

The biogenic migration of atoms comprises the whole of the biosphere and is the fundamental natural phenomenon characteristic of it.

In the aspect of historical time—within a decamyriad, a hundred thousand years—there is no natural phenomenon in the biosphere more geologically powerful than life.



From: *Aus den Tiefen des Weltmeeres,* by Carl Chun, 1903; Courtesy of NOAA

Radiolarians dredged from the seafloor. These single-celled creatures form skeletons of silicates. The fossils of such creatures settle in great masses on the seabed, forming much of the sedimentary layers over geological time.

(3) In the building and in the energetic aspect of the biosphere, three forms of the matter should be strictly distinguished: (1) the inert matter, created without direct participation of life; (2) biogenic matter, such as coals, oil, most of the limestones, etc., and finally (3) the living matter—the totality of the disseminated and separate living organisms.

The predominating mass, the whole skeleton of the biosphere, consists of inert matter, in which silicates, alumosilicates and their analogues are overwhelmingly prevalent in weight and in number of atoms. They compose the skeleton of the biosphere. The mass of biogenic substance for the biosphere constitutes some percent, much over 10, probably over 20 to 30 percent by weight. Here we return in a quite different scientific environment—to Lamarck's natural philosophic idea of the material planetary significance of life. Assuming the biogenic genesis of that manifestation of matter, which we call at present chemical elements, Lamarck considered the material substance of our planet to have been created by life. This we have to remember, although it is generally forgotten, when speaking of his ideas, of the evolutionary process of life. In his natural philosophy conceptions there was hidden a large grain of scientifically precise understanding—concerning the biosphere and not the planet—which was, however, concealed in the mist of vague philosophical intuitions.

The living matter, existing in the biosphere at a given moment, will hardly exceed some tenths fractions of a percent by mass when quantitatively estimating the biosphere. In

Archive of the Vernadsky Institute of Analytical and Geological Chemistry of the Russian Academy of Sciences
Alexander Pavlovitch Vinogradov (1895-1975)

preparing the table of clarks of the biosphere, the recalculation of the mass of the living matter and its critical evaluation will be the task of our Laboratory.

The chief geological importance of these masses of substance embraced by life, that seem small when compared to the mass of the biosphere, is connected with their exclusively great energetic capacity.

This property of the living substance, having nothing equal to it in the substance of the planet, not only at the given moment, but also in the aspect of geological time, completely distinguishes it from any other earthly substance and makes the distinction between the living substance and the inert substance of the planet quite sharp, the more so that all the living is derived from the living. The connection between the living and the inert substance of the biosphere is indissoluble and material within the geological time—of the order of a milliard of years, and is maintained exclusively by the biogenic migration of atoms. Abiogenesis is not known in any form of its manifestation. Practically, the naturalist cannot overlook in his work this empirically precise deduction from a scientific observation of nature, even if he does not agree with it due to his religious or philosophically religious premises.

In the scientific work of the naturalist, of the observer of the living nature surrounding him—the biosphere—no doubt can ever arise as to what he has to do with—a living or an inert natural body. Their sharp and fundamental material energetic distinction, the gap separating them, so to say—is striking. It seems to me that now for the first time in the history of scientific thought, in the filterable virus we come across a phenomenon where we are as yet unable to decide with precision and certainty whether we have to do with manifestations of the living or of the inert nature, of the living or of the inert substance.

This question will be settled in the nearest future. It is in this that lies the profound and philosophical interest of the scientific work which is now carried on in this field.

But one solution or another, the picture of nature, which is now revealed before us in the field of geochemistry and biogeochemistry, will not be affected, just in the same way as the discovery of the decay of atoms, of the variability of their atomic weight, does not in any way invalidate the laws of chemistry.

IV

The whole work of the Laboratory is based on such a structure of the biosphere, on the existence of an impassable sharp, materially energetical boundary between the living and the inert substance.

It is necessary to dwell on this point, since it appears to me that in this question there is a vagueness of thought, which impedes scientific works.

We do not proceed here beyond exact empiric observation, the deductions from which are obligatory for the scientist and as a matter of fact for every one; it is on this observation that he not only can, but must, base his work. These deductions may possibly be explained differently, but in the form of empiric generalization they are to be taken into consideration in science, for an empiric generalization is neither a scientific theory, nor a scientific hypothesis, nor else a working hypothesis. This generalized expression of scientifically established facts is logically as obligatory as the scientific facts themselves—if it has been logically correctly formulated.

The sharp material energetic distinction of the living organisms in the biosphere—of the living substance of the biosphere—from any other substance of the biosphere penetrates the whole field of phenomena studied in biogeochemistry.

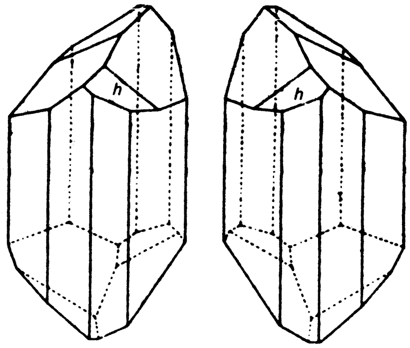
It is possible (this should be verified and investigated, but this study cannot be discarded, since it follows from the totality of biogeochemical facts) that among the phenomena characteristic and peculiar to living bodies alone, which sharply distinguish the living from the inert bodies, there is one phenomenon that is outstanding in its depth and significance, as well as in being little investigated; in the future, this field of researches may occupy a particular, dominating position in the work of our Laboratory, but as yet we can hardly approach it.

It was discovered over 70 years ago by L. Pasteur (who had predecessors, as for instance, Bechamp) and was not very suitably named by him "dissymmetry." Pasteur was the first to understand and express its fundamental meaning. He strongly emphasized it, but other problems diverted his attention from the work in this field. About 20 years later, the same phenomenon was taken up by P. Curie who died not only before having time to work his results, but even before being able finally to formulate them.

In his latest investigations he has defined these phenomena, as it seems to me, more deeply than Pasteur, pointing out the logical mistakes of the latter. Curie has pointed to the connection of dissymmetry with the thermodynamic and biochemical fields of life, with the volume of the organism, with the space occupied by it; he has indicated the spatial dissymetrical state of this space—the *state of space* in the biosphere, peculiar only to living beings.

From a painting by A. Edelfeld, 1889

Louis Pasteur (1822-1895). Pasteur's discovery of left and right-handed isomers of tartaric acid crystals led him to first express the meaning of dissymmetry.



PASTEUR'S SKETCHES OF LEFT-HANDED AND RIGHT-HANDED TARTRATE CRYSTALS

Vernadsky: "But in the sharp material and energetical distinction of the living substance in the biosphere from the dead, or inert matter, the phenomena of right- and left-sidedness hold so considerable a place, possibly a principal place, that in biogeochemistry we cannot overlook and pass them unnoticed."

A manifestation of Pasteur's dissymmetry and of Curie's peculiar "state of the space" of life is also found in the phenomenon of *right-sidedness* and *left-sidedness,* which has been known for thousands of years, but is only just beginning to be attacked by scientific thought. It has been up to now left outside the logical, mathematical, and philosophical analysis, although it is evidently connected with the deepest scientific problems.

In this respect it has shared, and shares, the destiny of the scope of reality, which corresponds to the conception of *symmetry,* within the boundaries of which operated the thought of both Pasteur and Curie. The experimenting physico-chemists are only just beginning to realize the significance of the theory of symmetry.

This insufficient logical, mathematical, and philosophical treatment of the phenomena of both symmetry and of right- and left-sidedness (dissymmetry) greatly hampers our work. But in the sharp material and energetical distinction of the living substance in the biosphere from the dead, or inert matter, the phenomena of right- and left-sidedness hold so considerable a place, possibly a principal place, that in biogeochemistry we cannot overlook and pass them unnoticed.

In phenomena embraced by the laws of symmetry, the dissymmetry is pronounced in the *inequality* of the quantitative and physico-chemical manifestations of right- and left-sidedness, the processes in these phenomena being *irreversible* since a dissymetrical space is characterized by polar vectors. They will express also the *time.* The *polar vector of time* characterizes just the irreversibility of the processes in time. In the inert nature, in its natural bodies—in crystals both natural and artificial—there is no inequality of right and left phenomena. In crystals, formed in the life processes, the inequality is most distinctly pronounced.

In the physico-chemical equilibria of our laboratories and in those in nature where life is absent, the right and left chemically similar components act similarly, as it follows from the laws of symmetry; they are chemically identical. In biochemical processes, going on, e.g., in the protoplasm, the inequality of the right and left component of the same racemic compound is most distinctly pronounced and may be both quantitatively and qualitatively traced to the end. In this field, in connection with our Laboratory, work has been started by Dr. G.F. Gause.

The study of dissymmetry is one of the current objects in the work of our Laboratory, but we shall be able to begin it only next year.

We cannot shut our eyes, however, to the fact that Pasteur was possibly right, when contemplating in the investigation of these phenomena a way towards the solution of the most important biological problems, and seeking in them the possibility of creation of life on our planet.

One point is doubtless. An analysis even of the present information, so incomplete and so far from perfect, shows that connected with dissymmetry are some of the principal distinctions of the living from the dead, some of the fundamental manifestation of life in the biosphere.

The deeper proceeds our work, the clearer this is revealed.

It was clear already for Pasteur that dissymmetry in its manifestations may be produced only by a *cause having a similar dissymmetry;* but a logically deep deduction of this was made only by P. Curie; this inference may be expressed as a special logical principle determining the existence of life in the biosphere. It may be termed the *Pasteur-Curie principle,* and formulated as follows: *a dissymmetrical phenomenon is produced only by dissymmetrical cause.*

Hence it logically follows that the living in the biosphere will always originate only from the living; from dissymmetry, a logical inference maybe made of that great empiric generalization (1669) which I have named the *principle of Redi,* who was the first to advance it: *all the living is born from the living.* Another conclusion logically follows from dissymmetry, namely, that a dynamic equilibrium connected with life cannot be reduced in its physico-chemical consequence to reversible processes, since the time vector in a dissymmetrical state of the space is always polar.

There is still a third conclusion that may be logically reached, which is characteristic of the phenomena of life in the biosphere. It is as follows: In a limited definite region, distinctly separated from the rest of the planet, in a special shell of the Earth formed by the biosphere, which is characterized by irreversible processes—*life will increase* and not decrease in the course of time *the free energy of this shell.* This deduction, empirically observed, may be logically made from dissymmetry.

Le Radium *magazine*

Pierre Curie (1859-1906). Curie's study of the laws of symmetry led to his prediction and later discovery of the piezoelectric effect.

V

I shall not dwell here on a further analysis of the idea and significance of dissymmetry. I wanted only to call the attention of our scientific workers to the enormous significance of the dissymmetry phenomena so little attacked as yet by scientific thought. Our Laboratory will inevitably have to study these phenomena, and I am sure to be furnished with all the material means required.

It is, however, a great and difficult task—there is no wonder that it has not advanced during two or three generations. It calls for the cooperation of different specialists—of the physicist, biologist, biophysicist, physicochemist, and mathematician. It ought to be considered in the geological aspect.

It seems to me that I shall not take up your time in vain, when—with the same object of calling your attention to the neglected domain of knowledge which in my opinion is one of the greatest importance—briefly summarize those highly important phenomena which sharply and decisively distinguish the living matter in the biosphere from the lifeless matter, geologically long periods of time (no less than two or three milliard years). The connection between them exists only in the form of a biogenic migration of atoms.

These are:

(1) Dissymmetry.

(2) Abiogenesis connected with it: a living organism originates in the biosphere only from a living organism.

(3) Irreversibility of life phenomena connected with it.

(4) The accumulation of free energy as a result of the life process within the biosphere, connected with dissymmetry. The biosphere becomes more and more active in the course of the geological and historical time. I shall return to this phenomena some other time.

(5) The spreading of life in the biosphere goes on by way of reproduction which exercises a pressure on the surrounding medium and controls the biogenic migration of atoms. It is absent in the inert substance. The reproduction creates in the biosphere an accumulation of free energy which may be called *biogeochemical energy.* It can be precisely measured.

In our Laboratory we have not yet started a systematic work on the biogeochemical energy, since it is clear that this problem is a biological rather than a chemical one. It requires a special scientific organization, since the vast biological material concerning it has not been systematized nor collected, but is scattered, partly lost, and not used rationally. In the first place, all that is already known, must be brought to a form accessible for scientific work. It is necessary to prepare first a card-index continually operating and as complete as possible, on the reproduction of organisms and their spreading in the biosphere. The two problems are inseparable. They should comprise all the precisely established quantitative data available that are required for the derivation of the constants of biogeochemical energy. Shortly before moving to Moscow, the Laboratory approached the organization of such a card-index in Leningrad. At present we are carrying on negotiations with the biologists of Moscow concerning its organization here, in connection with the Laboratory, but separated from the latter. The card-index should be used both by us and by biologists.

(6) Theoretically it is possible to derive the speed of spreading of every species of organisms in the biosphere, characteristic and constant for each species (the ν value). This speed is restricted within some limits, which are quantitatively determined by: (1) the dimensions of the biosphere, that is, of the planet in the long run, and (2) by the minimum dimensions of the organisms, connected with the Loschmidt's number, limiting the number of breathing organisms which can be present in a cubic centimeter of material space.

(7). The speed of spreading and reproduction is inversely proportional to the size of the organisms (generalization of A. Sniadecki, 1794). It attains its maximum value, ultimate under conditions of the biosphere. But life has a striking adaptability, and there can exist forms of life of an explosive nature, which are in a latent state during the greater part of their existence. These forms in the value of biochemical energy exceed the ν value, known for the usual manifestations of life.

Francesco Redi (1626-1698). Redi was the first to advance the principle that all the living is born from the living.

The whole biosphere is penetrated by life, embracing all its space. The spreading of life in the biosphere presents a full analogy with the spreading of gas in a limited space. Life, like gas, exercises pressure in the medium in which it penetrates.

(8) Every living organism has a certain autarchy; it actively selects from the surrounding medium the necessary chemical elements, may be, atoms. It is a biogeochemical and biochemical, but not a purely chemical reaction.

(9) Numerous other marked distinctions of a living substance from the inert matter of the biosphere may be noted. I cannot dwell on them at great length, but still I must say a few words on this subject, since it is concerned with a field of phenomena that have not attracted due attention on the part of naturalists. There is a marked difference in the rate of the biogenic migration of the chemical elements as compared with the migration of the elements of the inert matter of the biosphere. The biogenic migration is distinctly pronounced in a historically prolonged time; it takes place in the limiting cases with a speed of the order of the velocity of sound—the maximum possible movement in a material medium not connected with its destruction, with a permanent deformation of the medium itself.

The migration of chemical elements in an inert substance of biosphere proceeds at an exceptionally slow rate, and as a rule is manifested only in the duration of geological time, for which the relative duration of a hundred thousand years—a decamyriad—is not much greater than the duration of a second in the range of historical time. In a number of cases, for the bulk of the biosphere, not penetrated by life, the atoms are immobile, retaining their position for hundreds of millions—possibly up to two or three milliards years. A direct comparison of the composition of the natural objects, the living and the inert natural bodies, cannot be made without a correction for the velocity of spreading, for their biogeochemical energy. In the space time, in the volume occupied by a living organism, not only is the space in a particular dissymmetrical condition, but also time is manifested in a way different from that in which the time of the biosphere is manifested.

In the duration of geological time in the biosphere life manifests itself in the evolutionary process.

VI

Particular attention is to be paid to the presence of radioactive elements in living organisms. An investigation of these has been carried on at our Laboratory ever since the time of its foundation. We have established the constant contents in living organisms first of radium and then of its isotope—mesothorium I. It has been found that these elements are also characteristic—in their quantity—for every morphological and physiological expression of a living substance, for every taxonomic expression of such a substance, like other elements. This is, of course, quite comprehensible and could rouse no doubt, but in this case, due to the peculiar character of the decaying atoms—centers of radiation of an immense active energy produced by atomic concentration—a selective concentration of radioactive elements by living organisms—the investigation acquires a particular importance.

Evidently the organisms, in selecting radioactive elements, use the energy of the latter. It seems to me that this fact by itself is sufficient for an understanding of the importance of the connection between the phenomena of life and the structure of the biosphere.

The work of the Laboratory follows, on one hand, the line of collecting quantitatively expressed facts, and of increasing the number of radioactive elements investigated, on the other.

The Laboratory has proved not only the presence of a concentration of radium, but also of its isotope—mesothorium I. It has been for a year now that V.J. Baranov has been carrying on work concerned with the occurrence of actinium—a field as yet untouched by experiment and exceedingly difficult.

The investigations of our Laboratory have shown—on the basis of the considerations I have derived theoretically—the absence of usual thorium (with an accuracy within 1 percent) in the *Lemnae,* while the other isotope of thorium—radio thorium—invariably enters in the organism as a product of decay of mesothorium I.

This phenomenon enabled our radiologists to develop a new method for uranium determination. The problem of uranium and its occurrence in organisms, with its quantitative estimation, is now comprised in the plan of the work of the Laboratory.

It has been found possible to proceed deeper and to advance, using V.J. Baranov's method, the problem of the location of individual radioactive atoms in a living organism, in the cells, and of their connections with the morphology of the cell.

The investigation should give a clear picture not only of the concentration of radioactive elements, but also of a quantitative estimation of the heat energy received by a given living organism and the nature of its utilization by the organsim—in connection with its biological characteristics.

The results already obtained clearly show that the way we have chosen to follow is the right one.

Some technical difficulties have delayed the progress of our work for a whole year, but this is only a temporary delay.

VII

Among the other investigations of the Laboratory, that are of a more particular nature, I have to mention the work connected with the biogeochemical role of silicium and aluminium. The fact is that in the scientific material up to now collected there are no precise data that could serve for elucidating the biogeochemical process which is responsible for the accumulation of great masses of biogenic silicium—and probably aluminium—minerals. We know only that both at the present time and in the geological epochs of the past there exist and existed organisms siliceous and rich in silicium, and aluminous and rich in aluminium.

The biogenic migration of these elements is undoubtedly of an exceedingly great importance, since these two elements are predominant in the biosphere. The course of their migration may be said to have been only just suggested.

Due to the particular significance of these processes, which must play an exceptional part in the biosphere, and after a number of fruitless attempts to organize their study elsewhere, I have begun the investigation of one of them in our Laboratory—namely, the decomposition of kaolin clays, of the kaolin complex ($Al_2Si_2 0_7$), by the diatomaceous and bacteria. The investigations have been successfully carried on for a year by A.P. Vinogradov and E. A Boychenko.

It seems that the weathering of alumosilicates in nature—in soils—is connected with unicellular vegetable organisms and constitutes a part of a great process which is of a paramount importance for the vegetable cover of the Earth and for the geochemistry of the sea, where the free atoms of silicium, produced during the biogenic decomposition of the alumosiliceous complex, are collected in the algae.

In the recent years, more and more facts are collected which reveal the great part of the alumosiliceous complexes—of free alumosiliceous acids and oxyacids—in the soils and in the nutrition of plants. There is much evidence in favor of these bodies being formed in a biogenic way in the soils and presenting a characteristic feature of their chemistry.

I have no possibility to extend the scope of this investigation in our Laboratory. It remains for the pedologists or geochemists to carry this study to the end.

It seems to me that this investigation is now particularly timely in pedology. Sooner or later, it shall be started.

VIII

The study of the biogenic migration of the atoms of the living substance is the fundamental task of biogeochemistry. In spite of the fact that the mass of all living organisms is negligible when compared to the biosphere, since it is of the order of some tenth fractions of a percent—as a matter of fact, the living substance determines the whole chemical structure of the biosphere.

In the long run it leads to the creation of a considerable part of the substance of the biosphere; we do not know precisely how large it is, but it seems to be much in excess of one quarter of its mass.

In this biogenic mass we see marked differences distinguishing it from the remaining, inert matter of the biosphere.

Two forms of biogenic substance should be here distinguished: first, the one which is the final product of decay of a living substance—of its decomposition to simple fundamental compounds. Here belong the gaseous products of breathing and of biogenic metabolism CO_2, H_2, CH_4, N_2, H_2O, H_2S. The living substance, by way of a complicated process, passes to the final products of a simple composition, such as the above gases, or to solids and remains of skeletons—opals, carbonates, iron ores, phosphorites. They do not always bear traces of their biogenic origin. This is a return to inorganic bodies, partly original for the living substance; this is the completion of the cycle. It should be noted, that the Earth's gases which we generally encounter in the biosphere, in the form of vadose products, are the same as are created by the processes of life in the way indicated. Direct observations and calculations show that the atmosphere of our planet, the gaseous part of the planet, is in the overwhelmingly greater part a product of life. One may speak of the biogenic origin of the troposphere, for O_2, H_2O, N_2, CO_2. But the whole regime of the gases of the biosphere, of its underground atmospheres, where CO_2, H_2O, hydrocarbons play a prominent part, are genetically related to life.

From these biogenic minerals—gases and last inorganic rests—those products of dying, of the extinction of life, should be distinguished carbonaceons bodies in a solid or liquid state—great agglomerations of petroleum, coal, asphalt, humus—biogenic minerals. They play a conspicuous part in our civilization and with them, to a considerable extent, a new form of biogenic migration of elements is developed—the one created by human technics. Technics acts in the same direction, finally converting these products of life—of biochemical and biogeochemical reactions—to simplex compounds, finally to gases and inorganic rests partly creating new intermediate biogenic forms of matter. The laws of the technical biogenic migration of the elements, of the activity of *Homo sapiens,* are the same as for the other forms of biogenic migration.

The organic biogenic minerals are markedly different

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Shewanella, an iron-reducing bacterium, is found to fractionate iron (Fe) isotopes, selectively concentrating Fe-56 over Fe-54. As the sensitivity of modern techniques has increased, the existence of such fractionation by living processes has become amply illustrated.

from the minerals, composing the inert skeleton of the biosphere. We may always make sure of their particular state and can always distinguish them from the other minerals of the biosphere.

They have such features that distinguish them from the other inert matter of the biosphere which in some part possibly might have never been alive. They *have been living,* and this is seen both in their material composition and in definite biogeochemical manifestations, in the first place in their composition.

Due to the vast scale of biogenic migration, the composition of the living organisms is markedly different from that of the natural products of the inert matter of the biosphere. It is distinguished by the number of building compounds, amounting to hundreds of thousands or even to millions. The only number of species of insects probably approaches 10 million, of which about 800,000 are known at present. In every species there is a large number of its special chemical compounds. This variety of chemical structures is the manifestation of a special biochemical and biogeochemical energy of the living organism, of the biogenic migration of its atoms in the biosphere, proceeding in range of historical time, in seconds. For the minerals, leaving aside those of carbon (rightly considered by C. Harichkoff as a special part of the mineralog—mineralogy of carbon), but taking into consideration natural waters, over four- or five-thousand species may be expected. This number increases if we take into account the carbonaceous dead remains of organisms. Death abruptly interrupts the existence of an endless number of compounds. And still, the carbonaceous organogene minerals being fully deciphered should exceed (probably even several times) all the other minerals—the natural bodies of inert substance.

At the present moment of the history of biological sciences more important for us is another property of carbon, the manifestation of dissymmetry, the presence of traces of former life in the form of manifestations of inequality of right and left phenomena. Thus, the petroleums contain in a prevailing amount right isomers—their mixture, separated from their left isomers by the living process. The same is observed in humus, peats, and coals. The methods, indicated by L. Royer, enable us to establish it not by rotating the plane polarization of light as it is done for petroleums, but by rotating of the etching figures of crystals. And here right hand rotation seems to predominate. This work in a preliminary way has been begun at our Laboratory, but this year it has been postponed. We shall, however, resume it at the nearest opportunity, for connected with it are the principal questions of the biogeochemistry of carbon. It is probable that all the atoms of carbon, which are present in the biosphere, have passed during the geological time, during the milliards years of the existence of the biosphere, through the living substance.

For asphalts, however, this question cannot be considered as settled, The connection of some of them with V and Hg requires an investigation. The problem may be solved with the aid of etching figures. I have attempted to elucidate in my paper the significance and the interest of the new way which has brought us to the organization of the Biogeochemical Laboratory.

I am fully convinced, that in this field even the fundamental problems which will be opened before us, cannot be foreseen at present. Many problems in biogeochemistry, advanced in the recent years, have already attracted attention, and new facts, the basis of our knowledge, are rapidly collected in the course of work conducted not only within this country.

Moscow, 1936

Editor's Note

1. This manuscript is from the archives of the Columbia University Library. It was published in Russian in *Izvestiiakh Geologicheskoi Gruppy* AN, CCCP (Bulletin of the Geological Group, USSR Academy of Sciences), 1938.

A translation of Vernadsky's "Problems of Biogeochemistry II: On the Fundamental Material-Energetic Difference between Living and Nonliving Natural Bodies in the Biosphere," (1938) appeared in the Winter 2000-2001 issue of *21st Century.* A translation of Vernadsky's 1943 paper, *"Some Words About the Noösphere"* appeared in the Spring 2005 issue of *21st Century.*

For a brief biography of Vernadsky, see "Vladimir Ivanovich Vernadsky (1863-1945): Pioneer of the Biosphere" by George B. Kauffman, *21st Century,* Winter 2000-2001.