The Evolution of Species And Living Matter

Appendix to the French Translation of *The Biosphere*

by Vladimir I. Vernadsky

Translated from the French by Meghan Rouillard

Mollusk shells represent one of the first cases of biogenic migration of calcium.

TRANSLATOR'S NOTE

The text is from a speech given by Vernadsky to the Society of Naturalists of Leningrad on February 5, 1928. All footnotes were written by the translator.

From the Introduction to the French translation of *The Biosphere* written by Vladimir Vernadsky:

This book appeared in Russian in 1926. The French translation has been reviewed and in several instances, restructured, comparatively with the Russian text. It followed our essay on "Geochemistry," published in the same collection (1924), of which a Russian translation just appeared and of which a German translation will soon appear.

We will not give any bibliographic indications as they can be found in our "Geochemistry."

We have touched upon the same problems in various articles, of which the most important appeared in French in the Revue Générale

des Sciences *(1922-1928) and in the* Bulletins de l'Académie des Sciences de Leningrad *(Petersburg) (1926-1927)*.

The purpose of this book is to draw the attention of the naturalists, geologists, and above all, that of the biologists, to the importance of the quantitative study of life in its indissoluble relationships with the chemical phenomena of the planet.

We have tried to constantly stay on the empirical terrain without making hypotheses, a terrain which is still somewhat restricted, because of the small number of observations and precise, quantitative experiments which we had at our disposal.

It is essential at the present time to assemble in the shortest amount of time the greatest number of quantitative, empirical facts.

We cannot delay in trying to succeed in doing that, that is, only as soon as the great significance of the biosphere for living phenomena becomes clear.

Maybe this essay, whose purpose is to shed light upon this significance, will not go unnoticed.

I attach, as an appendix to the French translation, my speech, "The Evolution of Species and Living Matter," which seems to me to supplement the ideas established in The Biosphere.

Vladimir I. Vernadsky
December 1928

The Evolution of Species and Living Matter

1) Life constitutes an integral part of the mechanism of the biosphere. It is that which clearly stands out in the study of the geochemical history of the chemical elements: biogeochemical processes, so important, always require the intervention of life.

These biogeochemical manifestations of life constitute an ensemble of living processes, absolutely distinct, upon first view, from those studied by biology.

It still seems that there is an incompatibility between these two aspects of life, between its biological aspect and its geochemical aspect, and only a more profound analysis allows us to recognize the character of this difference.

It forces us to see that it is, in part, a question of identical phenomena which manifest themselves diversely, and in part, of living phenomena which are effectively different and considered differently; that is, either from the point of view of geochemistry, or, on the contrary, from that of biology.

The comparison of these two points of view transforms the scientific conception of the phenomena of life and gives more depth to it.

The difference between these two representations of life manifests itself in a particularly striking manner in the fact that the theory of evolution, which permeates the entire current biological conception of the universe, plays no role in geochemistry. Here, we will strive to shed light on the importance of the phenomena of the evolution of species in the mechanism of the biosphere.

From that standpoint, it is easy to convince oneself that the fundamental conceptions of biology must be submitted to radical modifications.

The species is habitually considered, in biology, from a *geometrical* point of view; the form—the *morphological characteristics*—are primary, in terms of importance. In biogeochemical phenomena, on the contrary, this is reserved to the number, and species is considered from an *arithmetic* point of view. Different species of animals and plants must be, in the manner of chemical and physical phenomena, composed of chemical compounds and physico-chemical systems, which are to be characterized and determined in geochemistry by *numerical constants*.

The morphological indicators which have been taken up by the biologists, and which are necessary for the determination of the species, are replaced by numerical constants.

In biogeochemical processes it is indispensable to take into consideration the following numerical constants: the mean weight of the organism, its mean *elementary chemical composition*, and its *mean geochemical energy*, that is to say the facility with which it produces displacements, otherwise called "the migration" of chemical elements in the living environment.

In biogeochemical processes, it is matter and energy which are primary instead of the inherent form of the species. The species can, from this point of view, be considered as a material analogous to the Earth's crust, as waters, minerals, and rocks, which, for the organisms, are the object of biogeochemical processes.

Seen from this angle, the species of the biologist can be envisaged as *living homogeneous matter*, characterized by mass, elementary chemical composition, and geochemical energy.

Normally, the characteristics of species are expressed by numbers informed by weight, chemical composition, and speeds of transmissions of geochemical energy, but these do not give anything but an abstract and very obscure idea of the reality.

It is possible to replace this idea with another, which relates more clearly to the character of the natural process which creates the organism. In this domain, we may take the point of view of physical chemistry and consider the organisms as autonomous fields where determined atoms in determined amounts are reunited.

This quantity constitutes precisely the characteristic

Drawings by Ernst Haeckel of early photosynthetic material.

property of each organism and each species. It indicates the number of atoms that the organism of a given species can retain due to its force outside of the field of the biosphere, atoms which are drawn, thus, from the ambient environment. The volume of the organism and the number of atoms which compose it, expressed numerically, give the most abstract formula, but, at the same time, the most real measurement of how the species is reflected in the geological processes of the planet. We obtain this formula in measuring the size of the organism, its weight and chemical composition. This *number of atoms* and the volume of the organism thus determined are indubitably characteristics of the species. The presence of life in a sphere of determined volume with the concentration of a certain quantity of atoms constitutes a real phenomenon of nature, as characteristic for an organism as its form or physiological functions.

Fundamentally, this idea probably expresses with the greatest depth the essential traits of its existence.

The numbers obtained are very considerable: For example, concerning the *Lemna minor*,[1] the number of atoms for an organism is greater than 3.7×10^{20}, and reaches the hundreds of quintillions.

These great numbers correspond to reality, and lend themselves to numerical comparisons between the different species.

This determination of the species according to the number of atoms comprised in the volume occupied by the organism, only deals with the more customary biological characteristic of the species, which does not take into account the form and the structure.

The homogeneous living matter of geochemistry and the species of biology are identical, but the modes of expression are different.

2) The study of living phenomena in the mechanism of the biosphere shows differences which are still more essential, among the ordinary biological notions.

The biosphere in its fundamental traits has not changed, in the course of geological epochs, since the Archeozoic, since at least two billion years ago.

This structure reveals itself through a great number of corresponding phenomena, among them the biogeochemical phenomena.

Thus the geochemical cycles of the chemical elements seem to remain immutable in the course of geological time. The Cambrian should have the same character as the Quaternary Epoch or that of our days.

The conditions of climate, volcanic phenomena, and the chemical and physical phenomena of erosion have remained, in the course of all the geological epochs, as we now observe them. In the course of the entire existence of the Earth until the appearance of civilized humanity, not a single new mineral was created. The mineral species on our planet have remained the same, or were modified over time in an identical way. The same compounds as those of today have been formed for all time. In no case would we know how to relate a mineral species to a determined geological epoch. It is in this that the mineral species sharply distinguish themselves from living homogeneous matter, from species of living organisms. These latter modify themselves in a very marked way in the course of geological time; they spring forth and are always new, whereas the mineral species remain identical. Life, considered from the geochemical standpoint, as an element of the biosphere, submitted to simple

1. i.e., duckweed.

oscillations, taken in its entirety, appears as stable and immutable.

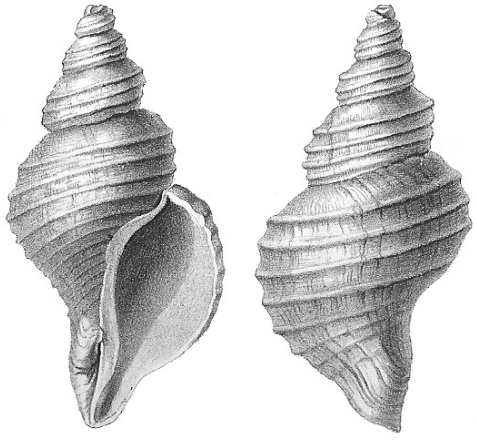
Life constitutes an integral part of the geochemical cycles which unceasingly renew themselves, but remain always identical, and it would not be able to undergo great changes in the course of phenomena studied by geochemistry. The mass of living matter, that is to say, the quantity of atoms captured by the innumerable autonomous fields of living matter, the mean chemical composition of the atoms of living fields, must, in sum, remain invariable across geological periods.[2] Moreover in the course of centuries, the forms of energy connected to life, the solar radiation and probably the atomic energy of radioactive matter, are not modified overall in terms of their amount.

We do not register in all these phenomena anything but oscillations, sometimes in one direction, sometimes in another, around a mean magnitude which appears to us as constant.

3) This immutability which characterizes all cosmic processes in the course of geological time, offers a striking contrast to the profound modifications undergone, at the same time, by the living forms studied in biology.

In particular, it is absolutely certain that all the characteristics of species, established by geochemical phenomena, are, again and again, radically modified throughout the geological epochs. Many a time have numerous animal and vegetable species disappeared, and new species were formed with a different weight, a different chemical composition, and another geochemical energy than those which preceded them. We cannot doubt that the chemical composition of bodies which are morphologically diverse is not altogether different. The extinct species necessarily corresponded to other forms of homogeneous living matter which have now gone extinct. Their numerical constants were different.

If, nevertheless, the general action of life remains identically the same in its details as compared, for example, with the phenomena of erosion, this indicates *the possibility of the formation of new groupings of the chemical elements, but not radical modifications of their composition and their quantity*. These new groupings do not affect



Mollusk shells mainly utilize calcium, whereas later structures like bone incorporate calcium in addition to other elements.

the constancy and immutability of geological processes.

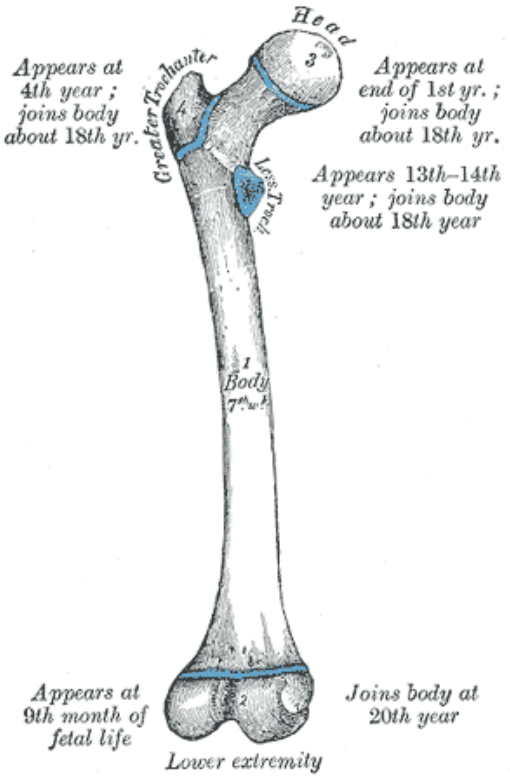
It is a new fact of enormous importance for science, and we are beholden to its introduction into the domain of biology, to the geochemical study of life.

Whereas the morphological, geometrical aspect of life, taken in its entirety, undergoes great changes and continually manifests itself by the great evolution of living forms since the Archeozoic Era, the numerical, quantitative formula of life, always taken in its entirety, remains immutable in its essential proportions and, it seems well to be the case, in its essential functions.

It is true that the attentive study of the phenomena of evolution, in the case of biology, reveal the extreme irregularity of its progress. It cannot be a question of a constant change of all species, of all forms of life. On the contrary, certain species remain immutable for hundreds of millions of years, as, for example, the species of radiolaria from the Precambrian Epoch, which are impossible to distinguish from those of today; the same also goes for the species of the *Lingula*, which, since the Cambrian until our days, have not undergone a single change: they have stayed the same during the course of hundreds of millions of years, across innumerable generations which succeeded. We can cite a great number of analogous examples for periods which may not be as long, during which, if there were changes, they were, in any case, of little consideration. We can also, consequently, observe and study in living forms, not their *variability*, but their extraordinary *stability*. It could even be that this stability of forms of species over the course of millions of years, millions of generations, is the most characteristic trait of living forms, and merits the most profound attention of the biologist.

These purely biological phenomena are probably the manifestation of the immutability of life, considered in its essence in the course of all of geological history, immuta-

2. Ten years after making this speech, Vernadsky had altered his formulation either due to new data available to him or perhaps a more ontological reason: "*The mass of living matter of the biosphere is close to the limit and, evidently, remains a relatively constant value on the scale of historical time. It is determined, above all, by the radiant energy of the Sun, falling on the biosphere, and by the biogeochemical energy of the process of colonization of the planet. Evidently, the mass of living matter increases in the course of geological time, and the process of the occupation of the Earth's crust by living matter has not yet been completed.*" -1938, "On the Fundamental Material-Energetic Distinction Between Living and Nonliving Natural Bodies of the Biosphere."



Bone incorporates other elements besides calcium, such as phosphorus.

bility which, in another form, is revealed through its role in the mechanism of the biosphere.

This stability of species, would merit, it seems, to draw more attention from the biologist than is currently the case.

The thought of the contemporary biologist orients itself in another direction. The evolution of forms in the course of geological time seems to be the most essential trait of the history of life; it embraces, for us, all of living nature.

This phenomenon was noted empirically, and in an absolutely rigorous way, one hundred years ago, by G. Cuvier, a naturalist of great profundity and precision, who demonstrated the existence of another universe, which we have ignored, of an earlier geological epoch.[3] This consideration served as a provocation during the lives of A. Wallace and C. Darwin, and later provoked a radical change of the entire conception of the scientific universe of the naturalist. The evolution of species occupies a central place in this conception, but draws attention to it to the point of forgetting about other biological phenomena which are just as important, if not more.

3. This likely refers to Cuvier's theories on catastrophism. Here, we quote his 1796 paper on living and fossil elephants: "All of these facts, consistent among themselves, and not opposed by any report, seem to me to prove the existence of a world previous to ours, destroyed by some kind of catastrophe."

The notion of the evolution of species occupies a certain space in scientific thought such that a new phenomenon or a new explanation in the domain of biology must, to be admitted, relate itself to this in a more or less explicit way.

It is important to shed light on the manifestations of this evolution in biogeochemical processes, because the latest developments in geochemical studies are now stopped short for lack of facts which only the biologists can supply. The biogeochemical phenomena have to enter into the sphere of the biologists.

But, in addition, the research of the relationship which certainly exists between the evolution of species and biogeochemical phenomena is, on its own, of great interest.

This relationship between the evolution of species and the mechanism of the biosphere, and with the progress of living processes, is not in doubt. The fact that the essential numbers which characterize these processes are properties of species which modify themselves in the course of evolution, would suffice to prove it, and it is precisely the study of this relationship which will permit us to determine those relationships which exist between the immutability of the laws of life, considered in their entirety, in geochemistry, and its evolution, always considered in its entirety, in biology.

It is one of most important scientific problems of our time.

4) We can take on this problem starting from the study of the *biogenic migration of chemical elements of the biosphere*, characterized by the regularity of forms which it takes.

We will call the migration of chemical elements all displacement of chemical elements whatever may be the cause. The migration in the biosphere can be determined by chemical processes. For example, at the time of volcanic eruptions, it occurs by the movement of liquid, solid and gaseous masses. In the case of evaporations and of the formation of deposits, it is present in the movement of rivers, marine currents, winds, sediment transport and displacements of the Earth's crust.

The *biogenic migration* provoked by the intervention of life, thought of in its entirety, counts among the most grandiose, and also, typical processes of the biosphere, and constitutes the essential trait of its mechanism.

Innumerable quantities of atoms are submitted to the action of this uninterrupted biogenic migration.

It is not useful to insist, here, on the effect produced in the biosphere by a biogenic migration at a given scale. We have treated this question more than once.

It is important, nevertheless, to point out several essential traits of the biogenic migration, because it is indispensible to know them to understand what follows:

In the first place, *there exist several absolutely diverse*

forms of biogenic migration. On the one hand, the biogenic migration is linked in the most intimate way, and genetically, to the matter of the living organism, to its existence. Cuvier gave a correct and precise definition of the living organism during its life, as an incessant current, a whirpool of atoms which come from the exterior and return there. The organism lives as long as the current of atoms subsists. The current encompasses all of the material of the organism. Each organism on its own, or all organisms taken together, continually creates, by respiration, nutrition, internal metabolism, and reproduction, a biogenic current of atoms, which constructs and maintains living matter. In sum, it is the essential form and principle of the biogenic migration, of which the numerical importance is determined by the mass of living matter existing in a given moment on our planet. But this is not yet the entire biogenic migration.

Evidently, the effect of the entire biogenic migration does not depend directly on the mass of living matter. It does not depend any less on the quantity of atoms than on the intensity of their movements in intimate relation with life. The biogenic migration will be all the more intense as the atoms circulate more quickly; this migration can be very diverse, even while the quantity of atoms encompassed by life is identical.

That is *the second form of biogenic migration, in relation to the intensity of the biogenic current of atoms.*

There exists still a third. This third form begins to take on, in our epoch, the psychozoic epoch, an extraordinary importance in the history of our planet. It is the migration of atoms, also sustained by organisms, but which is not genetically or immediately related to the penetration or to the passage of atoms through their body. *This migration is provoked by technological activity*. It is, for example, determined by the work of burrowing animals, of which we notice traces since the most ancient geological epochs, by the consequences of the social life of building animals, termites, ants, and beavers. But this form of biogenic migration of chemical elements has taken on an extraordinary development since the appearance of *civilized humanity*, since tens of thousands of years ago. Entirely new substances have been created in this way, as for example, metals in a free state. The face of the Earth transforms itself and virgin nature disappears.

This migration does not seem to be related directly to the mass of living matter; it is conditioned in its essential traits by the work of the thought of the conscious organism.

It is necessary finally, probably, in the fourth place, to also add the changes in the distribution of atoms provoked by the appearance, in the biosphere, of new compounds of organic origin. It is *probably, as for its effects, the most powerful form of biogenic migration*. It cannot yet be numerically evaluated, and I will not concern myself with it today.

This is the case, for example, for the migration which determines the release of free oxygen by chlorophyllic organisms, or that caused by the transformation of chemical compounds, unknown of until now in the biosphere, and for those transformations created by the genius of Man.

It is true that this type of chemical migration cannot always be easily distinguished from the first two. For example, the powerful chemical migration provoked by the destruction of bodies of dead organisms, is intimately linked to the processes of putrefaction and fermentation, sustained by the existence of special organisms.

Vernadsky points out that the "technological" mode of biogenic migration, as performed by burrowing animals, does not come close to what Man is able to achieve through his activity.

Photosynthesis from trees and forests allowed for a significant increase in the biogenic migration attributed to photosynthetic matter.

But the biogeochemical processes do not explain this entirely.

5) The different forms of chemical migration indicated here constitute a special feature which we should have in view for the rest of our report.

Another characteristic trait is given by the physical laws which govern them.

Biogenic migration is only an element of another, still more powerful process in the biosphere, otherwise called the *general migration of its elements*. This migration is carried out in part under the influence of solar energy, of the force of gravitation, and the action of internal parts of the Earth's crust upon the biosphere.[4]

All these displacements of elements, whatever may be the cause, respond to diverse systems of equilibrium, which are mechanically determined; in particular, in the history of diverse chemical elements, they give birth to new, closed geochemical cycles, to whirlpools of atoms.

They can all be reduced to heterogeneous laws of equilibrium and to the principles formulated by Gibbs.

The cyclical processes in which the biogenic migration participates are maintained by an exterior force, renewed by an uninterrupted influx. The forces of radiant solar energy and atomic energy play a dominant role in the renewal of these elements.

These equilibria, studied outside of this exterior influx of energy, are mechanical systems, which necessarily arrive at a stable state. Their free energy will be zero at the end of the process, because all the work capable of being accomplished in the system will necessarily be expended. In the equilibria of this species, the work always reaches a maximum, whereas the energy in a free state tends towards a minimum.

Biogenic migration is one of the principle forms of work in natural systems of equilibrium and evidently it must tend towards a maximal manifestation.

We can consider this property of biogenic migration as an essential geochemical principle which governs, in an automatic way, biogeochemical phenomena.

The *first biogeochemical principle*, as I call it, can be formulated as follows:

"The biogenic migration of chemical elements in the biosphere tends towards its most complete manifestation."

6) Let us now examine how these two properties of biogenic migration manifest themselves in the biosphere: the first biogeochemical principle and the existence of the two forms of its manifestation—first, that connected to the mass of living matter, and secondly, to the technology of life.

The mass of living matter must, evidently, at the time of the maximum biogenic migration in the biosphere, reach the ultimate limits, that is, if there exist such limits.

The invariability of this mass seems to indicate that the biogenic migration of this form has more or less reached its limits since the earliest geological epochs.

This is not the case for the biogenic migration of elements which is related to the technology of life. Here we notice a sharp jump to our psychozoic geological epoch.

We aid in the development of this form of the biogenic migration and we must, in conformity with the first biogeochemical principle, admit that this form of the migration of elements will inevitably reach, with time, its maximum limit, while supposing that such a limit exists, or that it will constantly strive to reach its maximum development.

7) We can easily evaluate the correctness of the first biogeochemical principle in studying biogenic migration. The tendency which it has to attain its maximum development in the biosphere, can be observed in nature with respect to two phenomena: In the first place, the migration will occupy the greatest space possible, the maximum space accessible to it due to the mass of the living matter and the living technology inherent in this latter. The phenomenon manifests itself by the ubiquity of life in the bio-

4. Perhaps this refers to volcanism, or something similar.

sphere, as we see everywhere.

But biogenic migration, in that which concerns its geochemical action, not only depends on the quantity of atoms caught by it at every moment in the biosphere, but also on the rapidity of their movement, the number of atoms passing through living matter in a unit of time, or on the displacement, in this same unit of time, provoked by an intervention of a technological order by living matter within the ambient environment.

Bird guano increased the biogenic migration of phosphorus.

The first biogeochemical principle manifests itself, then, by the pressure of life, which we effectively observe in the biosphere, and by the growing acceleration of the technological activity of civilized man.

It is especially important to take into account, at the same time, the phenomenon of the ubiquity of life, but also that of its pressure, and of the existence, in the biosphere, of living forms evolved in an environment of a radically different physical character.

We can and we must, fundamentally, admit that life manifests itself in two physically distinct spaces.

On the one hand, it appears in the gravitational field where we live. It is naturally the most customary for us.

But this gravitational field, where all is governed by the law of gravitation, does not embrace the entire domain of life.

The dimensions of the smallest organisms are akin to the dimensions of molecules, [although of another order of magnitude].[5] These organisms, whose diameter does not even attain one hundred thousandth of a centimeter, enter into the field of molecular forces, and their life, and their related phenomena, are not only regulated by universal gravitation, but are also submitted to the action of radiations which everywhere surround us: These radiations can overpower,[6] in that which concerns these organisms, the conditions of existence provided by gravitation.[7]

We know that these infinitely small organisms also enjoy this same ubiquity, fill the maximum space, and that the pressure of their life, the intensity of the current of atoms which they provoke, is extreme.

8) Thus, we can consider the ubiquity of life and its pressure, as an expression of the principle of ambient nature, which regulates the biogenic migration of chemical elements.

It is easy to convince oneself, when studying natural phenomena and the empirical facts which are treated therein, that the same ubiquity, along with the pressure of life, cannot be explained by the immutability of the present life of organisms.

These phenomena modify themselves in the course of geological time and develop, to a large extent, under the action of evolution.

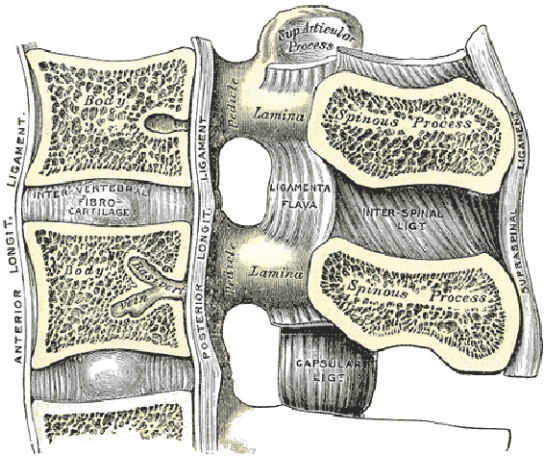
The creation resulting from this evolution of new living forms, adapts itself to new forms of existence, augments the ubiquity of life, and enlarges its domain. Life penetrates, thus, the regions of the biosphere where it had not earlier had access.

We see, at the same time, how, in the course of geological epochs, new forms of life appear. Their occurrence leads, however, to an acceleration of atomic current through living matter, and also provokes, within atoms,

5. "*Bien qu'appartenant a une autre décade.*" The meaning of décade in this context is not clear.

6. The French word is *abolir*. It means to repeal or outlaw, but overpower seems more appropriate.

7. A footnote, to clarify and restate the idea expressed here, from *The Biosphere*: "…the field of stability of life is clearly divided into the field of gravity for the more voluminous organisms, and the field of molecular force for the smaller organisms such as the microbes and ultramicrobes (on the order of 104 mm long). The lives and movements of the latter are primarily determined by luminous and other radiations. Although the size of these two fields are not well documented, we know that they must be determined by the tolerances of organisms."



The intervertebral disk incorporates calcium fluoride, and in greater density than is found in other parts of the human skeletal structure.

new manifestations, unknown of until now, along with the appearance of new modes of displacement.

The attention already given by three generations of naturalists to the phenomena of the evolution of species has permitted the analysis of living nature, and convinces us that the ubiquity and the pressure of life observed everywhere, is radically modified and increased in the course of the geological epochs. *It is a result of the evolution and the adaptation of organisms to the environment.*

Two or three examples will suffice to make my thought more clear. The analysis of cave fauna show that it is composed of organisms having lived (at an earlier time) in the light. They adapted themselves to new conditions and thus enlarged the domain of life. This is also true for at least a portion of the benthos of the ocean. They adapted themselves to conditions of high pressure, cold, and darkness, while they originated from organisms having lived in other conditions.

It is a new phenomenon which enlarges the domain of life in the biosphere. The analysis of these phenomena also seems to indicate that the domain of life continues to enlarge itself in our geological epoch, also by the populating of the depths of the ocean.

In that which concerns other phenomena, we can still observe at each step identical processes. The flora and fauna of thermal sources, the flora and fauna of high altitudes or deserts, those of the glacial regions and those with perpetual snow, develop conforming to the laws of evolution. Life, in adapting to this in its environment, slowly annexes new regions, and reinforces the biogenic migration of atoms of the biosphere.

The process of evolution not only enlarged the domain of life, it intensified and accelerated the biogenic migration. The formation of the vertebrate skeleton, without a doubt, modified and augmented the migration of atoms of fluorine, in concentrating them, and the skeleton of aquatic invertebrates did the same for the migration of atoms of calcium.

It is not useful to insist upon the extreme increasing of the pressure of life in the biosphere caused by the appearance of the evolved *Homo sapiens*, who we can, it seems, name by combining the terminology of Linnaeus and that of Bergson in employing the three-fold characteristic of the species, "*Homo sapiens faber*" The thought of *Homo sapiens faber* is a new fact which fundamentally changes the structure of the biosphere after myriad centuries.

9) Thus, the analysis of living, ambient nature establishes in a sharp and decisive way that the ubiquity and the pressure of life in the biosphere are the results of evolution. Said otherwise, *the evolution of living forms in the course of geological time on our planet, augments the biogenic migration of the chemical elements in the biosphere.*

Naturally, the mechanical condition which determines the necessity of this character of atomic migration, is maintained uninterrupted in the course of all geological time and the evolution of forms has always taken this into account.

This mechanical condition which caused this biogenic migration of elements is due to the fact that life constitutes an integral part of the mechanism of the biosphere and, fundamentally, it is the force which determines its existence.

It is also evident that the evolution of species is correlated with the structure of the biosphere. Neither life, nor the evolution of its forms, would have been able to exist independently of the biosphere, nor to be divided from it as separated natural entities.

Starting from this fundamental principle, and the fact of the participation of evolution in the ubiquity and pressure of life in the current biosphere, we are well situated, concerning the evolution of living forms, to pose a new *biogeochemical principle*.

This biogeochemical principle which I will call the second biogeochemical principle can be formulated thus:

"The evolution of species, leading to the creation of new stable, living forms, must move in the direction of an increasing of the biogenic migration of atoms in the biosphere."

10) It is certain that this principle cannot in any way explain the evolution of species and does not enter into the tentative explanations of the different theories of evolution which now preoccupy the great thinkers. This principle regards evolution as an empirical fact, or rather as an empirical generalization, and attaches it to another empirical generalization, that of the *mechanism* of the biosphere.

But it is far from being indifferent, from the point of view of evolutionary theories, and it indicates, in my opinion, with an infallible logic, the existence of a determined direction, in the sense of how the processes of evolution must necessarily take place. This direction coincides perfectly, in its scientifically precise terminology, with the principles of mechanics, with all our knowledge of Earth's physical chemical processes to which biogenic migration strives.

All theories of evolution must take into consideration the existence of this determined direction of the process of evolution, which, with the subsequent developments in science, will be able to be numerically evaluated.

It seems impossible to me, for several reasons, to speak of evolutionary theories without taking into account the fundamental question of *the existence of a determined direction, invariable in the processes of evolution, in the course of all* the *geological epochs*.

Taken together, the annals of paleontology do not show the character of a chaotic upheaval, sometimes in one direction, sometimes in another, but of phenomena, for which the development is carried out in a determined manner, always in the same direction, in that of the increasing of consciousness, of thought, and of the creation of forms augmenting the action of life on the ambient environment.

The existence of a determined direction of the evolution of species can be precisely established by observation.

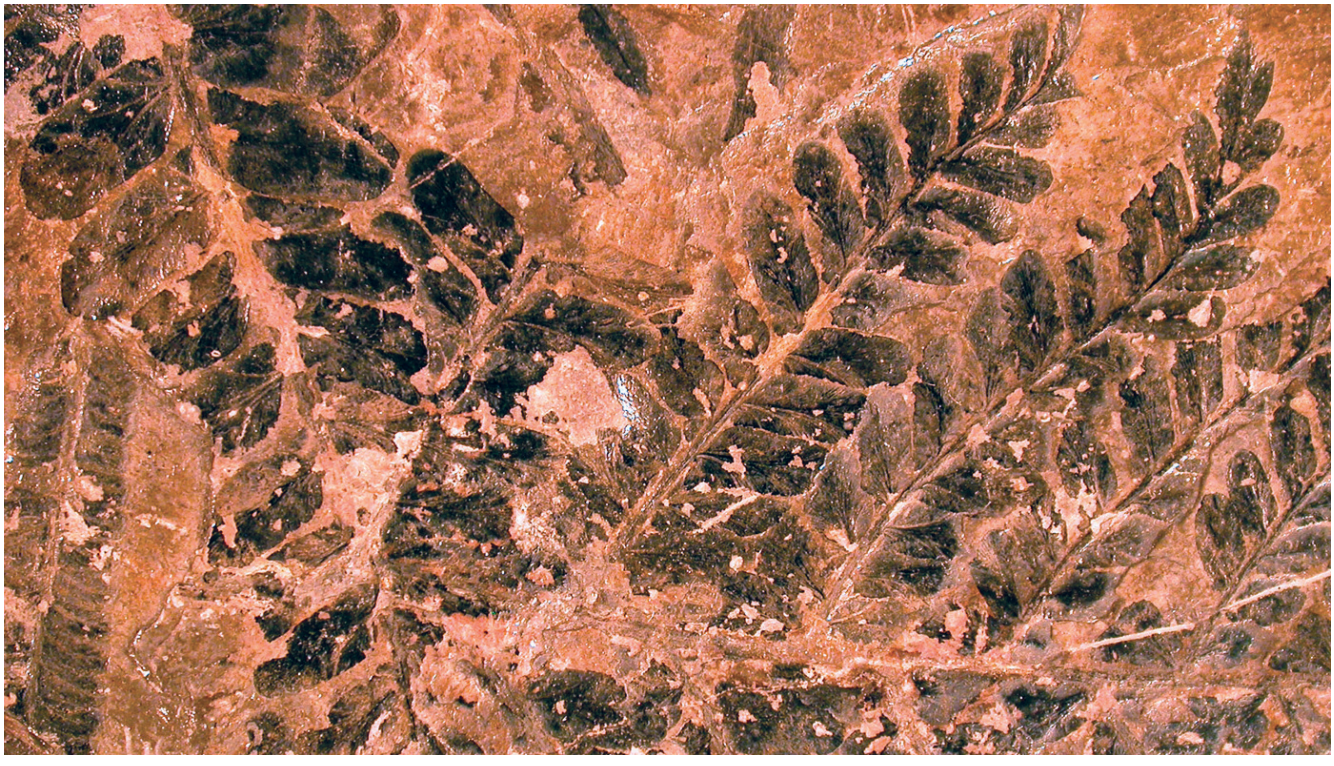
I will limit myself to a small number of general examples relative to the unfolding of processes of evolution, to paleontological indications considered from the point of view of the transformation of the biogenic migration in the course of geological epochs.

11) It was during the Cambrian period, at the limits of the ancient living world studied by us, when the higher invertebrates appeared. The fact in question is not absolutely established, but it is necessary to admit it to easily explain the sharp change which occurred shortly after the beginning of the Cambrian, concerning the conservation of organisms. The complete immutability in the course of the entire Pre-Cambrian period of the processes of erosion, their complete identity, if we consider their essential traits, with the analogous processes now, does not permit us to find the explanation of the absence of fossil remains in the different conditions of the surrounding environment.

There is not, at the same time, any reason to suppose that the metamorphosis of Earth's geological layers, occasioned by a determined duration of their processes, had, following this precise moment, an absence of organic fossils. It would otherwise be necessary to admit that all the oldest layers were completely transformed.

Now, we are quite familiar with the cases where the Pre-Cambrian layers were less metamorphised than those of the Cambrian and those of the more recent times.

It is probably the geologists, who here admit of a sharp



Photosynthesis caused a significant increase of the biogenic migration of carbon, oxygen, hydrogen, and nitrogen.

Feathers incorporate calcium, in addition to phosphosus. The activity of birds greatly increased the biogenic migration of phosphorus.

change of the *biogenic migration of atoms of calcium*, who are right. It is the first phenomenon of this type which we could establish.

It is possible that a similar modification of the biogenic migration of calcium, caused by the formation of new species endowed with skeletons rich in calcium carbonate, corresponds with the invasion of life into new domains of the biosphere. This modification must have had equal repercussions in the history of carbonic acid.

We can get an idea of the importance of this event by remembering the role, played in the biosphere, by the organisms which are very rich in calcium (the organisms containing it in fundamental preference to other metals), in the formation of the calcium deposits. The mechanism of the biogenic migration of calcium experienced great changes during the indicated time and this migration became instantly more intense. In order to judge it by that which we know of the intensity of the migration of calcium, sparked off by the creation of the higher invertebrate skeleton, for example, that of mollusks or of coral, in relationship to those of the microscopic organisms, whose calcium is released, in the end, by water, it is necessary to admit an extreme and sudden augmentation of the intensity of its migration since the creation of these new forms of life.

At the beginning of Paleozoic life, and maybe at the Cambrian period, another very important fact relative to the biogenic migration of atoms calls itself to our attention: It is the radical transformation of the sylvan vegetation of the continents.[8] The process of gradual perfection of these organisms, of which the full blooming seemed to be attained, its point culminating in the Tertiary Epoch, still prolonged itself in the course of further geological epochs. This process corresponds to the conquest by life of a new and immense domain, that of the troposphere. The appearance of forests, exuberant with life, brought about a great change in the migration of atoms of oxygen, of carbon, of hydrogen, and simultaneously in that of all the living atoms of which the cyclical movement, first of all, had to become more intense, because the forests, especially the forests with leafy trees, persisting through new geological epochs, concentrated life, as much vegetable as animal, in proportions unknown of up until then. If we compare from this point of view the spore-bearing forests of primitive times to our tertiary forests of seed-bearing trees, the difference of the intensity of the biogenic migration will seem enormous to us.

During the Mesozoic Epoch, a new fact, the appearance of birds, augmented the intensity of the biogenic migration of atoms, and life again enlarged its domain. It was not until the Mesozoic Epoch and the Tertiary Epoch that flying organisms attained their fullest development, in the form of birds. Two very important biogeochemical functions attach themselves to these two new forms of life. We can hardly conclude that there is a relationship between these forms and the flying invertebrates which emerged very long ago, around the beginning of the Paleozoic, although these flying invertebrates, in particular, had fulfilled these functions and fulfill them still to this day. In any case, only the creation of the birds gave an impetus to the mechanism of the biosphere which it had not had earlier.

In the mechanism of the biosphere, in the biogenic migration of atoms, the birds, as well as the other flying or-

8. i.e., forests.

Man increases the biogenic migration of atoms in a way which is consistent with the increasing biogenic migration throughout evolutionary history, but on a scale not seen before in the biosphere. This would be achieved by building the North American Water and Power Alliance (NAWAPA) pictured here.

ganisms, play an immense role for the exchange of matter between the solid earth and the water, principally between the continent and the ocean![9] The role of the birds differs from that of the rivers, but as far as the quantity of mass transported, it comes close. The migrations of birds renders this role even more important in that which concerns the biogenic circulation of atoms. The appearance of these species of winged vertebrates not only created new forms of biogenic migration that affected the chemical balance of the sea and of the continent, but it also provoked a new wave of biogenic migration in the course of the history of discrete bodies, in particular, for that of phosphorus.[10] The winged invertebrates, the insects, did not play as important a role. It is true that the flying saurians (reptiles) appeared before the birds, but everything indicates that they did not exercise actions comparable to theirs. The appearance of birds appears to be linked to that of new types of forests, or in any case seems to have coincided with them.

The role of civilized humanity, from the point of view of the biogenic migration of atoms, was infinitely more important than that played by the other vertebrates. Here, for the first time in the history of the Earth, the biogenic migration due to the development of the action of technology was able to have a greater significance than the biogenic migration determined by the mass of living matter. At the same time, the biogenic migrations changed for all of the elements. The process was rapidly effected in a relatively insignificant amount of time. The face of the Earth transformed itself in an unrecognizable way, and yet, it is clear that the era of this transformation has only just begun.

These transformations conform to the data of the second biogeochemical principle; the change led to an extreme growth of the intensity of the biogenic migration of atoms in the biosphere.

It is necessary to note here two phenomena: Firstly, Man (and this can not be doubted) is born of an evolution, and secondly, in observing the change which he produces

9. This exclamation point is in the French translation, but not in the Russian.

10. From Mark McMenamin's *Hypersea*: "The first aspect of Vernadsky's law involves actual transport by the motion of living organisms, such as the migration of phosphorus atoms from sea to land when shore birds leave their droppings inland. (To a Vernadskian, a seagull is phosphorus on the wing)."

in the biogenic migration of atoms, we note that it is a change of a new kind, which, with time, accelerates with an extraordinary rapidity.

We can then perfectly admit that the changes in the biogenic migration of atoms were effected in the course of paleontological periods under the influence of the creation of new animal and vegetable species, in a manner which is no less rapid.

The new quantitative form of the biogenic migration, corresponding to civilization, was prepared by the entirety of paleontological history. We would have been able to recover its first fossil remains, if we had known the laws of nature from the first pages of the annals of paleontology.

I stop myself here on several typical phenomena with respect to the evolution of species relative to the biogenic migration of the chemical elements. In all these cases, the agreement of evolution with the second biogeochemical principle is evident, as it always seems to manifest itself, in the analysis of the paleontological annals.

How did this agreement occur? Does it follow from a blind combination of circumstances or, indeed, from a more profound process, determined by the properties of life—incessant processes, always the same in their manifestations in the course of the entirety of the geological history of the planet? The future will decide this.

The regulating influence of the second geochemical principle will manifest itself in these two cases.

Even if the evolution of species happened randomly, accidentally, outside of the influence of the ambient environment, that is to say, the mechanism of the biosphere, a species which was accidentally created would, however, not have been able to survive and to enter into the whirlpool of the planet; at the same time, only the species which were sufficiently stable, and susceptible of augmenting the biogenic migration of the biosphere, would have survived.

It is, however, impossible to now oppose, in an elementary fashion, the organism in its environment, that is to say, the biosphere, as was done of old. We know that the organism is not an accidental inhabitant of the environment: It participates in the complicated mechanism and submits to fixed laws. Evolution itself constitutes a part of this mechanism.

The naturalist must exclude all the philosophical or religious notions, which have penetrated science from the outside, from his conception of the universe. For example, admitting the idea of the independence of the organism from its environment, and of an opposition between these two factors, would be a great error of this type.

From this point of view, there truly exists an intimate connection between the agreement of evolution and the principle which governs it and it is by no means a question of a simple confluence of circumstances.

12) Without preoccupying ourselves with the causes of evolution, while only indicating the necessity for it to have a determined direction, the study of biogeochemical phenomena thus circumscribes the domain of evolutionary theories admissible into science.

It seems that this study opens before us yet another domain of the phenomena of scientific activity, until now exclusively reserved to the speculations of philosophy or religion.

The new form of biogenic migration, at least new to this scale, was provoked, as we see, by the intervention of human reason.

However, it does not distinguish itself in any of the other manifestations of biogenic migration, which are connected to other vital functions.

We can, at the same time, establish in a precise way, that human thought changes in a sharp and radical way the course of natural processes, and modifies that which we call the laws of nature.

Consciousness, and thought, despite the efforts of generations of thinkers and wisemen, cannot be reduced to either energy or matter, however we define these bases of our scientific thought.

How can consciousness act on the work of natural processes which seem to be entirely reducible to energy and matter?

This question was last posed by the American mathematician A. Lotka, precisely on the question of biogeochemical phenomena. It is doubtful that his response was satisfactory. But he indicated the importance of the problem, and the possibility of tackling it.

It is probable that we will not be able to resolve this question until after having radically changed our fundamental physical notions, notions which have undergone and still undergo transformations with a rapidity for which we know of no prior examples in the history of thought.

The physical theories will inevitably have to concern themselves with the fundamental phenomena of life.

It is in this direction that thought now works, and it is impossible not to take into account these new and profound researches, among them the speculations of the mathematician and English thinker A. Whitehead; it is true, more philosophical than scientific, merit analysis. It is very possible that another English thinker, J. Haldane, was right in predicting, in the near future, a radical transformation of physics and its principles due to the introduction of the study of life phenomena into its sphere.

The study of biogeochemical phenomena, pushed to the forefront, allows us to precisely penetrate this domain of the connected manifestations of life and the structure of the physical universe, and, at the same time, future scientific theories.

This makes clear the profound philosophical interest which biogeochemical problems now present.