

Some Words About The Noösphere¹

by Vladimir I. Vernadsky

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Subheads have been added.

Vladimir Ivanovich Vernadsky (1863-1945), who developed the concept of the biosphere and how man's creativity has changed it into the noösphere.



We are approaching the climax in the Second World War. In Europe war was resumed in 1939 after an intermission of twenty-one years; it has lasted five years in Western Europe, and is in its third year in our parts, in Eastern Europe. As for the Far East, the war was resumed there, much earlier, in 1931, and is already in its 12th year. A war of such power, duration, and strength is a phenomenon unparalleled in the history of mankind and of the biosphere at large. Moreover, it was preceded by the First World War which, although of lesser power, has a causal connection with the present war.

In our country that First World War resulted in a new, historically unprecedented, form of statehood, not only in the realm of economics, but likewise in that of the aspirations of nationalities. From the point of view of the naturalist (and, I think, likewise from that of the historian), an historical phenomenon of such power may and should be examined as a part of a single great terrestrial *geological* process, and not merely as a *historical* process.

In my own scientific work, the First World War was reflected in a most decisive way. It radically changed my *geological conception of the world*. It is in the atmosphere of that war that I have approached a conception of nature, at that time forgotten and thus new for myself and for others, a geochemical and biogeochemical conception embracing both nonliving and living nature from the same point of view.² I spent the years of the First World War in my uninterrupted scientific creative work, which I have so far continued steadily in the same direction.

Twenty-eight years ago, in 1915, a "Commission for the Study of the Productive Forces" of our country, the so-called KEPS, was formed at the Academy of Sciences. That commis-



sion, of which I was elected president, played a noticeable role in the critical period of the First World War. Entirely unexpectedly, in the midst of the war, it became clear to the Academy of Sciences that in Tsarist Russia there were no precise data concerning the now so-called strategic raw materials, and we had to collect and digest dispersed data rapidly to make up for the lacunae in our knowledge.³ Unfortunately by the time of the beginning of the Second World War, only the most bureaucratic part of that commission, the so-called Council of the Productive Forces, was preserved, and it

became necessary to restore its other parts in a hurry.

By approaching the study of geological phenomena from a geochemical and biogeochemical point of view, we may comprehend the whole of the circumambient nature in the same atomic aspect. Unconsciously, such an approach coincides for me with what characterizes the science of the 20th Century and distinguishes it from that of past centuries. *The 20th Century is the century of scientific atomism.*

At that time, in 1917-1918, I happened to be, entirely by chance, in the Ukraine,⁴ and was unable to return to Petrograd until 1921. During all those years, wherever I resided, my thoughts were directed toward the geochemical and biogeochemical manifestations in the circumambient nature, the biosphere. While observing them, I simultaneously directed both my reading and my reflection toward this subject in an intensive and systematic way. I expounded the conclusions arrived at gradually, as they were formed, through lectures and reports delivered in whatever city I happened to stay, in Yalta, Poltava, Kiev, Simferopol, Novorossiysk, Rostov, and so on. Besides, in almost every city I stayed, I used to read everything available in regard to the problem in its broadest sense. I left aside, as much as I could, all philosophical aspirations and tried to rest only on firmly established scientific and empiric facts and generalizations, occasionally allowing myself to resort to working scientific hypotheses.

Instead of the concept of "life," I introduced that of "living matter," which now seems to be firmly established in science. "Living matter" is the totality of living organisms. It is but a scientific empirical generalization of empirically indisputable facts known to all, observable easily and with precision. The concept of "life" always steps outside the boundaries of the concept of "living matter"; it enters the realm of philosophy, folklore, religion, and the arts. All that is left outside the notion of "living matter."

In the thick of life today, intense and complex as it is, a person practically forgets that he, and all of mankind, from which he is inseparable, are inseparably connected with the biosphere—with that specific part of the planet, where they live. It is customary to talk about man as an individual who moves freely about our planet, and freely constructs his own history. Hitherto, neither historians, scientists in the humanities, nor, to a certain extent, even biologists, have consciously taken into account the laws of the nature of the biosphere—the envelope of Earth, which is the only place where life can exist. Man is elementally indivisible from the biosphere. And this inseparability is only now beginning to become precisely clear to us. In reality, no living organism exists in a free state on Earth. All of these organisms are inseparably and continuously connected—first and foremost by feeding and breathing—with their material-energetic environment.

The outstanding Petersburg academician Caspar Wolf (1733-1794), who dedicated his whole life to Russia, expressed this brilliantly in his book, published in German in St. Petersburg in 1789, the year of the French Revolution: *On the Peculiar and Efficient Force, Characteristic of Plant and Animal Substance.* Unlike the majority of biologists of his day, he relied upon Newton, rather than Descartes.⁵

Mankind, as living matter, is inseparably connected with

the material-energetic processes of a specific geological envelope of the Earth—its *biosphere*. Mankind cannot be physically independent of the biosphere for a single minute.

The 'Huygens Principle'

The concept of the "biosphere," i.e., "the domain of life," was introduced in biology by Lamarck (1744-1829) in Paris at the beginning of the 19th Century, and in geology by Edward Suess (1831-1914) in Vienna, at the end of that century.⁶ In our century there is an absolutely new understanding of the biosphere. It is emerging as a *planetary* phenomenon that is *cosmic in nature*. In biogeochemistry we have to consider that life (living organisms) really exists not on our planet alone, not only in the Earth's biosphere. It seems to me that this has been established beyond a doubt, so far, for all the so-called terrestrial planets, i.e., for Venus, Earth, and Mars.⁷ At the Biogeochemical Laboratory of the Academy of Sciences in Moscow, which has been renamed the Geochemical Problems Laboratory, in collaboration with the Microbiology Institute of the Academy of Sciences (director—Corresponding Academician B.L. Isachenko), we identified *cosmic* life as a matter for current scientific study already in 1940. This work was halted because of the war, and will be resumed at the earliest opportunity.

The idea of life as a cosmic phenomenon has been found in the scientific archives, including our own, for a long time. Centuries ago, in the late 17th Century, the Dutch scientist Christiaan Huygens (1629-1695), in his last work, *Cosmotheoros*, which was published posthumously, formulated this scientific question. The book was published in Russian twice in the first quarter of the 18th Century, on the initiative of Peter I.⁸ In this book, Huygens established the scientific generalization that "life is a cosmic phenomenon, in some way sharply distinct from nonliving matter." I recently named this generalization "the Huygens principle."⁹

By weight, living matter comprises a minute part of the planet. This has evidently been the case throughout all geological time, i.e., it is geologically eternal.¹⁰ Living matter is concentrated in a thin, more or less continuous layer in the troposphere on dry land—in fields and forests—and permeates the entire ocean. In quantity, it measures no greater than tenths of a percent of the biosphere by weight, on the order of close to 0.25 percent. On dry land, its continuous mass reaches to a depth of probably less than 3 kilometers on average. It does not exist outside the biosphere.

In the course of geological time, living matter morphologically changes, according to the laws of nature. The history of living matter expresses itself as a slow modification of the forms of living organisms, which genetically are uninterruptedly connected among themselves from generation to generation. This idea had been rising in scientific research through the ages, until, in 1859, it received a solid foundation in the great achievements of Charles Darwin (1809-1882) and [Alfred R.] Wallace (1822-1913). It was cast in the doctrine of the evolution of species of plants and animals, including man. The evolutionary process is a characteristic only of living matter. There are no manifestations of it in the nonliving matter of



University of California, Berkeley,
The Blue and Gold Yearbook, 1896



U.S. Geological Survey

The American geologist Joseph Le Conte (1823-1901), at left, developed the idea that living matter was evolving in a definite direction, which he called the Psychozoic era. James Dwight Dana (1813-1895), a geologist, mineralogist, and biologist, developed a similar idea, which he called cephalization. Dana was a member of the Wilkes Expedition.

our planet. In the Cryptozoic era, the same minerals and rocks were being formed which are being formed now.¹¹ The only exceptions are the bio-inert natural bodies connected in one way or another with living matter.¹²

The change in the morphological structure of living matter, observed in the process of evolution, unavoidably leads to a change in its chemical composition. This question now requires experimental verification. In collaboration with the Paleontology Institute of the Academy of Sciences, we included this problem in our planned work in 1944.

While the quantity of living matter is negligible in relation to the nonliving and bio-inert mass of the biosphere, the biogenic rocks constitute a large part of its mass, and go far beyond the boundaries of the biosphere. Subject to the phenomena of metamorphism, they are converted, losing all traces of life, into the granitic envelope, and are no longer part of the biosphere. The granitic envelope of the Earth is the area of former biospheres.¹³ In Lamarck's book, *Hydrogeologie* (1802), containing many remarkable ideas, living matter, as I understand it, was revealed as the creator of the main rocks of our planet. Lamarck never accepted Lavoisier's (1743-1794) discovery. But that other great chemist, J.B. Dumas (1800-1884), Lamarck's younger contemporary, who did accept Lavoisier's discovery, and who intensively studied the chemistry of living matter, likewise adhered for a long time to the notion of the quantitative importance of living matter in the structure of the rocks of the biosphere.

Cephalization—the Arrow of Evolution

The younger contemporaries of Darwin, J[ames] D[wight] Dana (1813-1895) and J[oseph] Le Conte (1823-1901), both great American geologists (and Dana, a mineralogist and

biologist as well) expounded, even prior to 1859, the empirical generalization that *the evolution of living matter is proceeding in a definite direction*. This phenomenon was called by Dana "cephalization," and by Le Conte the "Psychozoic era." Dana, like Darwin, adopted this idea at the time of his journey around the world, which he started in 1838, two years after Darwin's return to London, and which lasted until 1842.¹⁴

It should be noted here that the expedition during which Dana reached his conclusions about cephalization, coral reefs, and so on, was historically associated with the researches on the Pacific Ocean, done on ocean voyages by Russian sailors, notably Kruzenshtern (1770-1846). Published in German, they inspired the American lawyer John Reynolds to organize the first such American scientific sea voyage.¹⁵ He began to work towards this in 1827, when an account of Kruzenshtern's expedition came out in German. Only in 1838, 11 years later, did his persistent efforts result in this expedition taking place. This was the Wilkes expedition, which conclusively proved the existence of Antarctica.

Empiric notions of a definite direction of the evolutionary process, without, however, any attempt theoretically to ground them, go deeper into the 18th Century. Buffon (1707-1788) spoke of the "realm of man," because of the geological importance of man. The idea of evolution was alien to him. It was likewise alien to Agassiz (1807-1873), who introduced the idea of the glacial period into science. Agassiz lived in a period of an impetuous blossoming of geology. He admitted that, geologically, the realm of man had come, but, because of his theological tenets, opposed the theory of evolution. Le Conte points out that Dana, formerly having a point of view close to that of Agassiz, in the last years of his life accepted the idea of evolution in its then-usual Darwinian interpretation.¹⁶ The difference between Le Conte's "Psychozoic era" and Dana's "cephalization" thus disappeared. It is to be regretted that, especially in our country, this important empirical generalization still remains outside the horizon of our biologists.

The soundness of Dana's principle, which happens to be outside the horizon of our paleontologists, may easily be verified by anyone willing to do so on the basis of any modern treatise on paleontology. The principle not only embraces the whole animal kingdom, but likewise reveals itself clearly in individual types of animals. Dana pointed out that in the course of geological time, at least 2 billion years and probably much more, there occurs an irregular process of growth and perfection of the central nervous system, beginning with the crustacea (whose study Dana used to establish his principle), the mollusca (cephalopoda), and ending with man. It is this phenomenon he called cephalization. The brain, which has once achieved a certain level in the process of evolution, is not subject to retrogression, but only can progress further.

The Noösphere Comes of Age

Proceeding from the notion of the geological role of man, the geologist A.P. Pavlov (1854-1929) in the last years of his life used to speak of the *anthropogenic era*, in which we now live. While he did not take into the account the possibility of the destruction of spiritual and material values we now witness in the barbaric invasion of the Germans and their allies, slightly more than 10 years after his death, he rightfully emphasized that man, under our very eyes, is becoming a mighty and ever-growing geological force. This geological force was formed quite imperceptibly over a long period of time. A change in man's position on our planet (his material position first of all) coincided with it. In the 20th Century, man, for the first time in the history of the Earth, knew and embraced the whole biosphere, completed the geographic map of the planet Earth, and colonized its whole surface. *Mankind became a single totality in the life of the Earth.* There is no spot on Earth where man can not live if he so desires. Our people's sojourn on the floating ice of the North Pole in 1937-1938 has proved this clearly. At the same time, owing to the mighty techniques and successes of scientific thought, radio and television, man is able to speak instantly to anyone he wishes at any point on our planet. Transportation by air has reached a speed of several hundred kilometers per hour, and has not reached its maximum. All this is the result of "cephalization," the growth of man's brain and the work directed by his brain.

The economist, L. Brentano, illuminated the planetary significance of this phenomenon with the following striking computation: If a square meter were assigned to each man, and if all men were put close to one another, they would not occupy the area of even the small Lake of Constance between the borders of Bavaria and Switzerland. The remainder of the Earth's surface would remain empty of man. Thus the whole of mankind put together represents an insignificant mass of the planet's matter. Its strength is derived not from its matter, but from its brain. If man understands this, and does not use his brain and his work for self-



Portrait by Jean Louis Rodolphe, 1866, courtesy of University of Oklahoma Libraries, History of Science Collections

Louis Agassiz (1807-1873), introduced the idea of the glacial period into science.



NOAA Central Library

Captain Charles Wilkes, headed the U.S. Exploring Expedition, 1838-1842, which discovered the Magnetic South Pole and determined that Antarctica was a continent.

destruction, an immense future is open before him in the geological history of the biosphere.

The geological evolutionary process shows the biological unity and equality of all men, *Homo sapiens* and his ancestors, *Sinanthropus* and others; their progeny in the mixed white, red, yellow, and black races evolves ceaselessly in innumerable generations.¹⁷ This is a *law of nature*. All the races are able to interbreed and produce fertile offspring. In a historical contest, as for instance in a war of such magnitude as the present one, he finally wins who follows that law. One cannot oppose with impunity the principle of the unity of all men as a law of nature. I use here the phrase "law of nature" as this term is used more and more in the physical and chemical sciences, in the sense of an empirical generalization established with precision.

The historical process is being radically changed under our very eyes. For the first time in the history of mankind the interests of the masses on the one hand, and the free thought of individuals on the other, determine the course of life of mankind and provide standards for mere ideas of justice. Mankind taken as a whole is becoming a mighty geological force. There arises the problem of the *reconstruction of the biosphere in the interests of freely thinking humanity as a single totality*. This new state of the biosphere, which we approach without our noticing, is the *noösphere*.

In my lecture at the Sorbonne in Paris in 1922-1923, I accepted *biogeochemical phenomena* as the basis of the biosphere. The contents of part of these lectures were published in my book, *Studies in Geochemistry*, which appeared first in French, in 1924, and then in a Russian translation, in 1927.¹⁸ The French mathematician Le Roy, a Bergsonian philosopher, accepted the biogeochemical foundation of the biosphere as a starting point, and in his lectures at the Collège de France in Paris, introduced in 1927 the concept of the noösphere as the stage through which the biosphere is now passing geologically.¹⁹ He emphasized that he arrived at such a notion in collaboration with his friend Teilhard de Chardin, a great geologist and paleontologist, now working in China.

The noosphere is a new geological phenomenon on our planet. In it, for the first time, man becomes a *large-scale geological force*. He can, and must, rebuild the province of his life by his work and thought, rebuild it radically in comparison with the past. Wider and wider creative possibilities open before him. It may be that the generation of our grandchildren will approach their blossoming.

How Can Thought Change Material Processes?

Here a new riddle has arisen before us. *Thought is not a form of energy*. How then can it change material processes? That question has not as yet been solved. As far as I know, it was first posed by an American scientist born in Lvov, the mathematician and biophysicist Alfred Lotka.²⁰ But he was unable to solve it. As Goethe (1740-1832), not only a great poet but a great scientist as well, once rightly remarked, in science we only can know *how* something occurred, but we cannot know *why* it occurred.

As for the coming of the noosphere, we see around us at

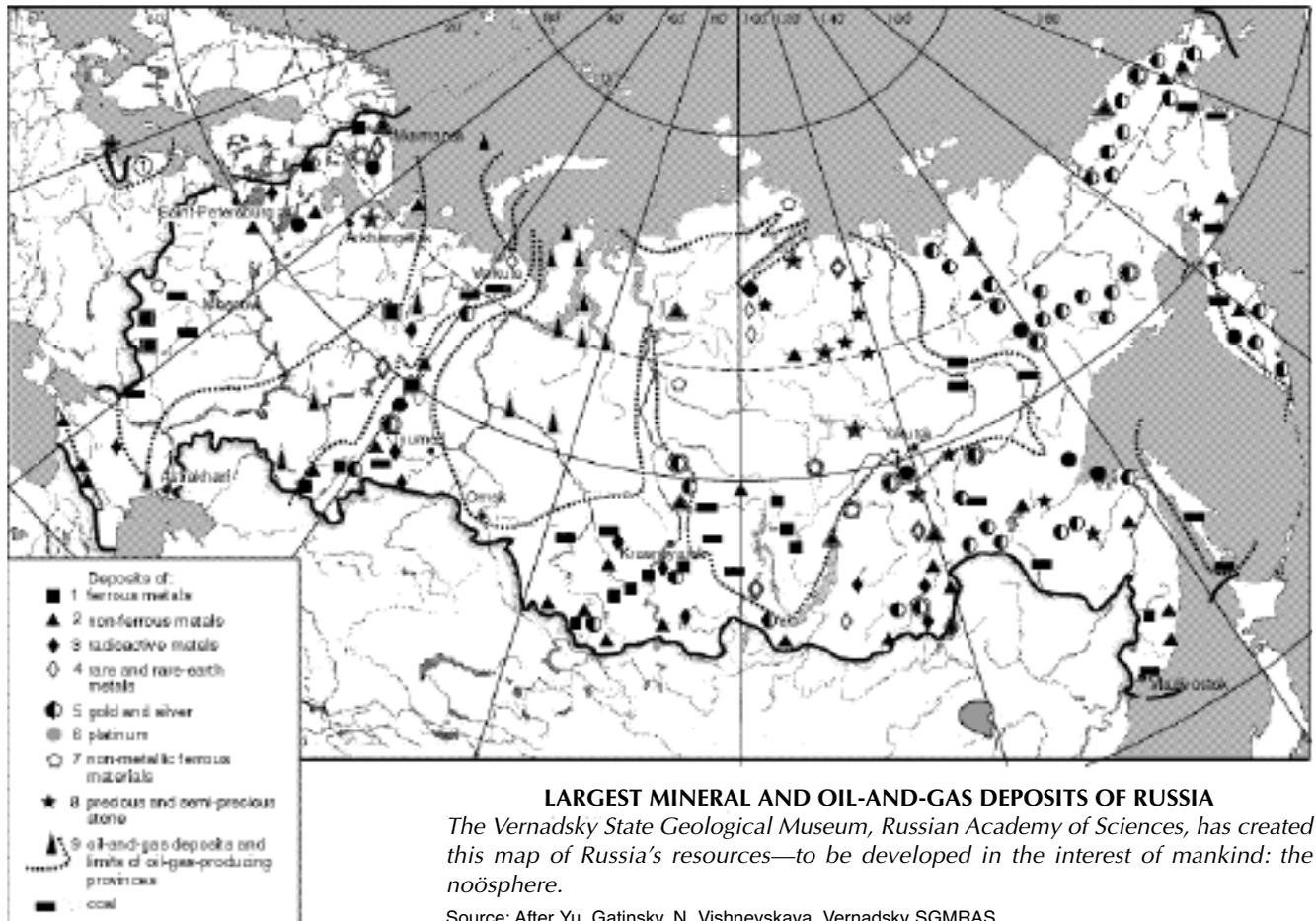


Russian Academy of Sciences

The Russian scientist Aleksei Petrovich Pavlov (1854-1929), emphasized that man was becoming a "mighty and ever-growing geological force."

every step the empirical results of that "incomprehensible" process. That mineralogical rarity, native iron, is now being produced by the billions of tons. Native aluminum, which never before existed on our planet, is now produced in any quantity. The same is true with regard to the countless number of artificial chemical combinations (biogenic "cultural" minerals) newly created on our planet. The number of such artificial minerals is constantly increasing. All of the *strategic raw materials* belong here. Chemically, the face of our planet, the biosphere, is being sharply changed by man, consciously, and even more so, unconsciously. The aerial envelope of the land as well as all its natural waters are changed both physically and chemically by man. In the 20th Century, as a result of the growth of human civilization, the seas and the parts of the oceans

closest to shore become changed more and more markedly. Man now must take more and more measures to preserve for future generations the wealth of the seas, which so far have belonged to nobody. Besides this, new species and races of



animals and plants are being created by man. Fairy tale dreams appear possible in the future; man is striving to emerge beyond the boundaries of his planet into cosmic space. And he probably will do so.

At present we cannot afford not to realize that, in the great historical tragedy through which we live, we have elementally chosen the right path leading into the noösphere. I say elementally, as the whole history of mankind is proceeding in this direction. The historians and political leaders only begin to approach a comprehension of the phenomena of nature from this point of view. The approach of Winston Churchill (1932) to the problem, from the angle of a historian and political leader, is very interesting.²¹

The noösphere is the last of many stages in the evolution of the biosphere in geological history. The course of this evolution only begins to become clear to us through a study of some of the aspects of the biosphere's geological past. Let me cite a few examples, Five hundred million years ago, in the Cambrian geological era, skeletal formations of animals, rich in calcium, appeared for the first time in the biosphere; those of plants appeared over 2 billion years ago. That calcium function of living matter, now powerfully developed, was one of the most important evolutionary factors in the geological change of the biosphere.²² A no less important change in the biosphere occurred from 70 to 110 million years ago, at the time of the Cretaceous system, and especially during the Tertiary. It was in that epoch that our green forests, which we cherish so much, were formed for the first time. This is another great evolutionary stadium, analogous to the noösphere. It was probably in these forests that man appeared around 15 or 20 million years ago.

Now we live in the period of a new geological evolutionary change in the biosphere. We are entering the noösphere. This new elemental geological process is taking place at a stormy time, in the epoch of a destructive world war. But the important fact is that our democratic ideals are in tune with the elemental geological processes, with the law of nature, and with the noösphere. Therefore we may face the future with confidence. It is in our hands. We will not let it go.

Notes

1. The word "noösphere" is composed from the Greek terms *noos*, mind, and *sphere*, the last used in the sense of an envelope of the Earth. I treat the problem of the noösphere in more detail in the third part of my book, now being prepared for publication, on *The Chemical Structure of the Biosphere of the Earth As a Planet, and Its Surroundings*.
2. It should be noted that in this connection I came upon the forgotten thoughts of that original Bavarian chemist, C. Schoenbein (1799-1868) and of his friend, the English physicist of genius, M. Faraday (1791-1867). As early as the beginning of the 1840s, Schoenbein attempted to prove that a new division should be created in geology—geochemistry, as he called it. See W. Vernadsky, *Ocherki geokhimii* (Studies in Geochemistry), 4th edition, Moscow-Leningrad, 1934, pp. 14, 290.
3. On the significance of KEPS see A. E. Fersman, *Voina i strategicheskoe syrie* (The War and Strategic Raw Materials), Krasnoufimsk, 1941, p. 48.
4. See my article, "Out of my Recollections: The First Year of the Ukrainian Academy of Sciences," to appear in the Jubilee volume of the *Ukrainian Academy of Sciences* in commemoration of its 25th anniversary.
5. It is to be regretted that the manuscripts left after Wolf's death have been, as yet, neither studied nor published. In 1927, the Commission on the History of Knowledge at the Academy of Sciences decided to do this work, but it could not be accomplished because of the constant changes in the Academy's approach toward the study of the history of science. Now that work at the Academy has been reduced to a minimum, which is harmful

to the cause.

6. On the biosphere, see W. Vernadsky, *Ocherki geokhimii*, 4th edition, Moscow-Leningrad, Index; *Biosfera* (The Biosphere), Leningrad, 1926: French edition, Paris, 1929.
7. See my article on "The Geological Envelopes of the Earth as a Planet," *Izvestiia of the Academy of Sciences. Geographical and Geophysical Series*, 1942, p. 251. Cf. H. Spenser Jones, *Life on Other Worlds*, New York, 1940; R. Wildt in *Proc. Amer. Philos. Soc.* 81 (1939), p. 135. A Russian translation of Wildt's study, regrettably not in full (which is not indicated in the paper) appeared in the *Astronomicheskii Zhurnal*, Vol. XVII (1940), No. 5, p. 81ff. By now, a new study by Wildt has appeared, *Geochemistry and the Atmosphere of Planets* (1941), but, to our regret, no copy of it has so far reached us.
8. It would deserve a new edition in modern Russian, with commentaries.
9. See *Ocherki geokhimii*, pp. 9, 288, and my book *Problemy biogeokhimii* (The Problems of Biogeochemistry) III (in press).
10. *Problemy biogeokhimii*, III.
11. In accordance with modern American geologists as, for example, Charles Schuchert (Schuchert and Dunbar, *A Textbook of Geology*, II, New York, 1941, p. 88ff.), I call the Cryptozoic era that period which formerly had been called the Azoic, or the Arcaeozoic, era. In the Cryptozoic era the morphological preservation of the remnants of organisms dwindles almost to nothing, but the existence of life is revealed in the organogenic rocks, the origins of which arouse no doubts.
12. On the bio-inert bodies see W.I. Vernadsky, *Problems of Biogeochemistry*, II, *Trans. Conn. Acad. Arts Sci.*, Vol. 35 (1944), pp. 493-494. Such are, for example, the soil, the ocean, the overwhelming majority of terrestrial waters, the troposphere, and so on.
13. See my basic work referred to in Note 1.
14. See D. Gilman. *The Life of J. D. Dana*, New York, 1899. The chapter on the oceanic expedition in this book was written by Le Conte. Le Conte's book, *Evolution* (1888), has not been accessible to me. His autobiography was published in 1903: W. Armes, Editor, *The Autobiography of Joseph Le Conte*. For his biography and bibliography see H. Fairchild in *Bull. Geol. Soc. Amer.* 26 (1915), p. 53.
15. On Reynolds, see the Index in "Centenary Celebration: Wilkes Exploring Expedition of the U.S. Navy, 1838-1842," *Proc. Amer. Philos. Soc.*, 82, No. 5 (1940). It is to be regretted that our expeditions in the Pacific, so active in the first half of the 19th Century, were later discontinued for a long time (almost until the Revolution), following the death of both Emperor Alexander I (1777-1825) and Count N. P. Rumiantsov (1754-1826)—that remarkable leader of Russian culture who equipped the "Riurik" expedition (1815-1818) out of his private funds.
In the Soviet period K. M. Deriugin's (1878-1936) expedition should be mentioned; its precious and scientifically important materials have been so far only partly studied and remain unpublished. Such an attitude toward scientific work is inadmissible. The Zoological Museum of the Academy of Sciences must fulfill this scientific and civic duty.
16. D. Gilman, *op.cit.*, p. 255.
17. I and my contemporaries have imperceptibly lived through a drastic change in the comprehension of the circumambient world. In the time of my youth it seemed both to me and to others that man had lived through a historical time only, within the span of a few thousand years, at best a few tens of thousands of years. Now we know that man has been consciously living through tens of millions of years. He consciously lived through the glacial period in both Eurasia and North America, through the formation of Eastern Himalaya, and so on. The division of historical and geological time is levelled out for us.
18. The last revised edition of my *Ocherki Geokhimii* (Problems of Geochemistry) appeared in 1934. In 1926, the Russian edition of *Biosfera* (The Biosphere) came out, and in 1929 its French edition. My *Biogeokhimicheskie Ocherki* (Biogeochemical Studies) was published in 1940. The publication of *Problemy biogeokhimii* (Problems of Biogeochemistry) was begun in 1940. (A condensed English translation of Part II appeared, under the editorship of G. E. Hutchinson, in *Trans. Conn. Acad. Arts Sci.*, Vol. 35, in 1944.) Part III is in press. *Ocherki geokhimii* was translated into German and Japanese.
19. Le Roy's lectures were at once published in French: *L'exigence idealiste et le fait d'evolution*, Paris, 1927, p. 196.
20. A. Lotka, *Elements of Physical Biology*, Baltimore, 1925, p. 405 ff.
21. W.S. Churchill, *Amid These Storms: Thoughts and Adventures*, New York, 1932, p. 274 ff. I plan to return to this problem elsewhere.
22. I deal with the problem of the biogeochemical functions of organisms in the second part of my book, *The Chemical Structure of the Biosphere*. (see Note 1).