VACLAV SMIL

THE EARTH'S BIOSPHERE

Evolution, Dynamics, and Change

The MIT Press
Cambridge, Massachusetts
London, England

This book was set in Galliard, Bodoni, and Futura by Graphic Composition, Inc.
Printed on recycled paper and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Smil, Vaclav.
The earth's biosphere : evolution, dynamics, and change / Vaclav Smil.
p. cm.
Includes bibliographical references (p.) and index.
ISBN 0-262-19472-4 (hc. : alk. paper)
1. Biosphere. I. Title.
QH343.4.S655 2002
577—dc21 2001058705

THE EARTH'S BIOSPHERE

Also by Vaclav Smil

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Preface

A random perusal of recent publications in such disparate fields as bacterial genomics and Internet encryption or organic chemistry and astrophysics shows that scientific reductionism, the practice I liken to the drilling of ever deeper holes, is thriving more than ever. Synthetic endeavors, such as scanning both nearby terrain and distant horizons, preoccupy only a small minority of scientists but their frequency and scope are increasing. One of the principal reasons for the rejuvenation of scientific syntheses (which used to make up such a large part of nineteenth century science) is the growing realization that the very survival of modern civilization is inextricably tied to the fate of our environment, to changes in the Earth's biosphere. And anybody with even the most basic understanding of the environment realizes that in order to minimize the impact on the biosphere modern societies need integrated, multidisciplinary studies that inform by the breadth of their syntheses.

I wrote *The Earth's Biosphere* to further this fundamental understanding. I have tried to do that by (1) offering a new synthesis that is informed by the latest advances in a multitude of disciplines, ranging from geochemistry and geophysics to ecology and energetics, (2) explaining both well-known and largely unknown fundamentals of the biosphere's structure and dynamics, and (3) trying to convey the many amazing attributes of the Earth's realm of life. These remarkable characteristics are met at every scale, from sub-cellular to planetary — the elaborate organization of protein machines within every living cell, the incredible abilities of microbial metabolism in both mundane and extreme environments, the grand-scale transfers of heat in the Earth's ocean and atmosphere, and the life-sustaining complexities of global biogeochemical cycles.

I have also tried to use some of my professional advantages and personal predilections — bridging the natural and the social sciences — in order to write a multifaceted book that does not fit easily into any simple categories. I know that some readers will find this approach too broad or too taxing. Their patience may be particularly tried as they encounter many pages devoted to the intricacies of microbial life — but this more-detailed focus on bacteria and archaea is merely an acknowledgment of the still underappreciated dominance and ubiquity of these organisms in the biosphere and of their irreplaceable roles in the cycles of life.

I am also sure that some specialists will feel that many topics have not been given enough attention or that explanations of some particulars would have benefited from a greater detail or from a more subtle understanding. I plead guilty on all counts. Syntheses cannot be written as lengthy encyclopedias and, no matter how hard one tries, subtle, confident understanding of myriads of details making up the mosaic of life is beyond anyone's abilities. Such are the perils of this nonreductionist intellectual adventure; its rewards, I hope, are some new perspectives.

As with any book of this kind, I am indebted to thousands of scientists whose work I cite, admire, or criticize and without whose findings and ideas I would not have been able to scan the global horizon and deliver this new synthesis. My particular thanks go to Marty Hoffert, John Katzenberger, and David Schwartzman, who read the entire typescript, corrected some lapses, and suggested numerous additions and improvements.

Any remaining mistakes and misinterpretations are mine — and only mine. As any true interdisciplinarian I have been always aware of numerous weaknesses in my quest for grand syntheses, and I have never had any illusions about the impact of my books. I just do my best. But I am also always mindful of Seneca's sobering verdict regarding our understanding of the world in general:

Veniet tempus quo posteri nostri tam aperta nos nescisse mirentur. (The day will come when posterity will be amazed that we remained ignorant of matters that will to them seem so plain.)

THE EARTH'S BIOSPHERE

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Evolution of the Idea

From Vernadsky to a Science of the Global Environment

A new character is imparted to the planet by this powerful cosmic force. The radiations that pour upon the Earth cause the biosphere to take on properties unknown to lifeless planetary surfaces, and thus transform the face of the Earth.
Vladimir Ivanovich Vernadsky, *Biosfera*

The Earth is not just an ordinary planet!
Antoine de Saint Exupéry, *The Little Prince*

Unlike so many ideas that have unclear, or contested, origins, there is no dispute about the first use of the term "biosphere." Eduard Suess (1831–1914)—a famous Austrian geologist who, together with Charles Lyell (1797–1875) and Louis Agassiz (1807–1873), was one of the three greatest nineteenth-century synthesizers of the rising discipline of Earth science—coined the term (fig. 1.1). Suess became eventually best known for his monumental, although now quite outdated, three-volume set *Das Antlitz der Erde* (Suess 1885–1904), which summarized the contemporary understanding of all major geological features of the Earth.

In fact, Suess literally tossed the new term away, just once and without an explicit definition, in his pioneering book on the genesis of the Alps (Suess 1875). Suess noted that

> *one thing seems to be foreign on this large celestial body consisting of spheres, namely, organic life. But this life is limited to a determined zone at the surface of the lithosphere. The plant, whose deep roots plunge into the soil to feed, and which at the same time rises into the air to breathe, is a good illustration of organic life in the region of interaction between the upper sphere and the lithosphere, and on the surface of continents it is possible to single out an independent biosphere.* (p. 3)

This is a peculiarly limited, and flawed, definition: it appears that Suess did not even consider microorganisms that are abundant both in the lower layer of the atmosphere and in the ocean. And perhaps only Suess's professional

1.1 Eduard Suess (1831–1914), Austrian geologist who coined the term "biosphere" in 1875. Portrait courtesy of Dr. Fritz Popp, Institut für Geologie, Wien Universität.

preoccupation with crustal forms and orogenesis explains his glaring exclusion of marine life from his concept of the biosphere. And seeing the biosphere as independent (*selbständig* in the original) is an inexplicable denial of myriads of links between organisms and their environment. In any case, the new term remained an oddity, and it took a long time before it entered the scientific vocabulary. Five decades had to pass before a Russian scientist reintroduced the concept, defined it in great detail and put it at the core of his interdisciplinary examination of life on the Earth. And incredibly, only more than four decades after that rigorous reintroduction did the concept become widely known outside Russia and begin providing stimulation for long overdue fundamental research as well as for raising public awareness of the need to protect the Earth's environment.

Two developments pushed the concept of the biosphere to the center stage of scientific attention during the last generation of the twentieth century: concerns about unprecedented rates and scales of anthropogenic environmental change and the global monitoring of the Earth's environment from increasingly sophisticated satellites. As a result, few challenges facing civilization during the twenty-first-century will be as daunting, and as critical, as the preservation of the biosphere's integrity.

Vernadsky's Biosphere

Vladimir Ivanovich Vernadsky (1863–1945) was the scientist who elaborated the concept of the biosphere and who is now generally acknowledged as the originator of a new paradigm in life studies (fig. 1.2).[1] Vernadsky belonged to that remarkable group of Russian researchers and thinkers who flourished during the last decades of the nineteenth and the first decades of the twentieth century and whose contributions proved so important for the progress of many disciplines because of their bold departures in new directions. The group's most illustrious names include Dimitri Ivanovich Mendeleev (1834–1907), the author of the periodic table of elements; Vasili Vasil'evich Dokuchaev (1846–1903), the founder of modern soil sci-

1. In references to his work published in French and English I am using the common transcription "Vernadsky"; in references to his Russian-language publications or books about Vernadsky I am using the correct transcription "Vernadskii." Perhaps the most useful book dealing with Vernadsky's life and scientific accomplishments in a wider setting of Russia's history, including reminiscences of his contemporaries, is the volume edited by Aksenov (1993). Other useful English-language books on Vernadsky's life and work include Tumilevskii (1967) and Sokolov and Ianshin (1986). Two additional English-language books are a translation of Balandin's (1982) work and Bailes (1990).

1.2 Vladimir Ivanovich Vernadsky (1863–1945). Photo courtesy of Eric Galimov, V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences, Moscow.

ence; Ivan Petrovich Pavlov (1849–1936) and Ilya Il'ich Mechnikov (1845–1916), Nobelians (1904 and 1908) in medicine and physiology; Konstantin Eduardovich Tsiolkovsky (1857–1935), the visionary pioneer of space flight; and Sergei Winogradsky (1856–1946), discoverer of chemotrophic metabolism in bacteria and one of the creators of modern microbiology.

Vernadsky's scientific career advanced smoothly. Born into a well-off Ukrainian family (his father was a professor of political economy in Kiev and in Moscow and was also engaged in liberal politics), he studied natural sciences at the Faculty of Physics and Mathematics of St. Petersburg University, where both Mendeleev and Dokuchaev were among his professors; mineralogy was his speciality. In 1888–1889 Vernadsky spent two years studying in Munich and in Paris, where he worked with Henri Louis Le Châtelier and with Pierre Curie. Le Châtelier (1850–1936) was an expert in high-temperature studies and in behavior of gas mixtures, and he remains best known for his eponymous principle: "Every change in one of the factors of an equilibrium occasions a rearrangement of the system in such a direction that the factor in question experiences a change in the sense opposite to the original change." Pierre Curie (1859–1906) was a corecipient (with his wife, Marie Curie-Skłodowska, and Henri Becquerel) of 1903 Nobel Prize in physics for their work on radiation phenomena.

Vernadsky's doctoral thesis was submitted to the Moscow University in 1897. A year later he became an extraordinary, and in 1902 an ordinary professor. His first book, *Osnovi kristalografii* (*Fundamentals of Crystallography*), came out two years later (Vernadskii 1904). In 1905, the year of Russia's first democratic revolution, Vernadsky became a founding member of the Constitutional Democratic Party, and between 1908 and 1918 a member of its central committee. Members of the party were known as *kadets,* the name derived from the first letters of the party's Russian name. In 1909 Vernadsky turned from crystallography to geochemistry, and three years later he was elected a full member of the Russian Academy of Sciences. Shortly after the beginning of World War I, he founded and chaired the Commission for the Study of Natural Productive Sources (Russian acronym KEPS), whose goal was to assist the country's military effort. Prominent scientists also participated in the war effort in Germany, France, and the United Kingdom, and later in the United States, foreshadowing the much greater impact of science during World War II.

Beginnings and Interruptions

In the spring of 1916 Vernadsky went to Crimea to the *dacha* of Mikhail Bakunin, brother of the famous anarchist. Then, in July, he prospected, with his favorite student Aleksandr E. Fersman (1883–1945), for bauxite in the Altai Mountains. Afterward he spent several weeks at his own comfortable *dacha* in Shishaki that he built in 1911 on the high left shore of the Psel River, halfway between Poltava and Mirogorod. These were the months and the places where he began to think systematically and to make notes — "with exceptionally broad intentions" in mind — about living matter as the transformer of solar energy and about its planetary importance.

His intentions were to go beyond the unsatisfactory ways in which contemporary biology was dealing with life: examining it either without any references to its environment or merely as adapting to diverse environmental conditions. Fossil fuels, carbonate and phosphate deposits, coral reefs, soils, and atmospheric gases were obvious manifestations of life's importance in actively shaping and transforming the Earth. Vernadsky intended to answer a critical question that he jotted down on a small piece of paper preserved in his archive: "What importance has the whole organic world in the general scheme of chemical reactions on the Earth?" But his answers had to wait: soon after he posed that question the old world of the Russian Empire fell apart. The revolutionary regime that overthrew the czar in February 1917 was short-lived: it was itself overthrown, with German help, by Lenin's Bolsheviks in October 1917, and after years of civil war a new Communist state emerged victorious and the Union of Soviet Socialist Republics was officially established in November 1921 (Walsh 1968; Bradley 1975).

The year 1917, so fateful for Russia, was personally eventful and tragic for Vernadsky. His daughter Nyuta died of tuberculosis, which he, too, contracted. As a prominent *kadet,* he became a deputy to S. F. Oldenburg, the minister of education in the provisional government. On November 6, shortly after the Communist takeover, he wrote in his diary: "Very sad and apprehensive about the future." Yet he was also lucky. When the Bolshevik revolution came in 1917 *kadets* were among the principal enemies to be eliminated by the new regime, and thousands of them, and hundreds of thousands of others, perished in the violence, anarchy, and hunger of the subsequent civil war (for the history of Russia's civil war and political parties see Bradley 1975 and Brovkin 1994).

Three years of disjointed, perilous, and uncertain life were ahead of him. In 1918 Vernadsky fled Moscow, organized the Academy of Sciences in a temporarily free Ukraine, and became its first president. Later he was separated and reunited with his family, got ill with typhoid in February and March of 1920, and two months later became a deputy rector, and in September a rector, of the Tauride University in Simferopol. He was joined in this Crimean refuge, protected by General Wrangel's army (the reactionary Whites, in the Communist parlance), by such outstanding scientists as Ioffe and Tamm. Abram Fedorovich Ioffe (1880–1960), whose main achievements were in crystal physics, was the founder of one of the USSR's principal schools of physics, and Igor Evgenievich Tamm (1895–1971) was a corecipient of the 1958 Nobel Prize in physics. The Communist reconquest of the Crimea in November 1920 ended abruptly that episode of Vernadsky's career.

His son Georgi evacuated with Wrangel's retreating forces, but Vernadsky remained. A letter from N. A. Semashko, Lenin's commissar for health care, spared Vernadsky any persecution. Moreover, he, with a few others, was assigned a special railway car in which to return to

Moscow. Soon after his arrival in Moscow, the family moved back to Petrograd, where Vernadsky tried to resume his work and accepted Fersman's invitation to do research in Russia's north, on the Kola Peninsula near Murmansk. But on July 14, 1921, Vernadsky was arrested and brought to the city's *cheka* headquarters. Without an intervention at the highest level, there would have been no hope: "No release could happen automatically, only shooting happened automatically" (Aksenov 1993).

After spending a day in prison he was, to everybody's surprise, released following two hours of interrogation: A. P. Karpinsky, the president of the Academy, sent telegrams to Lenin, Semashko, and Lunacharsky (the commissar for education) stressing that Vernadsky never fought against the Soviet power. Within a day after his release he left with his daughter Nina, a medical student, for Kola. In May 1922 Vernadsky, his wife, and Nina got passports to travel, via Prague, where his son Georgi settled as an emigrant, to Paris. They arrived on July 8, 1922, and their stay was to be just for one academic year. Vernadsky's Sorbonne lectures on geochemistry were published as a book (Vernadsky 1924), and his stay was extended, with the university's and the Rosenthal Foundation's help, as he searched for funds in the United States to establish a biogeochemical laboratory (Vernadsky 1923). Would he have joined thousands of Russian intellectuals in exile if this laboratory idea were realized?

From Paris, in a letter to his old friend Ivan Il'ich Petrunkevich (1843–1928), one of the leaders of the prerevolutionary democratic opposition to the czarist regime living in exile in Prague, he made his position, and his sense of duty, quite clear:[2]

> *If I were much younger — I would emigrate. My universal feelings are much stronger than my nationalist feelings. But now it is difficult and impossible, as one always needs to lose several years on securing a position. I have no illusions — to live in Russia is extraordinarily difficult. . . . Even if my attempts of moving to America were successful, I would still feel obliged to return and then to leave.*

But his last year spent in France was hardly wasted in waiting. He nearly completed a new book whose beginnings went to those prerevolutionary wartime thoughts and notes. The family left Paris in December 1925, and in February 1926, staying again with his son in Prague, Vernadsky penned the preface to his new book. In its very first sentence he made clear what makes it unique (Vernadsky 1998): "Among numerous works on geology, none has adequately treated the biosphere as a whole, and none has viewed it, as it will be viewed here, as a single orderly manifestation of the mechanism of the uppermost region of the planet — the Earth's crust" (Vernadsky 1998, p. 39). He stressed that he did not want to construct new hypotheses but "strive to remain on the solid ground of empirical generalization." Vernadsky and his wife returned home to a renamed city, Leningrad, in March 1926 (daughter Nina remained abroad). *Biosfera* was published just three months later, and the book's printing of 2,000 copies sold out fast (Vernadskii 1926).

Biosfera

Biosfera was made up of two lengthy scientific essays, the first entitled "Biosphere in the Cosmos," containing 67 sections (each one having typically between two and five paragraphs); the other, "The Domain of Life," containing 160 sections. Reading *Biosfera* at the beginning of the twenty-first century is a very interesting experience. Vernadsky's predilection for grand but concise generalizations

2. Vernadsky's letters to Petrunkevich are archived at the Columbia University; extensive excerpts are printed in Aksenov (1993), where the quoted passage (my translation) is on pp. 287–288.

continues to evoke frequent admiration at how well he set out many concepts, both fundamental and intricate ones, and how crisply he stated his conclusions. Inevitably, there are also generalizations and conclusions that have not withstood the test of time; indeed, some of them were arguable even at the time when they were written.

In addition, the meaning of some statements and sentences remains opaque or altogether obscure. And there are also signs of Vernadsky the mystic. But this is not a critical exposé of *Biosfera* aimed at singling out and discussing the book's factual errors and arguable opinions. My goal here is to review, with some brief comments, those fundamental generalizations and conclusions that have remained unassailable; only secondarily will I note some of those assertions or hypotheses that have been invalidated by subsequent research—or opinions that are distinctly unfashionable today. The latter include, above all, Vernadsky's progressivism, which is the very opposite of the idea of evolution driven by random mutations.

The term "biosphere" is mentioned for the first time in the book's second sentence—but without any definition:

The face of the Earth viewed from celestial space presents a unique appearance, different from all other heavenly bodies. The surface that separates the planet from the cosmic medium is the biosphere, *visible principally because of light from the sun, although it also receives an infinite number of other radiations from space, of which only a small fraction are visible to us. (Vernadsky 1998, p. 43)*

The third section would have made, I believe, a better opening:

Activated by radiation, the matter of the biosphere collects and redistributes solar energy, and converts it ultimately into free energy capable of doing work on Earth. . . . This biosphere plays an extraordinary planetary role. The biosphere is at least as much creation of the sun *as a result of terrestrial processes. (p. 44)*

And a few paragraphs later Vernadsky stressed that "we can gain insight into the biosphere only by considering the obvious bond that unites it to the entire cosmic mechanism" (p. 47).

The biosphere is thus seen as a region of transformation of cosmic energy, specifically of the solar radiation. Its major segments (ultraviolet, visible, and infrared) are transformed in different regions and by different means, and photosynthetic conversion of visible wavelengths producing innumerable compounds rich in free energy extends the biosphere "as a thick layer of new molecular systems" (p. 50). Diffusion of living matter by multiplication creates the ubiquity of life: as "organisms have developed and adapted to conditions which were initially fatal to them. . . . [L]ife tended to take possession of, and utilize, all possible space" (p. 60).

Living matter is thus "spread over the entire surface of the Earth in a manner analogous to gas" (p. 59) as a continuous envelope, and its most characteristic and essential trait is its uninterrupted movement, proceeding with "an inexorable and astonishing mathematical regularity" (p. 61). The result is life that occurs on land, penetrates all of the hydrosphere, and can be observed throughout the troposphere. It even penetrates the interior of living matter itself in the form of parasites. The section on growth contains a number of theoretical examples of the maximum possible reproductive capacities of arthropods and bacteria. And although properly stressing the importance of gaseous exchange involving living organisms, Vernadsky greatly underestimated the total mass of atmospheric oxygen, concluding that it is "of the same order as the existing quantity of living matter" (p. 70). In reality, the atmosphere contains about 1.1 Et (10^{18} t) of oxygen, whereas even the most liberal estimate of the Earth's biomass is no larger than 10 Tt of fresh matter (which is mostly water; see chapter 7). Consequently, oxygen is at least five orders of magnitude more abundant than biomass.

The remainder of the first essay is taken up largely by a discussion of photosynthesis. Here Vernadsky also erred by concluding that "the hydrosphere, a majority of the planetary surface, is always suffused with an unbroken layer of green energy transformers" (p. 80) and in maintaining that "the total mass of green life in the ocean exceeds that on land because of the larger size of the ocean itself" (p. 73). The latter claim was a common misconception during the late nineteenth century and the early decades of the twentieth. In reality, the standing terrestrial phytomass is at least 200 times as large as the biomass of marine phytoplankton and macrophyta (for details see chapter 7).

But Vernadsky presented accurate estimates of typical conversion efficiencies of solar radiation into new plant mass: their large-scale averages are mostly less than 1 percent. The cyclical link between the living matter and the atmosphere is also rightly emphasized: "The gases of the biosphere are generatively linked with living matter which, in turn, determines the essential composition of the atmosphere. . . . The gases of the entire atmosphere are in an equilibrium state of dynamic and perpetual exchange with living matter. Gases freed by living matter promptly return to it" (p. 87).

Finally, Vernadsky pointed out the distinction between rapid and slow cycling of dead organic matter: although most of it is recycled rather rapidly into new living tissues, a small share leaves the biosphere for extended periods and it "returns to living matter by another path, thousands or millions of years afterwards" (p. 87). Vernadsky called the generation of this enormous mass of minerals unique to life "the slow penetration into the Earth of radiant energy from the sun" (p. 88), and adding it to his vastly exaggerated estimated of photosynthesizers, he estimated the total weight of the biosphere at 10^{24} g. And he concluded the first part's last paragraph by maintaining that "although we do not understand the origin of the matter of the biosphere, it is clear that it has been functioning in the same way for billions of years" (p. 89).

The book's second, and longer, part deals mostly with the spatial extent of the biosphere. In its first sentence Vernadsky acknowledged Suess's authorship of the term "biosphere as a specific, life-saturated envelope of the Earth's crust" (p. 91). Then a rather detailed discussion of the Earth's various spheres begins by summarizing the contemporary ideas about the planet's core, the overlaying region ("mantle" in today's terminology), and the crust. Vernadsky also introduced five separate classifications of the Earth's envelopes: thermodynamic, gaseous, chemical, paragenetic, and radiation-based. Overlaps and duplications do not make this approach very clear.

As far as the organisms are concerned, Vernadsky followed the tripartite division—autotrophs, heterotrophs, and mixotrophs—proposed by W. Pfeffer (1881). Autotrophs use only inorganic matter to build their bodies, transforming raw materials into complex organic compounds. Heterotrophs must use ready-made organic compounds in their metabolism; mixotrophs combine organic and inorganic sources of nutrients. Autotrophs include photosynthesizing organisms—not just green plants but also many species of bacteria—and autotrophic bacteria lacking light-sensitive pigments and producing new living matter independent of solar radiation (for details see chapter 3).

Vernadsky rightly stressed the importance of single-celled organisms (Monera) in the biosphere: "Monera are ubiquitous, existing throughout the ocean to depths far beyond the penetration of solar radiation, and they are diverse enough to include nitrogen, sulfur, and iron bacteria. . . . One is led to conclude that bacterial abundance is a ubiquitous and constant feature of the Earth's surface." This led him to conclude "that we should therefore expect that the bacterial mass in the biosphere would far exceed the mass of green eukaryotes" (p. 109). Today's best appraisals confirm this beyond any doubt (see chapter 7).

Vernadsky also marveled at "curious secondary equilibria between sulfate-reducing bacteria and autotrophic organisms that oxidize sulfides" (p. 110), and at an analogical exchange between autotrophic bacteria that oxidize nitrogen and heterotrophic organisms that deoxidize the nitrates. But he was mistaken in concluding that during the Archean era "the quantity of living green matter, and the energy of solar radiation that gave it birth, could not have been perceptibly different in that strange and distant time from what they are today" (p. 108). We now know that the solar output was actually weaker at that time, and the total mass of "green matter" was smaller, than they are today (see chapters 3 and 4).

The remainder of the book is devoted to a fairly thorough exploration of the limits of life. Vernadsky only cited examples of short-term toleration of extreme pressures, temperatures, and radiation exposures rather than exploring the extremes of sustainable metabolism (see chapter 6). Some of his conclusions that are permanently valid (unless, of course, one subscribes to panspermia: see chapter 2) include the fact that "by all appearances the natural forms of life cannot pass beyond the upper stratosphere" (p. 119) and that the shortest wavelengths of electromagnetic radiation are deleterious to life. Vernadsky also estimated fairly correctly the maximum expected depth of the subterranean biosphere, but other conclusions, including the maximum depth of life in the ocean, have been altered considerably with the research advances of the last two generations.

After delimiting the biosphere Vernadsky turned to biogeochemical cycles in the hydrosphere, stressing the differences between planktonic and littoral organisms (or "living films," in his terminology), the reducing environment in the marine mud (the realm of anaerobic bacteria), the action of living organisms that "separates calcium from the sodium, magnesium, potassium and iron of the biosphere, even though it is similar in abundance to these elements" (p. 137), formation of biogenic phosphorite deposits, and releases of hydrogen sulfide by bacteria-reducing sulfates, polythionates, and complex organic compounds.

On land he assigned all living matter to just one living film of the soil and its fauna and flora and stressed the terrestrial life's dependence on water. The closing segment, on the relationship between the living films and concentrations of the hydrosphere and those of land, is very brief. Vernadsky reiterated that "life presents an indivisible and indissoluble whole, in which all parts are interconnected both among themselves and with the inert medium of the biosphere," and that "the biosphere *has existed throughout all geological periods,* from the most ancient indications of the Archaean" (p. 148).

And, immediately, he restated this conclusion once again in a slightly different form: "*In its essential traits, the biosphere has always been constituted in the same way.* One and the same chemical apparatus, created and kept alive by living matter, has been functioning continuously in the biosphere throughout geologic times, driven by the uninterrupted current of radiant solar energy." Still he was not satisfied and a few paragraphs later carried the conclusion too far. First he claimed that "all the vital films (plankton, bottom, and soil) and all vital concentrations (littoral, sargassic, and fresh water) have always existed." Then he reiterated that the changes in the total mass of living matter "could not have been large, because the energy input from the sun has been constant, or nearly so, throughout geological time." (pp. 148–149). We know now that both of these conclusions are wrong.

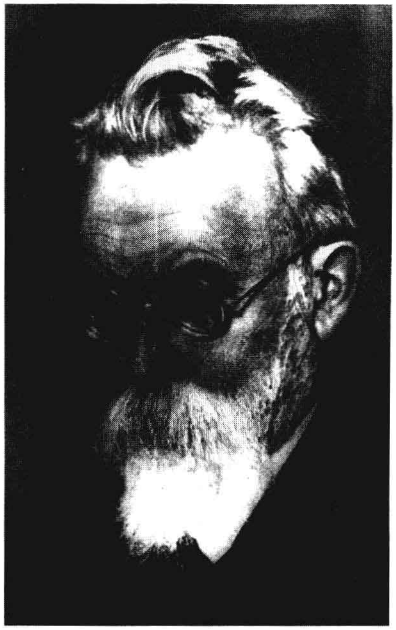
At the very end of the book Vernadsky returned to an idea that he explicitly stated at its very beginning and that sets him directly against the modern worshipers of blind randomness and selfish genes (see chapter 3). In the third section of the first essay he wrote:

> *Ancient religious institutions that considered terrestrial creatures, especially man, to be* children of the sun *were far nearer the truth than is thought by those who see earthly beings simply as ephemeral creations arising from blind and accidental interplay of matter and forces. Creatures on Earth are the fruit of extended, complex processes, and are an essential part of a harmonious cosmic mechanism, in which it is known that fixed laws apply and chance does not exist. (p. 44)*

Then he simply, but emphatically, concluded: "*But living matter is not an accidental creation*" (p. 149).

Later Elaborations

Biosfera and a number of Vernadsky's subsequent writings on this topic entered the canon of Russian science almost immediately. Vernadsky's name, mainly because of his political activities, was well known to Russia's prerevolutionary intelligentsia. When he returned from Paris as one of the doyens of Russian science, he was 63, but his white beard and hair made him look older (fig. 1.3). Although he



1.3 Vernadsky during the last decade of his life. Photo courtesy of Eric Galimov, V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences, Moscow.

withdrew from any political activity and refused to join the Communist Party, Vernadsky became known not only to a new generation of scientists brought up by a new state, but also to many ordinary educated Russians and Ukrainians. Knowledge and acceptance of Vernadsky's ideas abroad was another matter.

The first French translation of *Biosfera* was published by Félix Alcan as early as 1929 (Vernadsky 1929). In France, Vernadsky's ideas were already fairly well known to fellow specialists in geology and geochemistry, most notably to Pierre Teilhard de Chardin (1881–1955), a Jesuit geologist and paleontologist who later became world known for