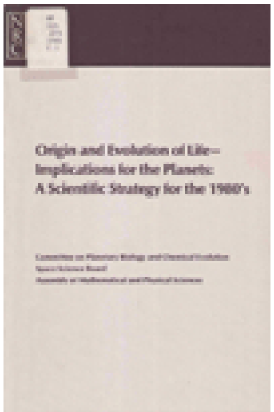

Origin and Evolution of Lifeâ€”Implications for the Planets: A Scientific Strategy for the 1980s

Committee on Planetary Biology and Chemical Evolution, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council

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THE NATIONAL ACADEMIES
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Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's

Committee on Planetary Biology and Chemical Evolution
Space Science Board
Assembly of Mathematical and Physical Sciences
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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Space Science Board
2101 Constitution Avenue
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Foreword

This document is one of a series prepared by committees of the Space Science Board (SSB) that develop strategies for space science over the period of a decade. Several reports in this series have been completed. *Report on Space Science 1975* (Part II, Report of the Committee on Planetary and Lunar Exploration, which covers the outer planets); *Strategy for Exploration of the Inner Planets: 1977-1987*; *A Strategy for Space Astronomy and Astrophysics for the 1980's* (1979); *Life beyond the Earth's Environment: The Biology of Living Organisms in Space* (1979); *Solar-System Space Physics in the 1980's: A Research Strategy* (1980); *Strategy for the Exploration of Primitive Solar-System Bodies–Asteroids, Comets, and Meteoroids*: 1980-1990 (1980); and *Strategy for Space Research in Gravitational Physics in the 1980's* (1981).

This document describes the emerging science of life as a planetary phenomenon. It assesses the status of our knowledge of the origin of life on Earth and of the precursers of life elsewhere in the Galaxy. It also outlines ways in which we can use the capacity that space technology provides to study the biological processes that are important on a global scale in shaping the surface of the Earth and the composition of the atmosphere.

The science of global biology is in its infancy, and much will have to be learned before the data are in hand to carry out definitive global studies. This report identifies some of the questions that must be answered before these data can be effectively gathered and intelligently analyzed. The promises of global biology are great, and the challenges that must be met to realize these promises are substantial. The next decade holds the promise of seeing significant progress in meeting these challenges.

The report of the Committee on Planetary Biology and Chemical Evolution was approved by the Board at its meeting of October 1980. The Board appreciates the efforts of the Committee and particularly its Chairman, Lynn Margulis, who devoted a substantial amount of her time over the past two years to bringing the report to its present state.

A. G. W. Cameron, *Chairman*
Space Science Board

Preface

The capability to look at the earth as a whole has been developed only recently. The space program, both by making us aware of the unity and uniqueness of the surface of the Earth (perhaps most clearly seen in the photographs of Earth taken by the astronauts on the moon) and by providing the technology to study the entire Earth from artificial satellites, has been a primary force in the beginnings of planetary biology. Space technology has also permitted comparative studies of planetary atmospheres and surfaces. These studies coupled with the growing awareness of the effects life has had on the entire Earth are opening new lines of inquiry in science.

Diverse government agencies have responsibilities related to various aspects of Earth and its atmosphere. At present, no single agency is responsible for the quality and direction of the scientific research for the investigation of the Earth viewed as a planet—that is, as a unified interacting system. Our major recommendations focus on the need for coordination of research on the global level. Accordingly, many of our recommendations call for interaction between components of the scientific community and the National Aeronautics and Space Administration. They involve requests for cooperation, information, and mutual education so that satelliteborne measuring devices may be most effectively applied to the understanding of Earth's surface processes. Interactions of several scientific disciplines, including chemistry, biology, geology, and atmospheric science, must occur in order that our understanding develops. No single discipline is adequate to the task.

Although this report deals with work in the established field of chemical evolution (the nonbiological production of compounds in the universe prerequisite to the origins of life), we are attempting to point the way toward a basis for a new scientific enterprise in planetary biology. The goals of planetary biology, which include discerning the effects life has had on the atmosphere, hydrosphere, and lithosphere, are complex. The application of space technology to planetary biological analysis will be a difficult task. Thus we have only outlined here a course of action (Chapter 3, Planetary Biology). We expect that a major future task will be to formulate specific scientific questions in this new field and to determine priorities for the research needed.

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1

Introduction to Chemical Evolution and Planetary Biology

Chemical evolution is the study of the nonbiological formation of organic compounds and their association into a living system. Chemical evolution includes mechanisms of formation in the absence of living organisms of the compounds found in organisms. Chemical evolution takes place in stars and interstellar space and asteroids, comets, meteorites, and planets. *Planetary biology* is the study of life, its chemical precursors, origin, and evolution and factors that lead to its persistence. Planetary biology is especially concerned with the effects that life has had on the atmophere, hydrophere, and sediments at the surface of the Earth; it includes the search for life on other planets in the solar system and beyond.

It has often been assumed that life passively adapts to the physical and chemical environment on the surface of a planet. This environment furthermore has been accepted to be a consequence of the position of the planet in the solar system and the conditions at the time of planetary formation. This is probably not the case. We now know that life has greatly altered the planet on a global scale, for example, the Earth has far more oxygen and far less carbon dioxide in its atmosphere relative to the other terrestrial planets, and many of the sedimentary rocks themselves can be attributed to organisms. Limestones, silicates, and magnetites are often produced by intracellular precipitation and biomineralization processes that occur in organisms living under conditions that are far from chemical equilibrium for the minerals in question (calcium carbonate, silicate, iron oxide). The extent to which the environment of life is the result of biological rather than physical and chemical processes is thus not a nineteenth-century problem: it is a central issue of twentieth-century science. Thus a major scientific goal becomes the untangling of the dynamic processes that maintain Earth as a planet and sustain life, and the major theme of planetary biology is advancement of our understanding of the origin and evolution of life as a planetary phenomenon. That understanding also involves learning more about the extraterrestrial distribution of the elements found universally in living organisms (primarily carbon, hydrogen, nitrogen, phosphorus, sulfur, and oxygen). A cosmic view of carbon chemistry and these other elements will contribute to understanding the origin and early evolution of life and the extent to which life may be an inevitable consequence of planetary evolution. Understanding the role of life as a planetary phenomenon includes knowing the extent to which life can modify a planetary surface.

By the year 2000, Earth is expected to support some 7 billion people, approximately 50 percent more than in 1980. So substantial a change is likely to have profound effects on the biosphere as a whole–changes ranging from food shortages to climatic changes produced by alterations in the reflectivity of the Earth and changes in the infrared absorbance of the atmosphere. Before we have any hope of predicting or counteracting these global changes, we must increase our understanding of the way the surface of the planet is modified by all of life including man.

Space technology can greatly enhance that understanding by making it possible to observe for the first time globally averaged biological processes. Once the relationship between processes on the ground and quantities that can be sensed from space have been established, aircraft and satellite observations will enable us to interpolate to a worldwide scale information obtained from sites that have been studied in detail on the ground.

In this document we outline the bases for the development of a scientific strategy for the study of planetary biology and chemical evolution.

Life originated early in the history of the Earth; we briefly assess the status of the solution to the problem of the origin of life. The evolution of life has profoundly affected the surface of the Earth for over 3 billion years. The nature of the effect of life on the planet and the atmosphere is largely unknown. We indicate the major problems in the understanding of the concomitant course of evolution of life and of its environment–emphasizing the global aspects of this study.

Our recommendations are summarized in Chapter 2. The detailed justification for the recommendations constitute the body of the document. Chapter 3 develops scientific approaches for a program in global ecology; in Chapters 4 and 5 we consider the status of knowledge of chemical evolution in the universe and review current concepts of processes that may have led to the origin and early evolution of life; in Chapter 6 we look back at the history of life from the point of view of the effects it has had on the Earth's surface.

The smallest stable biological system known at present is the entire interacting community of organisms and their environment on the surface of the Earth. Ours is one of the over 3 million species comprising the global community. Each of these interdependent species of organisms on Earth today exchanges gases with the atmosphere. Many, such as those precipitating calcium carbonate and iron, profoundly affect the sediments. The extent to which the global surface responds to biologically induced changes in atmosphere and surface is not known. Clearly the knowledge of the stability properties of surface life on the planet is of great practical as well as scientific interest. We attempt in this document to indicate the current state of knowledge of the biosphere and its component ecosystems, with emphasis on the possibilities for applying remote-sensing technology to the solution of problems of global ecology. We have tried to summarize our understanding of the role of life in maintaining the balance of reactive atmospheric gases. The extent to which remote sensing could have an impact on the quantity and quality of information on biogenic gases and geochemical element cycles is outlined. We review information about the changes of ecosystems through time and indicate where the application of remote sensing could enhance the depth of our understanding.

We view the search for present life in the solar system as completed: there is strong evidence that neither the planets (other than Earth) nor their satellites provide conditions consistent with the maintenance of life. The major limitations are the absence of liquid water or temperatures incompatible with the survival of the organic compounds requisite for living systems. On the other hand, carbon-containing precursors to life and water are abundant in the cosmos in many types of solar-system objects such as comets, asteroids, the satellites of the Jovian planets, and interstellar space. Thus we believe that continued exploration into the nature, distribution, and chemistry of carbon and water in the universe is an important element in the solution of the problem of the origin and evolution of life.

The last decade of space research has taught us that the Earth is probably the only planet in the solar system with life on its surface. The next decade, we hope, will lead us closer to understanding how it became so and cast some light on the extent to which the conditions under which life arose are found elsewhere in the universe.

2

Overview of Goals and Recommendations

I. NASA AND PLANETARY BIOLOGY

A major scientific goal of the National Aeronautics and Space Administration (NASA) is to understand the origin and evolution of life as a phenomenon in the solar system. The planetary exploration program has recently permitted detailed comparisons of the inner planets of the solar system and revealed the profound differences between the Earth and its lifeless neighbors Mars and Venus. The properties of the Earth's surface and atmosphere are not explicable on physical and chemical principles alone; biological processes must be considered in any realistic model of the Earth's surface. Life today reflects its history: life has an unbroken continuity through time to at least 3.5×10^9 years ago when it originated, and the character of the surface of the Earth strongly reflects the evolution of life.

The major goal of this scientific strategy is to understand the Earth as a planet that harbors life. Intrinsic to this understanding is knowledge of the origin of life and the interaction of life with its environment through time. In this chapter we present an overview of goals and recommendations. An enthusiastic scientific community from various disciplines (e.g., atmospheric science, geochemistry, microbiology, and ecology) exists; it lacks cohesiveness, because of the newness of the field of planetary biology as well as the absence of any organized research program. To obtain a valid picture of the dynamic processes at work on the Earth's surface, observations from many fields must be utilized. Our recommendations relate to the gathering together of the community needed to focus effectively on the goals of planetary biology. We believe that NASA has a critical role to play in this effort because of its capabilities for carrying out studies on a global scale. While the potential of remote sensing for planetary biological studies seems great, it is not yet clear how this potential can best be realized. Studies are now under way to assess the capability of remote techniques to contribute to biological measurements. The results of these studies will need to be carefully assessed by the scientific community. This document is intended to be an initial contribution to the intellectual framework for the science involved in global studies of life and its environment on Earth.

II. OBJECTIVES OF PLANETARY BIOLOGY

Three objectives are fundamental to an understanding of planetary biology and chemical evolution: (1) *understanding the origin and evolution of life;* (2) *understanding the cycles that sustain life–the interactions between the physical, chemical, and biological phenomena on the surface of the planet Earth;* (3) *understanding the effects of life, both past and present, on the planet.*

III. GLOBAL ECOLOGY

Global ecology is the scientific study involved in the first objective. The biosphere is the thin surface layer on the Earth in which the biota (the sum of all organisms) reside. It is composed of many semiautonomous units called ecosystems. These are distinctive ensembles of populations that share the same areas of land or water communities (e.g., seafloor, forest, or grassland ecosystems). Ecosystems may be grouped into larger units called biomes. Examples of biomes include northern boreal forests, tropical rain forests, and the abyss of the sea. Energy flows at a greater rate and matter is transferred faster within than between ecosystems. Continuity of life requires that essential chemical elements be delivered to individual organisms at rates that depend on the rate of growth and division of cells. Since these rates tend to be rapid (days and weeks) the transfer of certain elements between ecosystems occurs at rates far more quickly than most geological processes. Much of the flow of critical chemical elements between ecosystems is in the form of gases in the atmosphere, ions in solution, and solid particulates suspended in both the atmosphere and the hydrosphere. Biological processes dominate the rates of production and removal of many constituents of the atmosphere and hydrosphere; however, the extent to which the biota control the composition of the atmosphere and hydrosphere is not known. To identify the processes that control the composition of the atmosphere and hydrosphere we have to understand exchange processes between ecosystems and these global reservoirs, for example, the transfer of major biogenic gases and particulates from coastal salt marshes to the atmosphere. We must also know which communities of organisms are major sources of such gases and particulates. The rates at which the gases are cycled within their ecosystems and transferred to and from the atmosphere and hydrosphere as well as the rates at which they react with one another in the atmosphere must be determined. Examples of gases and dissolved ions of particular interest are N_2, O_2, CO, CO_2, COS, nitrogen oxides (N_2O, NO, NO_2), SO_2, CH_4, NH_3, H_2, H_2S, $(CH_3)_2S$, ozone, PO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, CH_3I, Fe^{2+}, Mn^{2+}, and Ca^{2+}. Particulates include solid suspended materials (often sulfate or phosphorus and organic-rich) of $\leq$10-μm diameter.

As a part of the NASA atmospheric program, a vigorous research effort is needed to identify the production of atmospheric gases and particulates by the most active communities of organisms. A complementary program of research to determine the sources and rates of flow of soluble ions and particulates is needed as well.

Measurements are needed of biogenic gas concentrations and fluxes at the surface of the Earth and as functions of height in the atmosphere; the extent to which gas fluxes are correlated with identifiable ecosystem processes needs to be ascertained.

Correlated ground-based and above-ground measurements of biogenic gases are needed on a global basis. Biogenic fluxes and concentrations change by orders of magnitude from place to place with diurnal, seasonal, and other rhythms, as well as secularly. Because of the limitations of remote sensing, many measurements can only be made from the ground. The extent to which biogenic gases should be measured on the ground and at high altitudes must be assessed. Data collection now is the responsibility of a variety of government agencies such as NASA, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, the Department of Energy, the U.S. Geological Survey, the Department of Agriculture, and the National Science Foundation. International agencies and individual countries also possess jurisdictional authority. With limited national resources available, it is important that redundancies be avoided and that NASA play an important role by taking an initiative in cooperative interagency programs involving the globally relevant measurement of biogenic gases.

The photosynthesis biota provide the major mechanisms whereby solar energy is made available to the rest of the biota by photosynthesis (primary production). The transduction of solar energy into the chemical potentials of carbon compounds is performed by photosynthetic organisms and on land in open bodies of water. More than half of the Earth's net photosynthesis is likely to be performed in grassland and forest ecosystems. The structure of some of these ecosystems has been modified by human activities, the structures of others drastically altered (e.g., the deforested Mediterranean Border and Amazon River Valley). Little is known about the autonomy of ecosystems and the quantitative role of the member organisms in the production of energetic and utilizable macromolecules and in the transfer of gases and particulates. The extent to which some species, for example the most abundant photosynthesizers, are required for stability and are irreplaceable to the system is not known. The details of matter, energy, and information flow within and between ecosystems has not been firmly established. Even less is known about the global consequences of changes in the relationships within and between ecosystems. For example, within each ecosystem (ranging in size from small ponds to large forests) there exist simultaneously chemically reducing zones from which oxygen is excluded as well as oxidizing zones. There is evidence that maintenance of the chemical disequilibrium between the reducing (anaerobic) and oxidizing (aerobic) sectors is crucial to the capacity of the Earth's surface to support aerobic life. Vertical stratification with underlying anaerobic and overlying aerobic zones is not only common (e.g., in salt marshes, lake sediments, and forest profiles) but probably required for ecosystem sustenance. These structural aspects of the organization and changes through time of living communities comprising ecosystems are poorly understood.

Research is needed to better delineate the structure and the boundaries of major ecosystems of the Earth. Because global coverage is only possible by making extensive use of remote sensing, a program is needed to identify the capabilities of remote sensing from aircraft and satellites to identify these ecosystems. Closely correlated ground-based studies must complement those made from altitude. A program of research is needed to determine what surface properties and structural patterns can be used to identify ecosystem types. The extent to which the presence of specific chemical elements and compounds can be inferred by techniques of remote sensing must be ascertained by ground-based correlations with remotely obtained data. Major studies are under way of the processes of matter and information exchange at the ocean, atmosphere, and land surfaces. The relationships between such studies and the remote sensing of ecosystems should be pursued further.

A major objective is the determination of the quantity and detailed nature of the products of global photosynthesis in the most productive ecosystems. Global assessment of productivity is also necessary for accurate determination of the carbon, nitrogen, sulfur, and phosphorus cycles. Multispectral scanners have shown great promise in permitting the quick and accurate assessment of the productivity in grassland converted to agriculture; such efforts should be expanded to other vegetation. Estimates of productivity require knowledge of ground and plant moisture. Remote sensing in the microwave and infrared as well as the visible regions of the spectrum show promise for providing knowledge about soil and plant moisture. In addition, measurements of such quantities as plankton productivity in inaccessible locations can be made by remote stations and the information communicated by satellite to appropriate centers. *NASA should support instrument development to provide improved measures of variables critical to ecosystem function such as primary productivity and ground moisture. Instrument development involves many skills: biologists should participate with other scientists and engineers in designing and evaluating this instrumentation.* In common with a variety of other scientific disciplines including oceanography and hydrology, planetary biology requires the establishment of automatic data-collection stations. *NASA can play a central role in establishing automatic data-collection stations for global biological studies and in managing the collection and distribution of data from these stations.*

Remote-sensing technology has improved our ability to monitor the quantity and kind of production by, for example, plankton in marine ecosystems. While technology exists to carry out such studies, the failure of the rate of information exchange to keep up with the rate of growth of technological innovation results in discrepancies; scientists and engineers making remote measurements often do not communicate effectively with those attempting to assess the productivity of aquatic and terrestrial ecosystems. *NASA should take the lead in coordinating the flow of information between those scientists designing and using remote sensing for productivity measurements and those making such measurements and models on the ground.*

The continuing stability of certain ecosystems such as the grain-producing grasslands is critical for the survival of the human species. Since we have no adequate understanding of how this stability comes about, research is needed to identify and then collect the relevant data from which a theory of the stability of ecosystems can be derived.

A major question in understanding the stability of ecosystems is the nature of critically important species. *Especially important for understanding global biology is the quantitative identification of major photosynthetic species and their role in the support of the ecosystem.*

How small can an ecosystem be and remain viable? Research is needed to determine the minimum sizes of at least certain ecosystems–theoretical and experimental determination of minimal units required for the long-term persistence of its members. One approach is to study how the characteristics of selected ecosystems (e.g., ponds to puddles, grasslands to field plots) change as their volumes decrease and their surface areas change.

In addition to carbon and other major component elements all organisms require certain mineral elements to meet their requirements for growth and reproduction; other elements and compounds are toxins that retard or prevent growth. Hence, the fluxes of certain elements into and out of solid and liquid phases represent processes of great significance for biological survival.

In turn, biological processes affect the chemistry of these mineral elements in both sedimentary and aquatic environments. For example, the concentrations of dissolved trace metals, inorganic phosphorus, silica, nitrate, and carbonate in seawater and ocean basins are known to be strongly affected by marine biota. Present-day calcium carbonate (limestone) deposition is virtually all biogenic. Certain species of organisms are directly or indirectly active in precipitation and thus deposition; other organisms are involved in dissolution and weathering of many minerals. The metabolic processes by which the biota form specific minerals and the quantitative importance of such biogenic production and dissolution are poorly understood. Among the minerals of major interest with respect to their interaction with the biota are specific mineral phases of carbonates, sulfides, silicates, phosphates, iron, and manganese oxides. The extent to which these minerals are uniquely produced only by living cells at moderate temperatures and pressures is not fully known.

A program of research is needed to identify and characterize biominerals and other crustal materials of biological origin and to determine the conditions under which they are formed. Research is also needed to determine the extent to which the fluxes of these minerals into and out of solid phases can be inferred by remote-sensing techniques.

IV. ORIGINS AND EARLY EVOLUTION OF LIFE

A variety of circumstances can lead to the abiotic formation of the compounds of carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus that are the precursors of life. Conditions conducive to the preservation of organic compounds in the universe are found in settings as diverse as the interstellar medium, comets, interplanetary dust, meteorites, and the atmospheres of the outer planets and satellites.

Studies of the interstellar and interplanetary media as well as the major and minor bodies in the solar system will continue to play a key role in developing our understanding of the conditions prerequisite to the formation of the carbon compounds necessary for the origin of life. Studies are needed to characterize the evidence for early organic chemical processes as well as physical conditions of temperature and pressure in primitive bodies such as comets, asteroids, and meteorites. The present organic chemistry in the atmospheres of the outer planets and their satellites such as Titan is of direct interest for understanding chemical evolution.

Laboratory work in prebiotic chemistry has led to the production of monomers and short polymers characteristic of living systems. However, the understanding of the mode of formation of long-chain polymers on the early Earth under prebiotic conditions is rudimentary. The role of nonenzymatic organic or mineral catalysts in the origin of macromolecular systems is not understood, nor are definitive laboratory data available that suggest how the earliest polymers might have interacted with one another to form primitive information transfer and energy-generating systems. It is likely that processes requiring the aggregation of organic matter within lipid membranes as well as the assembly of heterogeneous organic molecules (including nucleic acids, proteins, and their precursors) were prerequisite to the origin of the first cells.

Cells are minimal chemical systems that can be recognized as alive. They are capable of growth, reproduction, and the transmission of genetic information and thus show properties characteristic of all life. *An active program of research is needed to determine how chemicals (monomers and polymers that by themselves lack the properties of life) in the absence of enzymes can become organized to form precursors to cells and eventually cells.*

During the early evolution of life, the present replicating system was established; that is, the fundamental nucleic acid and protein chemistry system that is the basis for growth and reproduction of all living systems was developed. Pathways of fermentation and other mechanisms of carbon metabolism originated and have been retained to this day. Perhaps 2 billion years ago, life had one of its greatest impacts on the chemistry of the Earth's surface—the production of large quantities of free oxygen.

The course of biological and environmental evolution can be traced by several methods: study of stromatolites and microfossils, both remnants of microbial communities, and organic geochemical investigations of carbon compounds in well-dated sediments. For maximum interpretation of fossil sediments, comparable living microbial sedimentary communities should be studied and their preservation potential assessed. The course of early biological evolution can also be elucidated by the exploration of phylogenetic relationships among living microbes using analyses of sequences of monomers in biological polymers such as the nucleotides of nucleic acids and the amino acids of proteins as well as other methods of comparative biochemistry.

Critical to understanding the impact of life on the planet Earth is the identification and determination of the preservation potential of minerals, colloids, and morphologically distinctive structures that are produced by metabolic activity. A major question is the extent to which inference of environmental conditions prevailing at the time of deposition can be made from the sedimentary record.

Studies are needed of ancient and extant microbial ecosystems in order to understand the nature of the interaction between early life and its chemical and geological environment. To elucidate the early stages of life on Earth, research is also needed on the sequences of monomers in information-bearing macromolecules (proteins and nucleic acids).

A program of research is needed to determine those aspects of the atmospheric, hydrospheric, and sedimentary conditions of the Earth in the past that are amenable to verification by examination of the fossil record. Further work is needed to reconstruct paleoecosystems and study their changes through time and to determine what distinguishes the Earth, highly modified by life, from other planets.

V. IMPLEMENTATION OF THE PLANETARY-BIOLOGY STRATEGY

Planetary biology and chemical evolution are interdisciplinary sciences involving planetary astronomy, atmospheric sciences, microbial ecology, geology, paleontology, climatology, biochemistry, and physiology among others, to provide an understanding of the present and past biosphere. The solution of the critical research problems involving the use of space technology and correlated ground research will require a continued flow of dedicated young scientists. Scientists trained in the physical and mathematical sciences have made great contributions to our understanding of biology. The space program similarly requires not only young scientists trained directing in planetary biology but also the training of those in the process of changing their field of study. NASA should assume some responsibilities in providing the necessary supply of scientists. *Educational requirements in global biology can best be met by continuing internships in planetary biology, by predoctoral or postdoctoral training at universities and NASA centers, including the scientist-in-residence programs, by continuing use of conferences to bring interdisciplinary scientists together, and by the support of specialized training programs for those areas of the science that are relevant to the missions of NASA.*

To achieve true global coverage and understanding, an international program to organize global biospheric studies is needed. Furthermore, consideration should be given to the possibility of founding an institute of global studies of the planet Earth. Such an establishment would provide a focus for the development of the science. First, it would provide institutional support for the training of postdoctorates and senior scientists from all over the world in new techniques as well as exposure to relevant but often inaccessible information. This training would benefit both the development of the science and the countries from which the scientists come. Global biological studies will require the ground-truth data that can only be provided by trained scientific observers who are intimately familiar with local circumstances. On the other hand, scientists who understand the use of space technology can make these techniques optimally useful for the understanding of local biological changes only if they interact with those in need of the information who are aware of local problems. Such an interaction of global and local studies will provide great benefits for attempts to understand the conditions that are critically important for human survival. The institute or program will need a scientifically outstanding staff and a dedication to serving wider educational and coordinative functions. Since many studies of fundamental importance for global research require a magnitude of effort of interdisciplinary scientific activities including data gathering and analysis that exceed the capabilities of an individual investigator or university department, such a coordinated international program could provide a natural home for studies critical to the development of the emerging science of comparative planetology.

3

Global Ecology

I. THE BIOSPHERE AND ITS COMPONENTS (ECOSYSTEMS)

The Recognition of Ecosystems

The *biosphere* is the thin surface layer on Earth where life exists. The word has been used occasionally as a collective term for all life; we use the term *biota* to mean the sum of all life: microbes, animals, and plants. The biosphere extends from the depths of the oceans to the upper limits of the troposphere (the lower atmosphere, up to about 16 km over the equator and about 8 km over the poles) and occasionally beyond. Most life resides close to the surface boundaries between the land, water, and atmosphere. The biosphere has developed for over 3 billion years of Earth history through the continuous interactions of life with its environment.

From the perspective of planetary science, several issues concern global ecology. How do the biota modulate or control certain physical and chemical characteristics of the Earth's lithosphere, oceans, and atmosphere? What characterizes the conditions necessary for the long-term persistence of life on the Earth, in space, or on any planet? An approach to these issues is the division of the Earth's surface into ecosystems as meaningful components of study. An *ecosystem* can be defined as an assemblage of interacting populations grouped into communities in their local environment. (Ecosystems themselves may be grouped into larger units called biomes. For example, the cities of northeastern North America are located in the mixed conifer and deciduous forest biome.) *Populations* are made up of organisms that are members of the same species found in the same geographical location at the same time. *Communities* are interacting populations of individuals belonging to different species. Ecosystems then are assemblages of communities that are distinctive and geographically contiguous. Examples of ecosystems include tropical forests, Antarctic dry deserts, salt marshes, and hypersaline evaporite flats. However, the delineation and identification of individual ecosystems and their boundaries is a difficult scientific problem as we discuss below. Energy, from the sun or the interior of the Earth must be received by ecosystems and must flow through and be released by these systems. Information (e.g., in the form of microorganisms, complex organic compounds such as mate attractants or volatile toxins) and required chemical elements cycle through them. We will define ecosystems in terms of processes: energy flow and the cycle of matter. By definition, the rates at which chemical elements and information cycle within an ecosystem are greater than the rate at which they cycle between neighboring ecosystems.

The minimal system that can support life over long time periods must have two characteristics: a flux of energy and the flux and cycling of all the chemical elements required for life. That is, each element required for growth and reproduction of the members of the system must be available in a reusable form by the system: waste converted into food, food converted into waste, waste converted into food. No cell, which is the minimum unit of reproduction, is a sufficient system. No single species, which are organisms sharing many traits in common and which are generally able to reproduce and form fertile offspring, is a sufficient system. Furthermore, no single community, which comprises populations of species of organisms, suffices. That is, none of these limited biological units (cells, individuals, populations, species, and communities) is capable of complete cycling of all the elements required for its subsistence.

A crucial prerequisite for the persistence of life is that the chemical elements required for the species in a system must be available in atomic, molecular, or particulate form, at adequate rates and in appropriate amounts and ratios to ensure growth and reproduction of the organisms within the system. Each population may have its own growth characteristics and reproductive cycles and, therefore, a temporally changing requirement for chemical elements, compounds, and particulates. Thus, the flux of elements and the ecological and physiological mechanisms that control their delivery at appropriate rates and times are complex and at present poorly understood.

In any ecosystem, individuals of some species are far more prominent than others. Yet from the point of view of nutrition two kinds of species are always present: producers (autotrophs) and consumers (heterotrophs). Heterotrophs are animals and microorganisms that depend directly or indirectly on the organic compounds synthesized by producers. The producers comprise the photosynthetic populations (photosynthetic bacteria, including blue-green "algae," cyanobacteria, phytoplankton, vegetation). They are directly responsible for the conversion of solar energy as visible light into forms of chemical energy used for growth and development including energy for the biosynthesis of organic molecules from atmospheric CO_2. The organic molecules (e.g., sugars, amino acids, proteins, and nucleic acids) produced by autotrophs provide food on which the rest of the member populations absolutely depend for survival. In addition, some bacteria, the chemoautotrophs, are able to utilize as energy sources for biosynthesis the oxidation of inorganic compounds such as molecular hydrogen, ammonia, and hydrogen sulfide. Such bacteria produce organic molecules from CO_2 in the absence of light. Thus all ecosystems depend on energy and food made available by producers, organisms that remove atmospheric CO_2 and use either light or chemical energies to synthesize organic compounds. In today's ecosystems the major producers are photoautotrophs–the land plants and the phytoplankton.

Individual ecosystems vary greatly in size. For example, an ecosystem might be a small pool or mudflat, a forest, or a large estuary or grassland. Many ecosystem types extend over large areas and can be recognized from space; however, there is no consensus on the quantitative criteria for delineation of the sharp to diffuse boundaries of the major ecosystems of the Earth. A property of most ecosystems is the maintenance of a large chemical potential difference between its zones: the oxygen-producing and -utilizing aerobic zone and the anoxic or anaerobic zone. Generally the aerobic zone overlies the anaerobic zone. The transitions between the anaerobic and aerobic zones are often at sediment-water interfaces or within the sediment. The maintenance of the reducing or anoxic zones within ecosystems, which is a crucial property for the continued generation of many atmospheric gases such as methane and nitrogen, may be an obligatory feature of all functioning ecosystems.

The entries in Table 1 represent one possible listing of major types of ecosystems. Typically, ecosystems have been identified by using certain biological characteristics such as a list of species present and the abundance of member individuals of each species. However, ecosystems extremely similar in function and type are known that differ drastically in the composition of member species (for example, southwestern North American and Argentinean deserts). It is important to determine in practical terms measures that, taken together, can uniquely identify specific ecosystems.

Since carbon, nitrogen, oxygen, phosphorus, sulfur, and hydrogen are components of nucleic acid and proteins, universal macromolecules in organisms, these "big six" are the major critical elements that must be cycled to members of ecosystems. In addition, some two dozen or more elements are required in varying amounts and ratios by most species (e.g., magnesium, calcium, potassium, cobalt, iron). For survival and reproduction of any organism, certain specific molecules must be made, such as vitamins and metal chelated

TABLE 1 Primary Production and Biomass Estimates for the Biosphere[a,b]

1 Ecosystem Type	2 Area, 10^6 km^2 = 10^{12} m^2	3 Mean Net Primary Productivity, g C/m^2/year	4 Total Net Primary Production, 10^9 metric tons C/year	5 Combustion Value, kcal/g C	6 Net Energy Fixed, 10^{15} kcal/year	7 Mean Plant Biomass, kg C/m^2	8 Total Plant Mass, 10^9 metric tons C
Tropical rain forest	17.0	900	15.3	9.1	139	20	340
Tropical seasonal forest	7.5	675	5.1	9.2	47	16	120
Temperate evergreen forest	5.0	585	2.9	10.6	31	16	80
Temperate deciduous forest	7.0	540	3.8	10.2	39	13.5	95
Boreal forest	12.0	360	4.3	10.6	46	9.0	108
Woodland and shrubland	8.0	270	2.2	10.4	23	2.7	22
Savanna	15.0	315	4.7	8.8	42	1.8	27
Temperate grassland	9.0	225	2.0	8.8	18	0.7	6.3
Tundra and alpine meadow	8.0	65	0.5	10.0	5	0.3	2.4
Desert scrub	18.0	32	0.6	10.0	6	0.3	5.4
Rock, ice, and sand	24.0	1.5	0.04	10.0	0.3	0.01	0.2
Cultivated land	14.0	290	4.1	9.0	37	0.5	7.0
Swamp and marsh	2.0	1125	2.2	9.2	20	6.8	13.6
Lake and stream	2.5	225	0.6	10.0	6	0.01	0.02
TOTAL CONTINENTAL	149	324	48.3	9.5	459	5.55	827
Open ocean	332.0	57	18.9	10.8	204	0.0014	0.46
Upwelling zones	0.4	225	0.1	10.8	1	0.01	0.004
Continental shelf	26.6	162	4.3	10.0	43	0.005	0.13
Algal bed and reef	0.6	900	0.5	10.0	5	0.9	0.54
Estuaries	1.4	810	1.1	9.7	11	0.45	0.63
TOTAL MARINE	361	69	24.9	10.6	264	0.0049	1.76
FULL TOTAL	510	144	73.2	9.9	723	1.63	829

[a] From G. M. Woodwell and E. V. Pecan, *Carbon and the Biosphere*, Technical Information Center Office of Information Services, U.S. Atomic Energy Commission Conference 720510, AEC 30 Symposium Series, 1973.

[b] All values in columns 3 to 8 expressed as carbon on the assumption that carbon content approximates dry matter × 0.45.

ring compounds (porphyrins). The molecules themselves or their precursors must be available to the organisms. In general, these molecular requirements must be delivered to each organism at rates very rapid relative to most geological processes. The removal and delivery of required chemical elements, a property of ecosystems, profoundly affects geochemical cycles. Food particles, molecules, and inorganic plant nutrients such as nitrates and phosphates containing the critical elements and compounds are supplied to individuals and waste products removed. For any given species the form in which critical elements are delivered varies and generally is highly specific for that species. It may be as gases, specific organic compounds, ions in solution, small and large suspended or motile particulates, that is, various small forms of living food materials such as spores, bacteria, or algae as well as larger organisms or their parts such as seeds, fruits, leaves, birds, or fish. The phenomenon seen as distribution of food and waste in a community by biologists is often measured by the geochemist as gases and particulates that are "enriched" or out of equilibrium. Thus there is an intrinsic need for geochemists and biologists to interact in the collection, analysis, and interpretation of their data.

Ecosystem Borders

Ecosystem borders vary in width from millimeters (e.g., edge of a hot spring) to meters (riverbanks) and in length from centimeters (tide pools) to many hundreds of kilometers (forest boundaries). Sometimes ecosystem boundaries are easily recognized because the dominant species in one ecosystem are entirely absent or rare in the neighboring ecosystem. Boreal forests and the edges of crater lakes have easily defined boundaries. Even in cases such as the hardwood forests of North America that border on grasslands and seaside dunes that border on pinewood where a gradation can be seen, the ecosystem border can be identified with precision to within a kilometer or less. In other cases, for example the open ocean, the appropriate area to be taken as a functioning ecosystem is unclear. Boreal forests in northern latitudes may extend for thousands of square kilometers, but some important cycling of chemical elements appears to take place primarily in local areas of only a few kilometers or less. Sometimes, in such cases, a hydrological unit, a "watershed," becomes an appropriate ecosystem. A watershed is defined by the direction of the flow of rainwater over the terrain. Water flowing through the same surface and subsurface water channels to the same reservoir belongs to the same watershed.

Another aspect of ecosystem borders involves transport between different ecosystems. These processes can be of at least two types, (1) production and transport of volatile or soluble compounds that can be transferred into or out of ecosystems and (2) transfer of pollen, spores, seeds, or other propagules between ecosystems. There are many examples of the first case. Some seaweeds, *Polysiphonia*, apparently produce large quantities of oxidized sulfur gases that may be major sources for returning sulfur from the ocean, where sulfate is plentiful, back to the vegetation on land where sulfur may be limiting. Volatilization of toxic heavy metals (mercury or arsenic) or solubilization of nutrients (phosphate or nitrate) can have large general negative or positive effects on ecosystems. In addition there are many specific compounds called *allochemics* (toxins, growth inhibitors, or growth stimulants produced by one species of organism and responded to by another species that affect ecosystems.) Many small molecules acting as signals between reservoirs such as ethylene or terpenes are produced by one species and responded to by another; these may effect ecosystem structure. For the second case, there are abundant examples of low-mass, high-information material that flows within and between ecosystems, including propagules such as spores, seeds, viruses, and quickly settling marine fecal pellets containing bacteria. Such propagules may grow rapidly under favorable conditions and thus may amplify changes in the reservoir size, quality, and flux of material and energy in an ecosystem. Thus it is particularly important to determine which of these small-mass but high-information components may significantly affect ecosystem continuity.

The Interdependence of Ecosystems

The extent to which any ecosystem is a net producer or consumer of the products of photosynthesis, of biogenic gases, or of allochemics and propagules is not know in detail. That is, the independence of ecosystems relative to each other is unknown, although it seems likely that no ecosystem of the biosphere is entirely closed. The Sonoran Desert ecosystem (parts of southern Arizona, Sonora, Mexico, and eastern California) serves as a distinctive example. It is characterized by conspicuous vegetation (e.g., cholla, saguaro, *Cercidium*, and *Acacia) and a fauna entirely* limited to that system (e.g., *Pterotermes*). The directly observable borders of that ecosystem can be measured in meters. The extent to which products of photosynthesis, gases, alkaloids, and terpenoids produced by the leguminous trees, for example, cross ecosystem borders and hence influence the passage of materials and flux of energy is not known; neither is the extent of the importation into the ecosystem of such materials from the atmosphere and the water sources entering the area established. These problems have not been solved for other examples of clearly identifiable ecosystems that have been studied. The identification and description of ecosystems and their interactions to achieve global understanding are extremely difficult; however, progress has been made.

Ecosystem Research

Throughout this century a small portion of the scientific community has engaged in ecosystem research. This research gained support in the United States by the National Science Foundation and included U.S. participation in the International Biological Program. Terrestrial ecosystem research such as the Hubbard Brook Ecosystem Study in New Hampshire and the Andrews Forest Ecosystem Study in Oregon has been carried out in cooperation with the U.S. Forest Service. Attempts have been made to measure the flow of matter and energy within and sometimes between ecosystems, as well as to assess the amount of organic matter, living (biomass) and dead (detrital organics), in these systems. At first the emphasis was on energy flow, organic production, and storage and decomposition of carbon compounds; more recent research has attempted to construct numerical models by quantifying the major populations, by establishing the cycles of major chemical elements, and by determining the control that element fluxes exert on the constituent biota of the ecosystem.

Although progress has been made, ecosystem models have been severely limited. Data generally have been collected sporadically and over heterogeneous and often barely accessible areas. Thus the data on which models have been based are at best rudimentary. Although much information on local settings is often available, with the possible exception of data on carbon the data have seldom been integrated into global models of the Earth that attempt to describe accurately and eventually predict trends.

To model ecosystems adequately, coordinated efforts beyond the resources of any given program are required; furthermore, ecosystems apparently are too complex, heterogeneous, and have boundaries too ill-defined for a data-acquisition program based solely on ground-based measurements.

Application of Remote Sensing to Ecosystem Identification

Most biologists are only vaguely aware of the application of remote sensing to problems of ecosystem research. Most scientists designing remote-sensing imaging systems are not aware of the major problems of global ecology. One purpose of this document is to indicate how the unification of these scientific communities has the potential to effect a revolution in the level of understanding of the Earth.

What is the potential offered by remote sensing? Remote sensing permits data to be obtained from locations that cannot be studied in any other way for reasons of inaccessibility, distance, prohibitive expense, and social unrest; it allows data to be obtained from points too numerous to be studied by any existing ground methods. For example, strong inference concerning soil moisture, acidity, salinity, and other conditions can be made from the nature of remotely sensed ground cover or forest canopy (e.g., terophytic desert, acid bog, and evaporate flat vegetation, respectively). Remote sensing also allows one to obtain measurements of important transitory events, such as floods, fires, flowering and fruiting times. Such measurements often cannot be obtained at all by ground-based methods.

By remote-sensing data we include both the direct acquisition of spectral information by ground-based, airborne, and satellite stations and the acquisition, storage, and transmissions of data from ocean or ground-situated stations via satellite relays.

The phytoplankton populations in large patches in the southern oceans provide an example of the potential for remote sensing to obtain data. Measurement of the distribution, abundance, and temporal changes of the phytoplankton patches by ships or fixed stations has been expensive and inadequate. Estimates of the annual production of krill presumed to relate directly to the quantity of phytoplankton suggest that the krill populations contain more edible protein than the total catch of the world's commercial fisheries. However, little is known about their numbers, patch size, or how rapidly patches change in size and location.

A most impressive and extensive study undertaken in the grasslands of the midregion of the United States and several other selected sites was the Large Area Crop Inventory Experiment (LACIE). Only a single major species (wheat, *Triticum aestivum*) was censused and monitored through the season by LANDSAT, and attempts were made to predict the amount of edible products of its photosynthesis. Both the powers and limitations of the LANDSAT methods were revealed. The most germane here is the scientific prematurity of the questions asked; there is no scientific theory that allows the quantitative estimation of yield based on the parameters measured. However, the ability to obtain, relay, and process data of a dominant species quickly in a grassland ecosystem of large area and great economic importance was demonstrated without doubt. If the powerful tools, techniques, and expert personnel of the LACIE program were applied to basic scientific problems of ecosystem description, the rewards, in principle, would include assessments of estimable quantities such as the primary productivity of dominant populations in the ecosystem; eventually the wheat yield would be predictable.

The scientific information already obtained, for example by LACIE and by conventional ecosystems projects, is in need of coordination, interpretation, and expression of comparable measurements in comparable units. It is to be hoped that the successor, AGRISTAR, a broad-based survey of crop productivity, will benefit from the LACIE experience.

Aquatic Ecosystems

Evaluation of the productivity of the oceans, rivers, and lakes requires the identification of aquatic ecosystems and their boundaries. Although the components of benthic and intertidal ecosystems may be identified, studies of the productivity of vast areas of open ocean have been limited. These may be amenable to remote-sensing analyses combined with "sea-truth" methods. Present study of marine ecosystems largely uses fixed buoys or shipboard sampling to support the counting of organisms, measurement of chlorophyll, nutrients, temperatures, and other factors such as effects of water density gradients, eddies, and storms of importance to oceanic productivity. Oceanographic vessels are enormously costly in time and money and slow in sampling rate. Furthermore, they provide limited samples, which are determined by the ship's course. It often is impossible to sample at the time of most interest, for example to study storm-related events of significance to plankton distribution and fisheries research. Often the distribution of organisms changes at a rate that is similar to or even faster than that of the sampling period. Coverage by remote sensing can help to solve some of these problems. Continuous coverage over time even for a restricted range of parameters such as chlorophyll quantity, water temperature, and turbulence will allow examination of poorly understood phenomena.

Understanding water and organism transport is critical to the recognition of aquatic ecosystems and description of their productivity. Furthermore, synthetic-aperture radar imagery is particularly useful for tracking the movement of ocean and lake surface waters, with which the distribution of photosynthetic plantetonic food organisms can be correlated. This is particularly important in situations where visual imagery is severely restricted by cloud cover.

The detailed applications of remote sensing to ecosystem analysis will require further study and the development of a set of priorities. These priorities must take into account the capabilities of remote sensing in terms of the extent, depth, and timing of the sampling and the acquisition of an amount of data that can be processed effectively.

The Stability of Ecosystems

ECOSYSTEMS AS UNITS

Whereas the biologist focuses on studies of information, energy, and matter flow between individuals and populations that make up ecosystems, geologists and atmospheric scientists usually study matter and energy flow between the fluid and solid phases of these systems. The ecosystem itself has seldom been taken as a unit of study by geologists, chemists, atmospheric scientists, or even ecologists. Although a property of an ecosystem is that the rates of exchange of energy and matter inside it are greater than the rates of exchange between ecosystems, no ecosystem is entirely independent of another: gases, ions and particulates in suspension, propagules, and other matter transfer between ecosystems. Furthermore, ecosystems evolve through time. They may be severely affected by local high-impact events that fragment them (e.g., volcanic eruptions, patchy local urbanization within large forests). Indeed the determination of the minimal size and required properties of a recognizable ecosystem is relevant both to the support of people beyond the Earth's surface (see the earlier Space Science Board report, *Life Beyond the Earth's Environment: The Biology of Living Organisms in Space*, National Academy of Sciences, Washington, D.C., 1979) and to the stability of the urban, grassland, and other ecosystems on which our species and its culture depend.

The major routes of interecosystem transfer involving the fluid phase of the whole Earth–the atmosphere, oceans, rivers, and lakes–have seldom been made explicit. The fluxes of matter and energy between ecosystems via the fluid phases, the atmosphere, and the hydrosphere have been studied and described by atmospheric scientists, oceanographers, and geochemists with a vocabulary and in contexts different from those familiar to biologists. For example, atmospheric scientists tend to describe the "sources" (the organisms and chemical reactions producing the atmospheric gases), the "sinks" (the organisms and chemical processes removing the gases from the atmosphere, for example, carbon dioxide), and the "residence times" of gases (that is, the time it takes for a quantity of atmospheric gas to be reduced to $1/e$ or about 37 percent of the quantity measured). On the other hand, biologists looking at aspects of the same phenomena tend to perceive the same gases in a second context: they might measure CO_2 as a respiratory product of a particular animal or as a chemical precursor to organic compounds synthesized by plants or methanogenic bacteria and thus required by the physiology of the organism in question. Scientists are only beginning to recognize the extent to which gas release and uptake have altered the Earth's atmosphere on a planetary scale and that changes in composition and flux of gases of the lower atmosphere may be a general characteristic of a planet harboring life.

The major constituents of the atmosphere with the exception of the noble gases are all used and produced by some species of organisms. The conditions and rates of production and removal vary greatly (Table 2). The species of organisms in certain ecosystems (e.g., one called the "sulfuretum," sulfurous muddy marine shallows) are probably far more important than others (e.g., of those in deserts) in the production of certain gases such as H_2S, carbon disulfide, and dimethyl sulfide. Yet only limited attempts to measure the relative contribution of different ecosystems to the entire troposphere have been made, and most of these have been made in the context of attempts to determine the effects of anthropogenic sources on the human environment rather than in a fundamental scientific context. The determination of which ecosystems are most important from the point of view of quality and quantity of gas flux to and from the atmosphere has not been made. Although intensive studies have been made on certain aspects of some gases, such as CO_2 and ozone, knowledge of the production and removal mechanisms of reactive gases from the atmosphere is limited enough that the interpretation of worldwide trends is fraught with hazards. The fluxes and the relative importance of gases, particulates, propagules, and other forms of material exchange at ecosystem boundaries for the stability of ecosystems is not known. A theoretical context for material flux data evaluation and prediction has never been developed. Without a balanced strategy of global ecosystem research, any study of the particular effect of some portion of the Earth's biota on the atmosphere and climate such as man's effect on ozone and CO_2 will retain its *ad hoc* character.

We advocate the acquisition of accurate data on nonnoble tropospheric gas fluxes and particulates in the context of ecosystems.

CHANGES WITH TIME AND HUMAN ACTIVITIES

What is the relationship between the complexity of an ecosystem and its identity through time or stability? For example, are extensive ecosystems with a large number of species containing large populations that show great complexity in their feeding, predatory, parasitic, and other interactions, such as an Amazon forest, necessarily more stable than those ecosystems of the same size but with limited membership such as wheat- and corn-producing grasslands? Are ecosystems with great heterogeneity in local spatial and temporal conditions necessarily more persistent through time? Is heterogeneity only an index of time elapsed since some large perturbation (e.g., after the explosion krahaton was only uninhabital for about a year, however, the species list subsequent to eruption was shorter than that before it). Although the commonly held notion is that there is a direct correlation between stability and complexity, this has not been proven. Indeed the proper measure of both stability and complexity is subject to debate.

The persistence through time of any ecosystem implies some kind of stability, but the factors determining stability are not known. During the development of ecology in the twentieth century, stability in specific ecosystems has been defined and used in practice as analogous to stability of mechanical systems. That is, each ecosystem has been assumed to have an equilibrium condition following disturbances. An example is the conifer forest, a forest

TABLE 2 Tropospheric Composition[a]

Species	Chemical Symbol	Fractional Abundance	Lifetime	Thermal IR Band, μm	Sources[b]	Sinks[b]
Oxygen group						
Oxygen (molecular)	O_2	0.2	10^6 yr		B	B, P
	$O_2(1\Delta g)$	10^{-13}	0.26 sec		C	C
Oxygen (atomic)	O	10^{-16}	10^{-5} sec			
	$O(^1p)$	10^{-23}	10^{-9} sec		C	C
Ozone	O_3	3×10^{-8}[c]	2 mo	9.6	P, C	P, C
Carbon group						
Methane	CH_4	1.4×10^{-6}[c]	4 yr	7.7	B	C
Nonmethane hydrocarbons		$\sim 10^{-9}$				
Methyl radical	CH_3	10^{-21}	10^{-10} sec		C	C
Methoxy radical	CH_3O	10^{-15}	0.1 sec		C	C
Methylperoxy radical	CH_3O_2	10^{-11}	10^3 sec		C	C
Methylhydroperoxy radical	CH_3OOH	10^{-11}	2 days		C	P, C
Formyl radical	HCO	10^{-22}	10^{-8} sec		C	C
Formaldehyde	H_2CO	4×10^{-10}[c]	0.4 day		C, A	C
Acetaldehyde	CH_3CHO				C	C
Carbon monoxide	CO	1.2×10^{-7}[c]	4 mo		C, A	C, P
Carbon dioxide	CO_2	3.3×10^{-4}[c]	5 yr	15	B, A	B, P

Nitrogen group						
Nitrogen	N_2	0.8^c	10^6 yr		B, P	B, P
Nitrous oxide	N_2O	3.3×10^{-7c}	20 yr?	7.8, 17	B, P	C
Nitric oxide	NO	10^{-11}			A, B	C
Nitrogen dioxide	NO_2	10^{-10c}		7.6	A, B, C	C
Nitrogen trioxide	NO_3	10^{-14}	15 sec		C	C
Dinitrogen pentoxide	N_2O_5	10^{-14}	15 sec		C	C
Nitrous acid	HNO^2	10^{-12}	10^3 sec		C	C
Nitric acid	HNO_3	10^{-9}	1 wk	5.9, 7.5, 11.3, 21.8	C	P, C
Ammonia	NH_3	10^{-9c}	1 wk	10.53	B, A	C, P
Amino radical	NH_2	10^{-21}	10^{-5} sec		C	C
Aminoxy radical	NH_2O	10^{-16}	1 sec		C	C
Aminoperoxy radical	NH_2O_2	10^{-12}	1 min		C	C
Nitroxyl radical	HNO	10^{-14}	10 sec		C	C
Ammonium nitrate	NH_4NO_3	10^{-10}	1 wk		C	P
Hydrogen group						
Hydrogen (molecular)	H_2	5×10^{-7c}	10 yr		C, B, A	C
Hydrogen (atomic)	H	10^{-21}	10^{-7} sec		C	C
Water	H_2O	0.014	1 wk	6.25, 10.0, 20.0	P	P
Hydroxyl radical	OH	10^{-14}	1 sec		C	C
Hydroperoxyl radical	HO_2	10^{-11}	4 min		C	C
Hydrogen peroxide	H_2O_2	10^{-9}	2 days		C	C

TABLE 2 Tropospheric Composition (continued)

Species	Chemical Symbol	Fractional Abundance	Lifetime	Thermal IR Band, μm	Sources[b]	Sinks[b]
Sulfur group						
Hydrogen sulfide	H_2S	$2 \times 10^{-10\,c}$	3 days		B, A	C
Dimethyl sulfide	$(CH_3)_2S$				B	C
Dimethyl disulfide	$(CH_3)_2S_2$				B	C
Sulfur dioxide	SO_2	$2 \times 10^{-10\,c}$	Hours	8.7, 7.3	B, A	C, P
Carbonyl sulfide	COS	5×10^{-10}			B	C
Thiyl radicals	HS	10^{-21}	10^{-6} sec		C	C
Sulfoxy	SO	10^{-18}	10^{-3} sec		C	C
Sulfur trioxide	SO_3	10^{-22}	10^{-6} sec		C	C
Sulfurous acid	H_2SO_3	10^{-10}	1 wk		C	P
Sulfuric acid	H_2SO_4	10^{-10}	1 wk		C	P
Halogen group						
Trichlorofluoromethane (Freon 11)	CCl_3F	10^{-10}	50 yr	9.22, 11.82	A	C
Dichlorodifluoromethane (Freon 12)	CCl_2F_2	$2 \times 10^{-10\,c}$	100 yr		A	C
Dichlorofluoromethane (Freon 21)	$CHCl_2F$	$1.4 \times 10^{-11\,c}$	2 yr		A	C
Chlorodifluoromethane (Freon 22)	CHF_2Cl		16 yr		A	C
Carbon tetrachloride	CCl_4	10^{-10}	60 yr	12.99	A, B	C
Methyl bromide	CH_3Br	$4.7 \times 10^{-12\,c}$	1.5 yr	16.4, 10.5, 7.66, 6.92	A, B	C
Methyl chloride	CH_3Cl	$7 \times 10^{-10\,c}$	1.4 yr	13.66, 9.85, 7.14	A, B	C

Methyl iodide	CH_3I	10^{-11}[c]		18.76, 11.36, 7.99, 6.94	A, B	C
Hydrogen chloride	HCl	10^{-9}	1 wk		A, P	C
Chloroform	$CHCl_3$	9.4×10^{-12}[c]	7 mo		A, B	C
Trichloroethylene	C_2HCl_3	8.2×10^{-11}[c]	6 days		A	C
Tetrachloroethylene	C_2Cl_4	3.1×10^{-11}[c]	5 mo		A	C
1,1,1-Trichloroethane (methyl chloroform)	CH_3Cl_3	7×10^{-11}[c]	2.3 yr		A, B	C
Vinyl chloride	C_2H_3Cl		2 mo		A	C
Phosgene	$COCl_2$	2×10^{-11}[c]			A	C
Noble gases						
Argon	A	9.3×10^{-3}[c]			P	
Neon	Ne	1.8×10^{-5}[c]			P	
Krypton	Kr	1.1×10^{-6}[c]			P	
Xenon	Xe	9.0×10^{-8}[c]			P	
Helium	He	5.2×10^{-6}[c]			P	P
Radon	Rn		3 days		P	P

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[a] From R. W. Stewart, S. Hameed, and J. Pinto, "The Natural and Perturbed Troposphere," in *Man's Impact on the Troposphere*, J. S. Levine and D. R. Schryer, eds., NASA Reference Publication 1022, 1978.

[b] Key to entries in sixth and seventh columns: A, anthropogenic; B, biological or microbiological; C, chemical; and P, physical.

[c] Measured value. Other entries in third column were calculated.

fire, and subsequent natural reforestation. Furthermore, it has been assumed that the equilibrium state, the mature (or climax) forest, is the most desirable condition, as well as the most likely to persist over time, and in that sense is an optimal condition. This mechanical analogy proved inadequate. In fact, there is evidence that ecosystems must fluctuate in order to persist over longer time periods. They are not characterized by a single optimal equilibrium condition but by a series of relative equilibria interrupted and maintained by periodic disturbances (e.g., seasonal changes, fires, migrations, hurricanes).

In addition to natural conditions, human civilization and technology has introduced an array of changes. Some of these changes that have transformed entire landscapes have reached new states of equilibrium (steady state) and certain stability, others have threatened irreversibly to destroy the regulatory mechanisms essential for the ecosystem persistence through time. Some ecosystems, for example, the grasslands of the midwest United States, are essential for support of certain other ecosystems, for example, the urban ecosystem of the northeast Atlantic coast. The extent to which such productive ecosystems are perturbable or even destructible by imported propagules such as fungal spores, by climate changes, by insect pests, or by removal of key species is unpredictable at present. On the other hand, the environmental costs and long-term effects of maintenance of their present stability by means of chemical control of diseases and pests are equally unknown. Directional and irreversible changes that threaten the stability of ecosystems are also connected with human activity. The examples are deforestation and burdening of the environment with toxic substances, and industrial and municipal wastes. Some of these changes of regional importance have been successfully monitored by remote-sensing technology. They serve as models for extrapolations to global scales.

SPECIES LOSS AND ECOSYSTEM STABILITY

Human activities during the past 200 years have greatly increased the rate of extinction of certain animal and plant species. The role of threatened species and the effects of their losses is not known; it is possible that threatened species are critically important to their ecosystems and therefore must be protected. Large mammals and other top members of the trophic pyramid are the most vulnerable components of an ecosystem threatened by perturbations. Monitoring populations of these species may therefore constitute a most sensitive indicator of change of an ecosystem over time.

The Marine Mammal Protection Act provides an example of the need to identify ecosystems in order to act to prevent the loss of major species. This act makes the protection of marine mammals as parts of marine ecosystems a primary goal. The law states that the primary objective of the management of marine mammals should be "to maintain the health and stability of marine ecosystems." However, marine mammals move over long distances; some great whales migrate from the tropics to the Arctic Ocean each year, crossing putative ecosystem boundaries. The law thus requires the establishment of means to monitor the distribution and abundance of populations of marine mammals on a global scale. The necessity for the application of remote-sensing techniques for such projects is thus clear.

As another example, an International Whaling Commission Agreement has instituted a five-year moratorium for whaling in the Indian Ocean south of 54° latitude. This Commission, an organization having as one of its charges the optimization of populations of blue and gray whales, includes as members representatives from the United Kingdom, the United States, the Soviet Union, Japan, Norway, Canada, and others and supports a secretariat in Cambridge, England. After five years of monitoring, a decision on whether to relax the moratorium is to be made. However, there are enormous difficulties and expense involved in estimating the population structure of these whales.

For many threatened species, including the large mammals in these examples, even the most basic information is lacking: the current population size and its distribution, birth, growth, and mortality rates. Because these large mammals can be seen directly from aircraft and traced by satellites with radio transmission, remote sensing offers unequaled potential to obtain information on dominant and threatened species and to assess their current population structure, spatial distribution, and migratory patterns. The extent to which the investment in remote-sensing technology will be justified by the outcome in large-mammal studies must be ascertained.

We recommend a careful assessment of the capabilities of remote sensing and correlated ground-based research to identify changes in the major aquatic and terrestrial ecosystems of the Earth.

We advocate the acquisition of information on component organisms and their population patterns as well as on tropospheric gas, ion, and particulate fluxes from field studies of ecosystems likely to provide data essential to ecological theory. Many analytical tools are available, including a diversity of remote sensors and gas analyzers. Surface temperatures can be measured with IR sensors; wave action can be detailed remotely with synthetic-aperture radar. The application of these tools is expected to revolutionize ecosystem analysis. A major task for the immediate future is to evaluate the potential of remote sensing to contribute to extension of the coverage of the field studies.

The combination of remote sensing on a global scale and modern ecosystem analysis has the potential to make a major contribution to the study of global biology. Major problems that will have to be resolved include ecosystem identification, the measurement of fluxes at ecosystems borders, and the *stability of ecosystems as a function of size and critical-member species. We recommend that NASA support theoretical and experimental work in global ecology as components of its planetary-biology program.*

II. BIOGENIC GASES

Interaction with Biota

With the exception of the inert gases (He, Ne, Ar, Kr, and Xe) the atmospheric gases contain elements essential to the growth and reproduction of organisms and hence interact strongly with the biota. The atmospheric concentrations of many of them are determined, directly or indirectly, by biological processes, in the sense that biological processes either produce or remove the gases from the atmosphere more rapidly or in greater concentration than do abiological processes (Table 2).

Nitrogen is an element present in all proteins and nucleic acids and hence a nutrient on which life absolutely depends. Nitrogen (N_2) is converted into biologically useful (or "fixed nitrogen," NH_3 or NO_3^-) by lightning, by nitrogen-fixing bacteria, and, more recently, by human activities such as combustion of fossil fuels and fertilizer manufacture.

Nitrous oxide (N_2O) and nitric oxide (NO) are also produced biologically by bacteria living in environments deficient in oxygen in a process called anaerobic denitrification. Some N_2O also is produced in bacterial ammonia oxidation and in nitrate reduction by plants. Photochemical processes in the stratosphere convert most nitrous oxide to molecular nitrogen. Some small fraction, however, is converted to nitric oxide, a gas that catalytically destroys stratospheric ozone. Destruction of stratospheric ozone by NO is the basis of concern about the possible effects of increased denitrification resulting from increased widespread use of fertilizers.

Almost all of the conspicuous animals and plants require atmospheric oxygen (O_2) for respiration. Animals, plants, fungi, and many bacteria remove oxygen from the atmosphere in this process by which they derive energy for their vital functions by combining oxygen with organic compounds. The oxygen thus consumed is restored to the atmosphere primarily by oxygenic photosynthesis. Algae and plants use visible solar energy to convert carbon dioxide and water into a specific array of organic compounds required for growth and release oxygen as a by-product. After decay processes and during diagenesis, organic compounds relatively depleted in oxygen, nitrogen, phosphorus, and sulfur are buried in sediments. The burned carbon is thus removed from the atmosphere, concomitantly oxygen accumulates. Without these oxygen-releasing organisms and associated burial of organics it seems likely that little or no oxygen would have accumulated in the atmosphere. Indeed, it is generally agreed that the Earth's atmosphere lacked significant quantities of oxygen until free-oxygen-releasing photosynthesis evolved some 2.5 billion years ago.

Carbon dioxide (CO_2) is the source of carbon for all photosynthetic processes; it is also incorporated into cell material by nonphotosynthetic organisms. It is released in most respiratory processes by plants, animals, and microorganisms. In addition to secular changes in these processes, the combustion of fossil fuels, deforestation, and other human activities may be significantly changing the quantity of carbon dioxide in the atmosphere.

Methane (CH_4) is almost entirely a product of microbial decomposition of organic matter by fermentation in anaerobic zones. It is destroyed by photochemical processes in the troposphere and by photolysis in the stratosphere. Photochemical products in the methane oxidation chain include formaldehyde (H_2CO), carbon monoxide (CO), hydrogen (H_2), and ozone. These gases also result from the oxidation of higher-molecular-weight hydrocarbons released into the atmosphere by plants. Carbon monoxide is also released in significant quantities by internal combustion engines as well as by bacteria and plants. CO is also produced in reactions with methane and other natural hydrocarbon oxidation and to a lesser extent in photochemical smog.

Ammonia (NH_3) release accompanies the decay of organic matter. It is an important component of atmospheric aerosols. It is the end product of protein metabolism in many microbes and animals. It is removed from the atmosphere photochemically and by rain; it modifies the acidity of rainwater and hence affects organisms on the land.

Hydrogen sulfide (H_2S) is produced by anaerobic bacteria from sulfate. The sulfate from certain evaporite minerals such as gypsum (calcium sulfate) as well as sulfate ions in solution are converted to atmospheric gas by some bacteria in the absence of oxygen. Sulfur dioxide is produced from the combustion of fossil fuels such as coal. Both hydrogen sulfide and sulfur dioxide are toxic to people. Although they are expected to be biogenic, the major sources of several other atmospheric gases such as carbon disulfide (CS_2) and carbonyl sulfide (COS), nitric oxide, and nitrogen dioxide (NO_2) are not yet well established. H_2S oxidizes very rapidly; however, the roles of the other trace sulfur gases [e.g., dimethyl sulfide, $(CH_3)_2S$, dimethyl sulfoxide $(CH_3)_2SO$, COS, carbonyl sulfide, carbon disulfide CS_2] in the sulfur cycle have yet to be established. In summary, the relative importance of photochemistry, lightning, combustion, fossil-fuel burning, and microbial metabolism in the production and removal of these gases has not been precisely determined.

The fluxes of biogenic gases into and out of the atmosphere would be markedly different if the Earth lacked life. Furthermore, as they have done in the past, and still do today, microorganisms can alter the composition of the atmosphere on geologically short time scales. To understand past changes in atmospheric composition and to predict the future, more-reliable data on fluxes of biogenic gases into and out of the atmosphere and on the processes that control these fluxes are needed. These control processes are an aspect of the relationship between ecosystems. For most of the less-abundant biogenic gases there is inadequate information about their mechanisms of production and removal and uncertainty concerning global distributions, average concentrations, and variability in time.

Gas Measurements

The problem of global distribution and variability of atmospheric trace constituents may be suited to remote-sensing studies from space platforms. Data gathered from such platforms would have to be supplemented by ground-based measurements. It is especially important to amass data of gas emission by entire ecosystems so that production rates, transport, and residence times within and between ecosystems can be inferred. The extensive visual imaging of ecosystems by land and sea satellites will allow the extrapolation of accurate ground-derived data to the entire Earth's surface. A major problem has been the lack of standardization of instruments and sampling design. Even more serious is the failure to coordinate ecosystem information on the productive species with atmospheric measurements. Some ecosystems (e.g., coastal marshes) are much more likely to be important sources of certain gases (e.g., CH_4) than others. Hence, field studies of the fluxes of gases into and out of globally important terrestrial and marine ecosystems are needed. Meaningful information will not be available until scientists concerned with global ecology learn the aspects of climatology and atmospheric chemistry needed to design dedicated projects and instrumentation. Instrumentation to measure the concentrations of the atmospheric constituents falls into two main categories: *in situ* instruments (e.g., gas chromatography, mass spectrometry, and chemiluminescent detectors) and remote-sensing instruments. Remote-sensing instruments include the IR DIAL (infrared differential absorption LIDAR), which is potentially capable of measuring sulfur dioxide, carbon monoxide, hydrogen chloride, methane, carbon dioxide, water, nitrous oxide, ammonia, nitrogen dioxide, hydrogen sulfide, formaldehyde, methyl chloride, hydrogen bromide, hydrogen fluoride, and acetylene. The UV DIAL (ultraviolet differential absorption LIDAR) can measure sulfur dioxide and ozone. Other remote-sensing techniques to measure biogenic gases include infrared heterodyne radiometry, gas filter correlation, and interferometry and pressure-modulated radiometry.

Most of these remote sensors are in the development stage and are not yet in routine use; several are under development at the NASA Langley Research Center. A remote sensor in routine use at Langley is the infrared heterodyne radiometer used to obtain the vertical profile of ammonia through the troposphere and lower stratosphere. The UV DIAL, which remotely measures either sulfur dioxide or ozone from an aircraft platform, is currently being tested at Langley. MAPS, a gas filter correlation instrument, will be aboard one of the first orbital tests of the Space Shuttle (OSTA-1) and obtain measurements of mean tropospheric levels of carbon monoxide.

The relative merits of the various instruments for sensitivity, accuracy, ruggedness, applicability to field research, and ability to measure from aircraft or spacecraft are not generally known. The comparative expense, ease of use, and other properties of these instruments often need to be investigated or at least clearly communicated to potential users in the scientific community. Those developing and testing the instruments must work closely with those familiar with biospheric research so that the most important data are collected in an optimal fashion.

In spite of the large array of instruments under development, the method by which biogenic gases are usually studied now involves *in situ* gas chromatography with a variety of detectors. Electron-capture detectors allow the measurement in parts per billion of nitrous fluoroxide and the fluorinated and chlorinated hydrocarbons; iodide gases, such as methyl iodide, can be detected at levels less than one part per trillion. Flame photometric detectors equipped with an appropriate filter are used in the laboratory for the identification of sulfur gases. In the case of flame photometric detection, it is not known, for example, whether a linear relationship exists between detector response and gas concentration or how difficult the identification of one gas is in the presence of other related gases (e.g., carbonyl sulfide in the presence of hydrogen sulfide). These difficulties necessitate the establishment of detailed calibration curves, over a wide range of concentrations for each gas to be measured. In all cases, standard gases must be available for instrument calibration, and in no case has calibration under conditions thought likely to be present in the field been done for a single class of biogenic and anthropogenic gases (e.g., hydrogen sulfide, carbonyl sulfide, carbon disulfide, dimethyl sulfide, sulfur dioxide). Both field and laboratory chromatographic analysis of most reduced sulfur gases require an enrichment step prior to sample injection because ambient concentrations are below minimum instrument detectable levels. Because of the high reactivity of gaseous sulfur compounds, some gases may not prove to be stable between collection and analysis. Thus, they must be measured at their source. Flame-ionization detectors are sensitive and especially useful for measuring methane and other hydrocarbons, and thermal conductivity detectors are applicable to H_2, CO_2, and N_2. The fluxes of these gases may be high although their absolute quantity is low.

The extent to which certain tasks are more appropriately undertaken in the field or samples returned to the laboratories in some cases needs to be determined. Both portable gas-chromatographic detection and sampling systems must be improved to achieve greater sensitivity especially to the range of gases over the natural cycles of emissions: diurnal, seasonal, and secular. Trace atmospheric gases are of particular interest in models of biogenic atmospheric modulation. For example, it has been suggested that there are two ways in which the methane flux may be directly related to the regulation of atmospheric oxygen.

First, methane because it is released into the atmosphere spares carbon from burial; secondly, it escapes to the stratosphere and becomes oxidized to water and CO_2. The water is then available for photodissociation and hydrogen escape. Water itself mainly condenses before it reaches the stratosphere. Identification must be made of the organisms producing and removing the gases and their physiology and growth responses. Horizontal and vertical gradients of gas concentrations and detailed flux studies are required in order to determine the contribution of a specific biological source. Seasonal, diurnal, and other temporal variations may be critical variables in the emission of gases from their sources. The paucity of information and the patchiness of its distribution introduce enormous uncertainties in extrapolation of the results of local studies to the entire globe. A major remedy is regular communication among all scientists interested in the surface of the Earth.

Few studies of the physiology and metabolism of organisms are directed toward their geochemical roles rather than toward their biochemical mechanisms. Gas-measurement techniques seldom have been used to determine the quantity and control of biogenic gas fluxes within and between ecosystems. We recommend that far more information about the spatial and temporal relations of gas emissions in ecosystems be ascertained in order for extrapolations to the global ecosystem to be made with confidence.

Many atmospheric constituents produced directly or indirectly by organisms are destroyed by nonbiological photochemical processes in the atmosphere. Some understanding of the complex interactive chemistry and photochemistry of atmospheric gases can be accomplished by laboratory and theoretical investigations, but theoretical photochemical modeling is also needed both to refine our understanding of the relative roles of biotic and abiotic processes in controlling the composition of the atmosphere and to predict changes in composition. The acquisition of information on trace gas fluxes is prerequisite to a holistic global model of the Earth's atmosphere. Without such a scientific basis we believe that there will be no meaningful predictions of atmospheric trends. To understand the dynamic exchange processes that dominate the Earth's surface, a common language and mutual goals must be developed among scientists studying varying aspects of material and energy transfer between and within ecosystems. Accurate models based on reliable data are intrinsic to the development of planetary biology.

A vigorous program of research is needed to understand the biological origin and modulation of atmospheric gases. A program of development and evaluation of instruments for measuring trace gases at the surface of the Earth and at altitude should be undertaken.

III. PALEOECOSYSTEM ANALYSIS AND THE EFFECT OF THE BIOTA ON THE GEOLOGY OF THE EARTH

Paleoecological Models

There is evidence that the biosphere has persisted as a series of loosely connected ecosystems since the beginning of the Phanerozoic (580 million years ago) and probably far longer. For example, several pre-Phanerozoic ecosystems dominated by microorganisms have been described recently. The major goal of global ecology is the development of an understanding of the biosphere. This task involves the creation of realistic, flexible, and predictive models of current ecosystems and their interactions. Since temporal changes are intrinsic to ecosystems, any realistic model must include changes in ecosystems over time. Thus such models would be potentially useful for extrapolation into the past. Since, for example, species distribution, flux rates of major essential elements, and climatic regimes are correlated with each other, on the basis of such models one would be able to make inferences about the fossil record of organisms and paleo-atmospheric, paleocontinental, and paleooceanic changes at specific times in the past. Such extrapolations from models of present ecosystems into the recent past would be potentially verifiable by close examination of the sedimentary fossil record, that is, direct information on paleoecosystems can be derived from the study of fossilferous sediments, mineralogy, and geochemical data. Current ecological models are based on collections of data from extant communities of organisms in environments characterized by certain climatic, sedimentary, and other nonbiological factors. The comparison of the models with historical data would provide tests of how realistic the models are. Thus reconstruction of paleoatmospheres and other aspects of paleoecosystems would expand the data base against which general ecosystem models can be tested by extrapolation to the past.

We recommend that NASA support paleo-ecological research as an essential component of understanding the impact of the evolution of life on the Earth in the recent past and the near future.

Biomineralization

Certain unique relationships between live organisms and stable inorganic compounds provide the best and most persistent evidence for planetary processes of biological origin. To understand the effect life has on the Earth's surface and especially in order to reconstruct paleoecosystems it is necessary to understand the mechanisms of biomineralization: the formation of minerals by living cells. The fact that the number of minerals identified as biogenic has increased from 13 in 1964 to 31 in 1979 reflects changes in scientific attitudes and increased intensity of work on this problem (see Table 3). For example, although calcium carbonate of shells and calcium phosphate of teeth have long been recognized as biogenic, it has recently been discovered that some sedimentary magnetite is formed inside cells by magnetotactic bacteria. The chemistry, mineralogic details, and degree of preservability of bacterial magnetite is not known. An assessment of the role of life in geological processes depends intrinsically on advances and communication in various disciplines that have little tradition of interaction with each other, for example, geology, microbiology, and ecology. *The distinction between processes in the lithosphere that are strictly controlled by inorganic processes and those largely determined by biological activity is not made easily and represents a scientific goal of high priority.*

One example is manganese oxides in iron-manganese-rich nodules and crusts. To what extent are these precipitates produced by communities of bacteria capable of iron and manganese oxidation? Certain mineral phases such as MnO_2 as birnessite seem characteristic of nonmarine manganese deposits, whereas others such as MnO_2 as todorokite seem characteristic of marine environments. The potential of such mineral phases as indicators in the reconstruction of paleoenvironments may be high. This is only one example of the general question posed by all the entries in Table 3. Some other questions are: (1) Are there phases of minerals that are unique products of living systems? (2) What is the preservation potential of such biominerals? (3) What information about the past can be gained through studies of these biominerals?

The formation of structurally recognizable biomineralization products, for example, the calcium phosphate skeletons of invertebrate animals, was a late innovation in the evolution of life. Living organisms have also tended to displace inorganic processes in the precipitation of carbonates and silica, especially in sediments and seawater during the Phanerozoic aeon. The mineral content of skeletalized hard parts and the trace element content of the biominerals provides information on the nature of the ancient marine environment. In addition to carbonate, silica, and phosphate-bearing hard parts, organisms synthesize a variety of minerals and colloids that previously were thought to be chemical precipitates (see Table 3.).

Research is needed to identify inorganic materials formed by living organ-

isms and to assess their contribution to recent and ancient sediments. Intrinsic to this effort is research to understand the biochemical mechanisms of synthesis of minerals by cells.

Reconstruction of Ancient Environments and Climates by Study of the Sedimentary Rock Record

The last three decades have witnessed the most significant advances in deciphering the history of life, determining the time and conditions under which life arose, and defining the environmental framework in which life has evolved. A start has been made in the determination of the role life has played in modifying and even controlling certain atmospheric and sedimentary processes. On other planets of this solar system and on Earth before the appearance of life, gas and particulate exchange was regulated, as far as we know, by inorganic processes alone.

The most far reaching of recent discoveries has been the documentation of the fossil record from the late Proterozoic about 600 million years ago to the early Archean, approximately 3.5 billion years ago (Figure 1). Evidence for earliest life includes the pre-Phanerozoic fossils of prokaryotic microorganisms, bacteria including oxygen-releasing cyanobacteria (in recognition of their bacterial nature blue-green algae are currently called cyanobacteria). The evidence for these microbes includes lithified community structures often large and extensive in the form of finely laminated rocks composed of carbonates or silicates called stromatolites. These structures, trace fossils of microorganisms, allow one to make strong inferences about the interactions of life with the sediments and may help to provide bases for grossly bracketing dates of the major alteration of the gaseous composition of the atmosphere—the increase in atmospheric oxygen. It is highly unlikely that purely chemical and physical processes would allow the persistence of highly reducing gases such as methane and hydrogen in the presence of 20 percent oxygen. Furthermore, the continual flux of reduced gases such as H_2, H_2S, CH_4, and NH_3 by microbes is probably directly related to the sedimentation of large deposits of certain economically important minerals.

Thirty percent or more of the world's ore reserves of copper, uranium, lead, and zinc are found in sedimentary rocks. Of such deposits there are several principal types. These include evaporite-associated deposits of copper, sandstone-hosted deposits of uranium and other (Athabasca-type) ores of uranium, and ores (Mississippi Valley type) of lead and zinc found within caronbate-rich sediments. There is evidence that the metals in all of these types of deposits were derived in trace amounts from oxidized land-derived clastic strata (called "red beds"). The metals apparently were transported by oxidized waters, enriched in either oxygen or chlorine. The ore metals were

TABLE 3 Biogenic Minerals[a]

KINGDOM	*MONERA*	*PROTOCTISTA*													*FUNGI*		*ANIMALIA*											*PLANTAE*	
PHYLUM		*Dinoplagellata*	*Haptophyta*	*Bacillariophyta*	*Phaeophyta*	*Rhodophyta*	*Chlorophyta*	*Zygnematophyta*	*Sarcodina*	*Siphonophyta*	*Actinopoda*	*Foraminifera*	*Myxomycota*	*Ciliophora*	*Basidiomycota*	*Deuteromycota*	*Porifera*	*Coelenterata*	*Platyhelminthes*	*Ectoprocta*	*Brachiopoda*	*Annelida*	*Mollusca*	*Arthropoda*	*Sipuncula*	*Echinodermata*	*Chordata*	*Bryophyta*	*Tracheophyta*
Carbonates:																													
Calcite	●	●	●			●	●			●		●	●				●	●	●	●	●	●	●	●	●	●	●	●	●
Aragonite	●		?		●	●	●			●		●					●	●		●		●	●	●	●		●		●
Vaterite						●																	●	●			●		●
Monohydrocalcite	●																						●				●		
Amorphous hydrous carbonate													●						●				●	●			●		
Phosphates:																													
Dahllite	●													●		●											●		?
Francolite																					●		●				●		
$Ca_3Mg_3(PO_4)_4$																						●							
Brushite																							●						
Amorphous dahllite precurser																				●			●	●			●		
Amorphous brushite precurser																							●						
Amorphous whitlockite precurser																			●			●	●						
Amorphous hydrous ferric phosphate																						●	●			●			
Halides:																													
Fluorite																							●	●		●			
Amorphous fluorite precurser																							●				●		

Oxalates:																			
Whewellite			●	●		●			●	?					●			●	●
Weddelite									●	?				●		●	●		
Sulfates:																			
Gypsum												●						?	●
Celestite							●												
Barite			●		●														
Silica:																			
Opal		●			?		●	●			●		●	●	●	●			●
Fe-Oxides:																			
Magnetite	●													●	●		●		
Maghemite	?																		
Goethite														●					
Lepidocrocite											●			●					
Ferrihydrite	●								●	●			●	●			●	●	●
Amorphous ferrihydrates								●					●				●		
Mn-Oxides:																			
Birnessite	●																		
Fe-Sulfides:																			
Pyrite	●																		
Hydrotroilite	●																		

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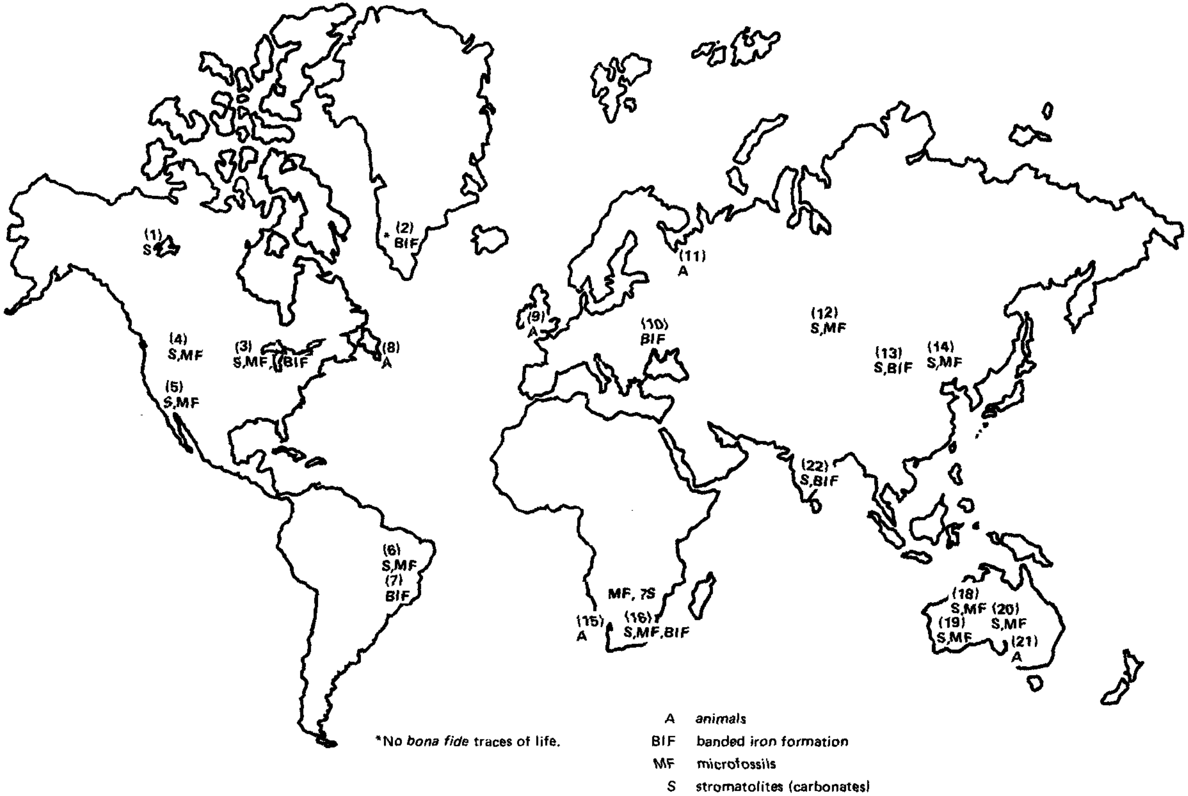
[a] Adapted from H. A. Lowenstam, Bioinorganic Constituents of Hard Parts, in *Proceedings of the First Conference on Amino Acid Geochemistry*, P. A. Hare and T. Hoering, eds., John Wiley and Sons, New York, 1979.

FIGURE 1 Locations of evidence for Precambrian life.



Locality	Name of rocks (in literature)	Age (millions of years ago)	Nature of evidence[a]
1.	Great Slave Supergroup	2200-1800	S
2.	Isua supracrustal belt	~3800	BIF[b]
3.	Gunflint Iron Formation	~2000	S, MF, BIF
4.	Belt Supergroup	~1300	S, MF
5.	Beck Spring Formation	? 1300	S, MF
6.	Bambui Group	<1350	S, MF
7.	Rio des Belhas Series	>2700	BIF
8.	Conception Group	>570	A
9.	Charnwood Forest	>570	A
10.	Krivoy Rog	2200-1900	BIF
11.	Valdai Series	>570	A
12.	Sulfur Springs Suite	1350-950	S, MF
13.	Changzhougou Formation	>1700	S, BIF
14.	Jixian Section of Sinian Suberathem	1950-800	S, MF
15.	Nama System	>570	A
16.	Transvaal Supergroup	2300-2100	S, MF, BIF
17.	Swaziland Supergroup	3400-3500	MF, ?S
18.	Warrawoona Group	~3500	S, MF
19.	Fortescue Group	~2800	S, MF
20.	Bitter Springs Formation	~900	S, MF
21.	Pound Quartzite	>570	A
22.	Dharwar and Aravalli Groups	2600-2100	S, BIF

[a] *Key*: A, Animals, S, stromatolites (carbonates); MF, microfossils; BIF, banded iron formations–relation to microorganisms, if any, not known but may indicate oxygenic photosynthesis.

[b] No *bona fide* traces of life.

precipitated when the migrant, metal-bearing oxidized source waters were chemically reduced—barriers were encountered within strata that were enriched in organic carbon compounds such as hydrocarbons and subsequently were enriched in hydrogen sulfide.

The solubility and chemical mobility of many metals are often a function of their oxidation state. Some metals (e.g., Mn and Fe) precipitate when oxidized and are soluble when reduced, while others (U and Cu) exhibit opposite solubility patterns. Furthermore, metal sulfides are generally quite insoluble. Thus different types of microorganisms that can alter the environmental redox levels may be potentially important in the precipitation or mobilization of metals, either through direct or secondary oxidation or reduction or by indirect effects such as production of sulfides or organic chelating agents.

The role of microbes in the formation of ores, especially in ancient deposits, is not understood, but the almost universal presence of abundant reduced carbon in these deposits is suggestive of biological activity, since organic matter by itself does not effectively precipitate metals. The precipitation most likely occurred in association with those ancient microbial communities.

Several satellite and airborne remote-sensing techniques are currently being utilized to explore for various types of metal deposits. Air color photography, color-enhanced satellite imagery, and airborne spectrometer and electromagnetic data are sources most frequently employed in search of these metals. Color imagery may be useful in identifying rock outcrops whose color has been altered by the passage of mineralizing fluids. Spectrometer and scintillometer surveys are especially useful in identifying exposed uranium deposits by pinpointing anomalous sources of radioactive uranium daughter products. Currently, electromagnetic surveys are being used successfully to identify buried masses of graphite that are associated with Athabasca-type uranium deposits. As the relationship between the deposits and the history of the biosphere becomes clearer, inferences from such observations can use words about environmental evolution.

Projects worthy of further investigation and accelerated research effort include remote-sensing systems that will identify abrupt reduction-oxidation interfaces on rock outcrops by other than tonal differences. Data generated by such systems could be combined with color imagery to identify likely areas of metal concentrations. Another possible approach to the detection of metallic sulfides is the development of remote-sensing systems that can measure seasonal ground-temperature data such as the heat capacity mapping mission (HCMM). For example, sulfide minerals when exposed to the zone of weathering are prone to oxidize rapidly, especially with the aid of aerobic bacteria. Such deposits may maintain a slightly higher ground temperature than surrounding strata; if so, unusual snow and ice melting patterns or other temperature-related phenomena may indicate such metallic sulfide deposits. Sedimentary sulfide deposits are most likely related to bacterial sulfide reduction, although the details of bacterial involvement are not understood.

Vegetation on the surface of rocks and soil often provide excellent indicators of the nature of the underlying geology. For example, the presence of certain trace metals in soils can be detected by the color, health, population density, and species composition of the overlying plants. Often the vegetation is easily seen by remote sensing. Studies of the earliest history of Earth's crust may be aided by the use of remote imagery. In the Komati River Valley of the Republic of South Africa some of the oldest unmetamorphosed rocks outcrop. The pillow lava structures, representative of marine igneous activity, are underlain by ultramafic rocks having a composition similar to today's mantle material, suggesting that crust-building processes that occurred on the Earth over 3 billion years ago may be studied directly. The presence of magmatic rocks of periodotite composition, which come from great depth, can be seen at the surface. The presence of remnants of the interior of the Earth dated at over 3 billion years in age is clearly detectable by aerial or satellite surveillance. The absence of mineral nutrients for the overlying vegetation leads to a barren surface over the ultramafic rocks, in contrast to immediately adjacent areas where silicious and graphitic sediments come to the surface and the vegetation is well developed.

The above is one of many possible examples of reconstruction of the history of the Earth's crust by inference from remote imagery. Systematic aerial studies would help to solve such questions as: Were the processes of magmatic flow forming oceanic crustal rocks 3 billions years ago the same as those observed to occur, e.g., at the East Pacific Rise, today? The fact that the surface vegetation may reflect the composition and thus the origin of the underlying bedrock permits strong inference over large areas at great distances. In some cases, remote observations may replace expensive and time-consuming geomorphological and correlated biological studies–the aerial work may include far more-extensive areas than are possible by direct field observations on land, especially in geographically remote and inaccessible areas.

We recommend studies correlating the surface characteristics, the vegetation, and the nature of the underlying bedrock and soil in selected areas where the rock systems have been well dated so that the properties of ancient environment reflected in the sediments can be reconstructed.

4

Chemical Evolution: Distribution and Formation of Biologically Important Elements

I. COMPONENTS OF ORGANIC COMPOUNDS IN SPACE

In 1975 the Space Science Board adopted the following goals for the exploration of the solar system:

> The primary scientific goals in investigating the solar system are to determine the composition, structure, and environment of the planets and their satellites in order to define the present morphology and dynamics of the solar system and with the purpose of making major steps in understanding the processes by which the planets formed from the solar nebula, how they have evolved with time, and how the appearance of life in the solar system is related to the chemical history of the system. The investigation of the interplanetary and interstellar medium is considered an intrinsic part of such an endeavor.

Our sun apparently formed some 4.5 billion years ago as a result of processes known to be occurring now in dense interstellar gas clouds. Dust, inferred from IR measurements, and many kinds of molecules including organic ones with more than 10 atoms have been observed in the larger clouds (see Table 4). The sun, planets, and smaller solar-system objects–asteroids, comets, and meteoroids–apparently formed from the solar nebula rather rapidly. Meteoroids are defined as solar-system objects ranging in size from dust grains to about 100 m in diameter, a size just visible by telescope. They include meteors and meteorites and are believed to have derived from comets and asteroids. Although diverse, because of their small size these objects are thought to have undergone less alteration than the planets and satellites. They are believed to retain evidence of the earliest chemical evolutionary processes that shaped solar-system material. The chemical history of these objects, as well as that of the early stages in planetary formation is thus related to problems of chemical evolution leading to the origin of life.

The origin of life on Earth is considered to be especially tied to the abiotic formation and chemical history of the compounds of carbon and the five other major elements characteristic of organic chemicals (i.e., H, N, O, S, and P). These elements have the unique property of forming highly ordered and reactive compounds, both monomers and polymers. In particular, they form nucleic acid polymers capable of replication in the presence of catalysts. The catalysts are usually proteins with enzymatic activity. Such genetic polymers and enzymes are the essential constituents of living systems. Minimal chemical living systems, which are spherical bacterial cells, contain at least 2000 different proteins and 5 different classes of nucleic acids. Monomers and polymers in selective molecular association in water manifest fundamental properties of life: replication and the required catalysis to permit replication (i.e., metabolism).

Astronomical observations made with optical and radio telescopes have shown that a large number of low-molecular-weight organic molecules are present in the interstellar medium, comets, planetary atmospheres, and probably asteroids and meteroids. Laboratory analyses of carbonaceous meteorites have shown that these extraterrestrial objects contain examples of several classes of organic compounds present in living systems. Continuing investigations indicate that many of the compounds found in meteorites are the same as those produced in laboratory studies on abiotic organic syntheses. Pathways of early solar-system synthesis of organic compounds of biological significance may be related to those followed in the origin of life on Earth.

This chapter discusses briefly the formation, distribution, and biological significance of organic compounds in the interstellar medium and solar system, offering recommendations for future research needed to solve the major problems in this field. Emphasis is placed on the scientific questions and the approach to their solution rather than on specific space missions.

II. BIOLOGICALLY IMPORTANT ELEMENTS IN THE INTERSTELLAR MEDIUM AND IN COMETS

Interstellar Medium

Compilations of cosmic elemental abundances show that with the exception of the noble gases helium and neon, the four most abundant elements in the universe are H, C, N, and O. These, together with the less abundant S and P, are the elements that form organic compounds present in all life. The compo-

TABLE 4 Molecules Detected Spectroscopically in Interstellar Space[a]

Inorganic		Year of Discovery	Organic		Year of Discovery
Diatomic					
OH	hydroxyl	1963	CH	methylidyne	1937
H_2	molecular hydrogen	1970	CH^+	methylidyne ion	1937
SiO	silicon monoxide	1971	CN	cyanogen	1940
SO	sulfur monoxide	1973	CO	carbon monoxide	1971
Sis	silicon sulfide	1975	CS	carbon monosulfide	1971
NS	nitrogen sulfide	1975	C_2	diatomic carbon	1977
NO	nitric oxide	1978	–	–	–
Triatomic					
H_2O	water	1968	HCN	hydrogen cyanide	1970
H_2S	hydrogen sulfide	1972	HCO^+	formyl ion	1970
N_2H^+	diazenylium ion	1974	HNC	hydrogen isocyanide	1971
SO_2	sulfur dioxide	1975	OCS	carbonyl sulfide	1971
HNO	nitrosyl radical	1977	CCH	ethynyl radical	1974
O_3	ozone	1980	C_3	triatomic carbon	1975
–	–	–	HCO	formyl radical	1976
–	–	–	HCS^+	thioformyl ion	1981
4-Atomic					
NH_3	ammonia	1968	H_2CO	formaldehyde	1969
–	–	–	$HNCO$	isocyanic acid	1971
–	–	–	H_2CS	thioformaldehyde	1971
–	–	–	C_2H_2	acetylene	1976
–	–	–	C_3N	cyanoethynyl	1977
–	–	–	$HNCS$	isothiocyanic acid	1979
5-Atomic					
–	–	–	$HCOOH$	formic acid	1970
–	–	–	HC_3N	cyanoacetylene	1970
–	–	–	H_2CNH	methanimine	1972
–	–	–	H_2NCN	cyanamide	1975
–	–	–	H_2CCO	ketene	1977
–	–	–	HC_4	butadiynyl	1978
6-Atomic					
–	–	–	CH_3OH	methyl alcohol	1970
–	–	–	CH_3CN	methyl cyanide	1971
–	–	–	$HCONH_2$	formamide	1971
–	–	–	CH_3SH	methyl mercaptan	1979
–	–	–	C_2H_4	ethylene	1981
7-Atomic					
–	–	–	CH_3C_2H	methylacetylene	1971
–	–	–	CH_3CHO	acetaldehyde	1971
–	–	–	CH_3NH_2	methylamine	1974
–	–	–	CH_2CHCN	vinyl cyanide	1975
–	–	–	HC_5N	cyanodiacetylene	1976

8-Atomic		–	$HCOOCH_3$	methyl formate	1975
9-Atomic					
–	–	–	$(CH_3)_2O$	dimethyl ether	1974
–	–	–	C_2H_5OH	ethyl alcohol	1975
–	–	–	CH_3CH_2CN	ethyl cyanide	1977
–	–	–	HC_7N	cyanotriacetylene	1977
11-Atomic					
–	–	–	HC_9N	cyanotetracetylene	1978

[a] After R. J. Lovas, L. E. Snyder, and D. R. Johnson, 1979, and other investigators. Since microwave spectrum detectability depends on permanent dipole movement, nonpolar compounds (e.g., CH_4, N_2) have not been detected but probably are present in interstellar space.

sition of living matter is a better sample of the composition of the universe than the bulk composition of the solid earth or other inner planets. These elements also form the most abundant compounds identified in interstellar clouds by radio astronomy during the last decade.

Perhaps one of the most remarkable surprises that has emerged from the radio-astronomical observation of our galaxy is that about one third of the identified molecules are precisely the ones that are used or produced in laboratory experiments of prebiotic organic syntheses. Specifically, eleven of these interstellar organic and inorganic molecules and one detected on Jupiter can be considered as chemical precursors to essentially all the major classes of biochemicals. These precursor molecules are molecular hydrogen, ammonia, carbon monoxide, water, formaldehyde, acetaldehyde, and higher-molecular-weight aldehydes, thioformaldehyde, hydrogen cyanide, cyanoacetylene, cyanamide, and phosphine. Phospine (PH_3) is especially significant; it has been detected in the atmosphere of Jupiter and Saturn and may be present in interstellar space as well. The significance of molecules containing phosphorus stems from their possible role as precursors of the phosphate present in nucleic acids of the genetic material, in the energy-generating systems, and in the coenzymes of all cells. Life could not originate in interstellar space because of the absence of an aqueous liquid phase at temperatures (0–100°C) that permit molecular interactions to proceed at reasonable rates. Thus there is no direct relation between interstellar organic matter and life on Earth. Since the reaction products of precursor molecules similar to those in Table 4 have been found in carbonaceous meteorites, similar organic molecules may have formed in the solar nebula in secondary processes. However, because of the difficulties in generating and maintaining liquid water and requisite concentrations and types of organic compounds, life probably did not originate in comets or in the parent bodies of meteorites.

Scientific questions concerning interstellar distribution of biologically important elements and molecules that have a bearing on the problem of the origin and distribution of life include the following:

What are the mechanisms responsible for the formation and destruction of the organic molecules and radicals in interstellar space?

What determines the abundances of these molecules? Does the thermal stability of triple- and double-bonded compounds at the temperatures of cool stellar atmospheres determine the abundance of carbon monoxide, hydrogen cyanide, and other highly condensed molecules? Is phosphorus found mainly in its elemental forms, as phosphine, or as phosphates?

What new methods, in addition to radio astronomy, visible, ultraviolet, and infrared astronomy, or improvements of existing techniques, can be used to study interstellar clouds and molecules in more detail? How can we apply these methods to elucidate the evolution of large and dense molecular clouds that emit infrared or microwave radiation and are presumed to be solar-like nebulae undergoing gravitational contraction? How does the molecular composition of these clouds compare with that of other interstellar clouds as well as with that of some of the primitive bodies of the solar system, such as comets and the gaseous outer planets?

A major goal in the study of comets, asteroids, and meteoroids is to determine their diversity of composition and structure with particular emphasis on the chemical form and quantity of their organic carbon constituents.

Comets

Comets are among the least-altered bodies of the solar system. They are expected to be less differentiated than the planets, and their composition seems to reflect solar and cosmic elemental abundances; in this sense they are considered primitive bodies of the solar system. The observation that the light elements H, C, N, and O are, relative to solar abundance, much less depleted in comets than in carbonaceous meteorites is consistent with this view. In fact, comets and possibly some asteroids are bodies of the solar system least depleted in H, C, N, and O (with the exception of the giant planets).

Comets have three major parts: nucleus, coma, and tail. The nucleus is thought to have a density about that of water, 1 g/cc or less. Comet nuclei are thought to be composed of water and other ices of lower-molecular-weight gases such as carbon dioxide mixed with silicates, carbon compounds, and traces of other elements. Comet nuclei range in size from 1 km (Encke) to 10 km (Halley) in diameter. The coma is the gaseous envelope or atmosphere surrounding the nucleus with a diameter (10^4-10^5 km) many times larger than the nucleus. The coma forms from the sublimation or volatilization of the cometary ices. The plasma tail, a very long extension of the comet (10^7-

10^8 km), always points away from the sun. A tail of dust made of particulate cometary matter accompanies the plasma tail. The atoms, radicals, and ions found in the comas and tails of comets, primarily by optical spectroscopy, probably result from photodissociation and ionization by solar radiation of neutral molecules present in the nuclear ices. Recently, the presence of neutral parent molecules of biological interest, including hydrogen cyanide, methyl cyanide, hydrogen, and water, has been reported by radio astronomy and other methods. These observations need to be confirmed and further extended.

Comets provide a natural laboratory for the formation of organic compounds germane to an understanding of the physical and chemical processes that led to the origin of life in the solar system. Major scientific questions include the following:

What is the structure and composition of comets? How do these vary in the major comet types? As far as is known, the composition of comets is similar to that of interstellar gas and dust clouds (Table 5).

What, if any, is the relationship between cometary and interstellar organic matter?

What, if any, is the relation of comets to organic matter in the early solar system? Do they contain solar-system matter characteristics of the earliest stages in solar-system development? Are comets directly related to certain asteroids and less-differentiated meteorites, such as the carbonaceous chondrites?

What was the contribution of cometary volatiles, including compounds of H, C, N, O, and S to the atmospheres of the inner planets and the Earth's hydrosphere? Inferences from comparative planetology about the cratering rate suggest that there were many early collisions of comets with the Earth. A significant quantity, perhaps as much as 10^{22} g, of carbon and other volatiles may have been brought into the Archean Earth. A major scientific question is the relationship of cometary impacts to the prebiological environment on Earth.

What is the relationship of comets to interplanetary dust? Meteor showers may be associated with dissipated comets. The bulk of interplanetary dust

TABLE 5 Constituents Observed in Cometary Heads and Tails

Organic:	C, C_2, C_3, CH, CN, CO, CS, HCN, CH_3CN
Inorganic:	H, NH, NH_2, O, OH, H_2O
Metals:	Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V, Si, K
Ions:	CO^+, CO_2^+, CH^+, OH^+, H_2O^+, Ca^+, N_2^+
Dust:	silicates (infrared emission bands)

falling on the Earth may be of cometary origin. The study of this dust in a pristine state, before it has plunged into the Earth's atmosphere, is expected to provide information on the chemical composition and physical state of the less-volatile cometary matter.

Measurements of the major components of the surfaces of comet nuclei are required to answer these questions. We support the recommendations of the Space Science Board's Committee on Planetary and Lunar Exploration (COMPLEX) that the concentrations of all minerals making up more than 5 percent of the surface material be measured with a spatial resolution of better than 10 percent of the diameter of the comet nucleus and that the abundances should be determined of all atmospheric components with molecular weights in the range 1 to 150 that are present at relative concentrations by number in excess of 0.1 percent of the total. We emphasize the importance of measuring the volatile elements and their isotopes (O, C, N, Ar, Ne) as well as identifying and analyzing compounds of C, N, S, and O of molecular weights between 15 and 300 to levels of detection of the instrumentation employed. We support the recommendation of COMPLEX to measure cometary atmospheric composition including trace volatile composition over a range of activities of the comet.

In order to elucidate the chemical composition and structure of comet nuclei and atmospheres to determine their relation to chemical evolution, a rendezvous mission with a comet must be undertaken.

III. DARK OR "CARBONACEOUS" ASTEROIDS

The main-belt asteroids are solid bodies that orbit the sun between Mars and Jupiter. Devoid of atmospheres, they may represent remnants of planetesimals from which the larger planetary bodies accreted in the early history of the solar system. Recent information suggests that they may contain organic matter representative of that produced under natural conditions early in the history of the solar system. Thus asteroids are of direct interest to chemical evolution.

About 20,000 asteroids and their orbital characteristics and approximate diameters have been recorded. They vary in size from less than 1 km to, for example, Ceres, which is over 10^3 km. The total mass of all the currently known asteroids is less than 10^{-3} times that of the Earth. In addition, other objects, those called the Apollo-Amor asteroids, have Earth-crossing orbits. These may come from comets by loss of volatiles or from main-belt asteroids.

Asteroids are studied by measuring their relatively stable orbits and their temporally varying spectral emission properties. Their masses and densities are in general poorly known. Their albedos and compositions are inferred from reflection spectroscopy. They are suggested to include metals, carbonaceous solids, pyroxene, olivine, and other silicate minerals. The spectral classes are not distributed randomly: near the inner edge of the asteroid belt a large fraction of the asteroids have reflectance properties similar to silicate-rich rocky meteorites, whereas farther from the sun most of the asteroids have reflection spectra similar to volatile-rich carbonaceous chondrite meteorites. Thus the asteroids may retain important information about *in situ* processes of formation of planetary bodies in the solar system.

Remote sensing of asteroids has led to the discovery that up to 75 percent of these objects have a very low albedo. These dark reflectance spectra resemble those of the C1, C2, and C3 carbonaceous meteorites. The asteroids are classified into three major types: C (carbonaceous), S (siliceous), and M (metallic). Other asteroids belong to less-well-characterized groups (E, U). The high percentage of C asteroids suggests that many asteroids may contain substantial amounts of organic carbon similar to the meteorites called carbonaceous chondrites.

Major questions of asteroidal science related to the formation of organic compounds and the origin of life in the solar system include the following:

What is the relation between the asteroids and the carbonaceous chondrites? What are the parent bodies of dark asteroids? The irregular shape and heterogenous nature of most asteroids as well as evidence of shock, fracturing, and different cosmic-ray exposures of meteorites have led to the inference that most asteroids have been formed by the collision and fragmentation of a few larger parent bodies. Some carbonaceous chondrites contain noble gases of solar isotopic and elemental composition. These components are thought to have originated from the interaction of the solar wind with regolith materials on the surface of the parent bodies. The parent bodies were probably large and stable within the asteroid belt long enough to have developed substantial regoliths. Do C1 and C2 carbonaceous chondrites come from asteroidal parent bodies or from comets? The analysis of composition, including noble gases and organic constituents of dark asteroids, might help to answer this question about the formation and conversion of organic compounds as well as shed light on the processes of their production in asteroids.

What, if any, is the relation of the asteroids to the comets? Apollo-Amor asteroids may have been derived from long-period comets that acquired smaller-period orbit through perturbation by Jupiter and have lost their volatiles because of proximity to the sun. Whether they are cometary nuclei can be inferred from analyses of the less-volatile organic constituents. Solar radiation is predicted to have measurable effects on the distribution of organic compounds. Furthermore, the state of differentiation in these asteroids may correspond to the early stages of condensation of matter from the solar nebula.

We reiterate the primary objectives of COMPLEX for the exploration of the asteroids.

The determination of the composition, density, and surface morphology of the asteroids is the goal of highest priority. The C asteroids farther from the sun are the objects of most interest for investigation in our context of chemical evolution. We emphasize the importance of measuring the relatively volatile components, H_2O, CO_2, and organic compounds, establishing the presence of 0.1 percent or more by weight of such molecular components and identifying those components representing more than a few percent by weight.

We concur with the judgment of COMPLEX that to make significant advances in the science objectives for asteroid study *rendezvous-mode investigations of several selected asteroids will be required. The Committee on Planetary Biology and Chemical Evolution, recognizing that the use of* in situ *measurements for asteroid analyses will need detailed assessment, recommends that particular attention be paid to the possibility of direct study of the C-type asteroids.*

IV. METEORITES: CARBONACEOUS CHONDRITES

Meteorites are meteoroids that survive passage through the Earth's atmosphere as discrete objects or associated fragments. Meteorites range in weight from many tons, such as the great meteorite that produced Barringer Crater in Arizona, to only a few grams. In the three cases in which recovered meteorites were observed on entry, it was deduced from their orbital parameters that they may have been derived from the asteroid belt. Meteorites can be placed into two broad categories: differentiated and undifferentiated. Undifferentiated meteorites, also called chondrites, contain nonvolatile elements in nearly their solar proportions, while volatile elements are depleted to varying extents. Those least depleted in volatiles are the carbonaceous chondrites, which are thought to have had the lowest formation temperatures and to have suffered the least thermal and chemical alteration of any extraterrestrial materials available for detailed laboratory studies. The organic chemistry of such meteorites has been studied since the 1806 analysis of the Alais meteorite by Thenard.

The carbonaceous meteorites are classified as C1, C2, or C3, depending primarily on their carbon content. The C1 chondrites contain up to about 10 percent total carbon, the C2 meteorites contain about 2.5 percent carbon, and the C3 meteorites contain 1.5 percent carbon. Carbonaceous meteorites also contain water, sulfur, and other volatiles, including large quantities of noble gases. The major components of these meteorites are ferromagnesian silicates and smaller amounts of many other elements. Spherules up to 1 to 2 mm in diameter (chondrules) were probably formed by rapid cooling of molten droplets. They are common constituents of C2 and C3 chondritic meteorites, whereas the C1 meteorites lack macroscopic high-temperature spherules, but they have microscopic chondrules. Surrounding the chondrules in C2 and C3 chondrites is a dark matrix that contains organic and inorganic compounds as well as water-soluble salts. Two major carbonaceous fractions are observed: the largest contains amorphous forms of carbon and highly polymerized organic matter; whereas the smaller, which can be extracted by water and organic solvents, contains a great variety of simple organic compounds.

The organic compounds found in meteorites include many that are present in living systems. These include amino acids, hydroxy acids, polycarboxylic acids, purines, and pyrimidines and other nitrogenous bases, fatty acids, sugars, aliphatic and aromatic hydrocarbons, and other related carbon compounds.

Differentiated meteorites–irons, stony irons, and achondrites–have chemical compositions distinctly different from the undifferentiated chondrites. Their compositions indicate fractionation resembling processes by which igneous rocks were formed on the Earth and moon. On the other hand, carbonaceous chondrites do not show signs of differentiation. The organic compounds in them may have formed, for example, during condensation of the solar nebula or as consequence of the action of ultraviolet photolysis and electrical discharge in the primitive atmospheres around the parent bodies of meteorites. The original inventory of complex organic molecules on Earth may have been significantly influenced by the influx of such carbonaceous material and may be intimately linked to the origin of life on Earth.

Meteorites provide the most abundant clues from which early solar-system history can be inferred, and many fundamental ideas about the origin and evolution of the solar system and its life can be traced to the results of meteorite studies.

Continuing analysis of uncontaminated meteorites, especially carbonaceous chondrites newly fallen or recovered from known ice fields, is vital.

Acquisition of carbonaceous chondrites in a pristine state is important. Meteorites are identified and collected only after they fall through the atmosphere. Those carbon-rich meteorites of greatest interest are friable and easily weathered, wetted, and contaminated with terrestrial materials. Their organic constituents are easily transformed. With time and changes in temperature they soon become indistinguishable from soil. The high preservation potential of carbonaceous meteorites falling on the polar blue ice field of Antarctica has somewhat alleviated this problem. The return of pristine meteoritic material from space would lead to development of sample techniques for extraterrestrial materials, including carbon compounds that would have implications for analysis of any returned sample missions.

Although in some of the earlier analyses there were serious problems of contamination, Murchison, a C2 chondrite analyzed shortly after its fall, and the Allan Hills-77306, also a C2 chondrite preserved uncontaminated in the blue ice field of Antarctica, contain indigenous organic compounds that probably were synthesized during the formation of the meteorite parent bodies soon after formation of the solar system. Protein and nonprotein amino acids are present as racemic mixtures or in equal amounts of enantiomeric amino acids of the D- and L- configurations. Isovaline, a nonprotein amino acid in which the α-hydrogen atom is replaced by a methyl group, and consequently cannot be hydrolytically racemized, is present. Since these amino acids are not obtainable by racemization of protein derivatives, they are not contaminants but were formed by direct chemical synthesis in the parent bodies of the meteorites. Ionizing radiation may decompose a number of these compounds.

We recommend complete characterization of the organic compounds in the C1 and C3 chondrites for comparison with C2 meteorites such as Murchison and Murray. There is a remarkable similarity observed between the amino acids found in Murchison and those synthesized by electrical discharges in "prebiotic chemistry" experiments. The amino acid products, including isovaline, are very similar, and they are synthesized as racemic mixtures in relative quantities comparable with those present in carbonaceous chondrites. This may imply that the amino acids of meteorites were synthesized in the solar nebula or in C2 chondrite parent bodies by ultraviolet photolysis or electrical discharges on gaseous mixtures (CH_4, NH_3, H_2O or CO, N_2, and H_2O). The mechanism of synthesis may involve a Strecker condensation of an aldehyde with hydrogen cyanide in which both the HCN and the aldehyde were formed by electric discharges in the presence of nitrogen or ammonia; still other condensation reactions are possible.

We recommend continued characterization of the C1, C2, and C3 organic constituents of undifferentiated meteorites. We recommend studies to compare mechanisms of amino acid synthesis in prebiotic laboratory experiments and in meteorites.

V. INNER SOLAR SYSTEM

Mercury and Venus

We assume that liquid water, atmospheric gas, and reduced carbon are prerequisites for the presence of life on any planet. In the inner solar system we have enough information about the moon, Mercury, and Venus to know that there is neither significant organic chemistry nor life on these bodies. The surface temperature of Venus is 480°C, and the cooler upper atmosphere of this planet contains clouds of sulfuric acid that would hydrolyze macromolecules. Mercury and the moon lack atmospheres. It is now clear that if we were to invest great effort to plant and nurture life on the moon, Mercury, or Venus we would have serious difficulties assuring its survival and persistence. The precise range of conditions required for a planet to harbor life are not known in detail, but these inner planets are well outside this range; the planetary surfaces are so extraordinarily inhospitable to life that seeding them may even be impossible. Furthermore, we now know as a result of the Viking Mission that the present surface of Mars is uninhabitable as well.

Mars

The Committee on Planetary Biology and Chemical Evolution prepared a report, *Post-Viking Biological Investigation of Mars*, which was adopted by the Space Science Board and published in November 1977. This report begins:

> The predecessors to this Committee stated in 1974 that "At present time, Mars is the only real target for exobiological searches in the solar system. All other objects, with the possible exception of Titan, appear to be excluded as possible habitats for life, owing either to the lack of an atmosphere or to temperature regimes that are incompatible with complex organic chemistry."

The Committee went on to say

> . . . we continue to support that . . . Mars is the only real target for exobiological searches in the solar system.

The 1977 report concluded "Viking has neither confirmed nor ruled out current or past Martian life . . . [However] we believe that it is preferable to predicate future strategy on the assumption that the [Viking biology experiments] signals are not biological in origin." We reaffirm the 1977 Mars strategy. On the basis of post-Viking laboratory simulations and experimental results, a stronger conclusion can now be drawn: There is no evidence for current life on Mars (see Appendix B). For this reason, we conclude that Mars is no longer a target for the direct search for life in the solar system. We would not categorically state that there is no life on Mars; we believe, however, that the probability is so small that it is not useful to plan strategy based on the hope that life can be found on Mars.

We reaffirm the statements made in the 1977 report that the question of past life on Mars is open. We believe that this is an important unsolved scientific problem worthy of careful consideration.

VI. THE OUTER PLANETS: JUPITER, SATURN, URANUS, NEPTUNE, AND THEIR SATELLITES

In the outer solar system, the massive atmospheres of the giant planets, Jupiter and Saturn, are predominantly made of hydrogen and helium (with a ratio of 9 to 1) and of smaller amounts of reduced compounds of C, N, O, S, and P. In spite of the presence of the most important biogenic elements, there is no evidence that life can even persist, let alone originate, in an atmosphere. A solid surface in contact with a fluid phase at temperatures between the freezing and boiling points of water seems to be required for any life. No species of organism on Earth can complete its life cycle in the atmosphere, even given the moist permissive conditions that prevail on much of our planet's surface. Organic chemical processes leading to the origin of life may have been thwarted by many factors on the outer planets. Convection currents drawing materials from freezing atmospheric levels to lower, incinerating depths is a major obstacle to life. The ubiquity of ammonia and the absence of open bodies of water and of essential trace constituents at upper, cooler levels pose severe limitations to life as we know it.

The colored clouds of Jupiter have long been interpreted as possible evidence for the atmospheric production of organic polymers. Recently, this hypothesis has been severely challenged. Mixtures of free sulfur, ammonia, polysulfides, red phosphorus, and products of their interaction are considered to provide more plausible explanations for the colors. The internal energy source lightening on Jupiter is expected to drive nonequilibrium reactions; this needs further theoretical investigation. The detection of CO, which will be at equilibrium for $T = 1000$ K, suggests that relatively high-temperature chemical products may be synthesized in the Jovian atmosphere.

The other outer planets have less-active meteorologies and are less brightly colored. Whether internally driven chemistry occurs below the clouds on Saturn and Neptune is not known. Uranus seems to lack an internal energy source. The nature of the atmosphere and surface on that planet make the probability of life there seem very low as well.

We recommend continued study of the chemistry of the Jovian planets in the context of their potential for complex organic synthesis.

Among the satellites of Jupiter and Saturn, Europa and Titan deserve special consideration. Europa is about the same size and density as our moon. Its bright icy surface is practically devoid of craters but displays a complex array of long brownish-colored streaks or markings. The smooth topography indicates that the icy crust is young, being continuously renovated, and that it floats on an ocean of water or soft ice (slush), which has been estimated to be about 80 km deep. Some streaks are supposed to be surface fractures caused by the tidal forces generated by Jupiter's gravitation, which also contribute to the heating of Europa's interior. The tidal heating of Europa has been estimated to be about 10 percent of that of Io.

It would be interesting to find out if the colored material of the markings is made of organic or inorganic compounds left when the underground water emerges through fissures or fractures to the surface of the satellite. Although Europa has no atmosphere, the presence of organic matter in its subsurface oceans is quite likely, since there is usually a direct correlation between water and carbon compounds in the solar system. *Therefore, we recommend the further study of Europa from the point of view of the chemical processes that may be taking place in its subsurface and may be reflected in its surface composition.*

Titan, the largest satellite of Saturn, is the only object of the outer planets that we believe possesses both an atmosphere and a solid surface. According to Voyager's data, nitrogen is the major component of its atmosphere (>90 percent) with a few percent of methane. Trace amounts of several organic compounds, such as ethane, ethylene, and acetylene, as well as hydrogen cyanide and cyanoacetylene, have also been detected. Some of these compounds, which probably form photochemically from methane and nitrogen in the upper atmosphere, may be the precursors of the reddish smog particles. The atmospheric pressure at ground level is at least 1500 mbar and probably somewhat higher. The atmospheric surface temperature is -176°C, which lies close to the triple point of methane, the temperature at which methane can coexist as a solid, liquid, or gas. Thus, methane would act as a buffer, maintaining Titan's surface temperature always at the triple point. The atmospheric temperature profile is such that there is a minimum (-202°C) at about 50 km. At this altitude the temperature is cold enough to condense methane into snow, which would fall on the surface and evaporate again depending on the temperature and pressure conditions.

Titan's density (1.9) is lower than that of Europa and other satellites. It is likely that Titan is rich in ices of compounds made of carbon, nitrogen, and oxygen, probably dominated by water. The reddish color suggests that chemical reactions among the atmospheric constituents are producing substances of sufficient complexity to absorb visible radiation.

Titan appears to us a more likely site for chemical evolution than are the major planets. Its low mass allows the escape of hydrogen, drastically reducing the probability of recombination of hydrogen with organic molecules produced by photodissocation. The chance reactions forming organic compounds of greater complexity is correspondingly enhanced. Organic substances produced by photochemical reactions in the atmosphere are expected to settle out on the surface of Titan, where they may be examined directly using appropriately equipped soft landers.

We recommend study of Titan from the point of view of the organic chemical processes likely to be taking place in its atmosphere and on its surface.

We know little about the existence of other planetary systems. We believe that before great sums are committed to search for life outside the solar system, a search for planetary systems other than our own should be made. Although we are probably alone in the solar system, we may not be alone in the universe. We recommend that the search for extraterrestrial life proceed by logical steps. The work that we recommend on chemical evolution is important not only *per se* but also for estimating the likelihood, given appropriate conditions, that life will arise from chemical systems.

5

Chemical Evolution — Early Earth Prior to Life

I. PREBIOTIC ENVIRONMENT OF THE EARLY EARTH

An understanding of the origin of life draws on advances in scientific disciplines with very different traditions of inquiry, for example, cosmology, organic cosmochemistry, atmospheric chemistry, geochemistry, comparative biochemistry and molecular genetics, and micropaleontology. It requires studies on the chemical synthesis of biochemicals under conditions thought to have prevailed in the early solar system including the Earth.

Chemical-evolution studies are based on the premise that life originated early in the history of the Earth from complex interactions between carbon compounds. Recent studies of the impacted surfaces of the terrestrial triad, Mars, Earth, and Venus, suggest that substantial amounts of carbonaceous chondritic material were acquired by the Earth during the late phases of its accretion. The early atmosphere of our planet may have contained in addition to its major components, CO_2, CO, N_2, H_2O, H_2, smaller amounts of noble gases and volatile compounds such as H_2S, NH_3, CH_4, and HCN, derived from accreted chondritic material.

At least three major steps are likely to have occurred in the synthesis of organic matter before the emergence of early life:

1. The synthesis of monomers. Energy from sources such as electric discharges (lightning), solar ultraviolet radiation, and catalysis by inorganic substances are thought to have acted on the simple molecules from the atmosphere that dissolved in the hydrosphere or otherwise accumulated at the surface. These processes presumably led to the formation of a wide variety of low-molecular-weight organic compounds such as the components (monomers) of macromolecules (polymers) found in all living cells, e.g., amino

acids, fatty acids, sugars, and nucleic acid derivatives. Some of these compounds have been found in carbonaceous chondrites. Also, some of these compounds or their precursors are probably present in comets and in the atmospheres of the Jovian planets, indicating that they are produced naturally from cosmochemical processes.

2. The synthesis of polymers. The accumulation of monomers in bodies of water subject to evaporation is thought to have led to further condensation and polymerization reactions, which yielded higher-molecular-weight compounds. Polymers of amino acids and nucleotide oligomers are thought to have formed and acted as catalysts, thus furthering polymerization reactions.
3. The aggregation of organic matter into replicating units. It is thought by most investigators that the monomers and polymers were enclosed in lipid membranes, and thus some entities were formed that maintained conditions within them, which allowed continued interaction of the macromolecules. On the other hand, the surfaces of clay minerals, gas–liquid interfaces, or other boundaries with repetitive structure may have been important in the aggregation and organization of appropriate molecular mixtures. Eventually, by unknown means, the interaction of proteins, nucleic acids, and lipids resulted in the genesis of the minimal unit of replication–the cell. With development of great fidelity of replication emerged mutation, and natural selection acted on populations of replicating cells. At this time, Darwinian evolution began.

In cooperation with geologists, a more accurate understanding of the conditions prevailing during the early Archean Aeon on Earth should be obtained and used in laboratory simulations. Specifically the nature of the possible diurnal temperature variation, humidity, radiation fluxes, and atmospheric composition of the early Archean should be explored. This information should be applied in prebiotic chemical experiments that simulate conditions on the early Earth. We know little about the first 800 million years or so of Earth's history (from 4600 million to 3800 million years ago, the Hadean Aeon). This problem requires interaction of at least four fields of investigation, namely, cosmogony, geology, atmospheric chemistry, and organic chemistry. *We recommend interdisciplinary studies to infer as closely as possible the environmental conditions on the early Earth.*

II. NONENZYMATIC SYNTHESIS OF BIOLOGICAL MONOMERS AND POLYMERS

Many of the monomers synthesized enzymatically by cells are thought to have originally accumulated spontaneously on Earth as a result of nonenzymatic reactions. These include amino acids, components of proteins and nucleotides, and components of nucleic acids (DNA, RNA). This concept derives from many observations that gaseous mixtures, for example, methane, nitrogen, ammonia, and water, if supplied with energy such as spark discharges, produce the amino acids including those found regularly in proteins. The distribution of monomers so produced is qualitatively and quantitatively similar to that found in carbonaceous meteorites. In addition, most protein amino acids may be produced nonenzymatically starting with simple organic compounds such as formaldehyde and hydroxylamine.

Furthermore, the abiotic routes of formation of all the components of DNA and RNA are known. Sugars easily form spontaneously from formaldehyde; polymerization occurs under alkaline conditions. The condensation of hydrogen cyanide in the presence of ammonia produces amino acids as well as the purine nucleotide bases, adenine and guanine, components of all nucleic acids. Cytosine, a base found in nucleic acids, can be readily synthesized from cyanoacetylene. By deamination, cytosine yields another major base of RNA, uracil. Thymine, a major base of DNA, which, in today's genetic code is informationally equivalent to uracil, can be formed from the condensation of uracil with formaldehyde. In the presence of phosphate the phosphorylated forms of the nucleotides of these bases can be produced nonenzymatically. Fatty acids may be formed from carbon monoxide and hydrogen in the presence of nickel-iron catalysts, catalysts that might have been brought in by meteorites. Glycerol is a component of fats that has also been obtained nonenzymatically in the laboratory by reduction of glyceraldehyde. Glyceraldehyde itself, a common intermediate in cell energy-yielding reactions, may be formed by condensation of formaldehyde under alkaline conditions.

Important precursors for the abiotic formation of amino acids, sugars, purine and pyrimidine bases, and fatty acids have been identified in interstellar space, suggesting the universality of organic cosmochemistry. In fact, with only 12 of these cosmic molecular precursors (Table 6), one could synthesize most of the biochemical monomers and polymers essential to life. For the appearance of such monomers, two conditions are required: slightly alkaline solutions and the absence of free oxygen (O_2). Such conditions are hypothesized to have prevailed on the early Earth. The ease with which those organic monomers found in life today are formed under conditions thought plausible for the Archean Earth suggests that complex solutions of organic compounds probably accumulated early. It is assumed that conditions permitted these molecules to condense and form the protein and nucleic acid macromolecules that characterize all life today. However, less is known about the nonenzymatic synthesis of some of the nitrogen- or sulfur-containing ring compounds, which have catalytic activity as co-enzymes when attached to proteins.

Several mechanisms exist for nonbiological condensation of monomers into polymers. These include thermal condensation reactions, condensation

TABLE 6 Biochemical Monomers That Can Be Derived from Interstellar Molecules and Their Properties

	Interstellar Molecules	Formulas	Biochemical Monomers and Properties
1.	Molecular hydrogen	H_2	Reducing agent, protonation
2.	Water	H_2O	Universal solvent, hydroxylation
3.	Ammonia	NH_3	Base catalysis, amination
4.	Carbon monoxide	CO	Hydrocarbons and fatty acids
5.	Formaldehyde	CH_2O	Monosaccharides (ribose) and glycerol
6.	Acetaldehyde	CH_3CHO	Deoxypentoses (deoxyribose)
7.	Aldehydes (HCN)	RCHO	Amino acids
8.	Thioformaldehyde	CH_2S	Cysteine and methionine
9.	Hydrogen cyanide	HCN	Purines (adenine, guanine) and amino acids
10.	Cyanacetylene	HC_3N	Pyrimidines (cytosine, uracil, thymine)
11.	Cyanamide	H_2NCN	Polypeptides, polynucleotides, and lipids
12.	Phosphine (Jupiter)	PH_3	Phosphates and polyphosphates

reactions using polyphosphates and polyphosphate esters, and condensation reactions using inorganic catalysts or organic condensing agents such as imidazole or cyanamide, under aqueous or desiccating conditions. Abiotically synthesized high-energy compounds such as amino acid adenylates and nucleoside triphosphates also may serve as condensation agents. Cyanamide, a two-carbon molecule present in the interstellar medium, has been used as dehydrating agent in the abiotic synthesis of polymers. Thus dehydration-condensation reactions for the nonenzymatic synthesis of biological polymers similar to those that might have occurred on the early Earth are attainable in the laboratory.

Cyanamide, a simple condensing agent, may have played an important role in the abiotic condensation and polymerization of monomers. It is known to promote dehydration-condensation in reactions that result in the formation of phosphate esters, chemical bonds important in cells today. Examples of such bonds include those in AMP (adenosine monophosphate), glycerophosphate, and the phosphodiester bonds of RNA and DNA, adenosinetriphosphate (ATP) as well as the amide bonds of polypeptides and the ester bonds of lipids. This list includes nearly all molecules presumed necessary to initiate self-assembly processes, prerequisite to cell formation.

Research in chemical evolution designed to understand the origin of life should concentrate on major inadequacies in our knowledge of processes discussed above as steps likely to have been involved in the emergence of cells, especially synthesis and aggregation of monomers and polymers into cell-like units.

Among the experiments on synthesis, emphasis should be placed on those that analyze the formation of nitrogen and sulfur compounds, especially nucleotide derivatives, which are parts of co-enzymes, because of their crucial role in catalysis. Furthermore, nonenzymatic synthesis of small peptides should be coupled with functional studies of their potential catalytic activity. Further studies of the replication of oligomers and of larger polymers with linear coding capacity should be performed. Small DNA and RNA polymers do replicate in the laboratory, although enzymes or activated mononucleotides (imidazolides) are required. Attempts to replace the enzymes with organic potential inorganic catalysts, especially those such as Fe, Mn, Cu, and Zn, known to be required trace elements, should be undertaken.

It is possible that some of the organic products formed in prebiotic simulation experiments as well as mineral elements have specific catalytic activities that have not been studied in the chemical evolution context.

We recommend continued research on the nonenzymatic formation and possible catalytic activity of trace elements, monomers, and prebiotically formed polymers that are components of all living cells.

III. ORDERED AGGREGATION OF MACROMOLECULES

The synthesis of macromolecules such as proteins and nucleic acids was probably requisite to the formation of a system with the essential attributes of live cells, e.g., the abilities to replicate, translate, and enzymatically catalyze. The macromolecules may have been shorter than the enormously long macromolecules in today's cells.

Cooperative interaction of the three classes of polymers is required for all cells to divide: DNA is required for replication, RNA is required for information transfer to make proteins, and proteins are necessary for catalysis, including the continued synthesis of DNA. All three classes of macromolecules found within lipid membranes probably preceded the emergence of the first living entity.

Although research on simulation of such precellular entities has been undertaken, seldom have all these types of molecules been studied together. Because lipids spontaneously concentrate other organic compounds, recent studies with abiotically synthesized lipids are particularly promising. Furthermore, simple phospholipids simulate to some extent the chemical composition of cell membranes. How do such lipids interact with polymers such as nucleic acids and proteins? Phospholipids self-assemble to form bilayered membranes. They tend to form self-repairing vesicles or liposomes. Polypeptides and proteins may have been plugged into lipid bilayers as they are in modern cells. Such lipid-protein membranes may have assisted in making more complex synthesis possible. Since so many biochemical reactions involve molecules immobilized on internal lipid membranes, these molecular associations may have evolved very early. Lipid-protein structures enclosing peptides may have been critical components in the emergence of the first cells.

A revolution in biological thought was brought about by the recognition of the structure of DNA and its function, via cell information through to RNA. If an interacting macromolecular system that duplicated itself by forming catalytic molecules were to be made under conditions thought plausible for the early Earth, the origin-of-life problem would be considered solved in principle. Studies that elucidate the relationships between the duplicating molecules (DNA) and the catalytic ones (proteins) shed light on the origin of the genetic code—the rules by which the sequence of amino acids in proteins are determined by the sequence of nucleotide base pairs in DNA.

Thus, we recommend studies attempting to elucidate the origins of the genetic code and the origins of the RNA-based information transfer system.

Further studies on the interaction of simple peptides and nucleotides need to be carried out. Selective interaction at relatively low molecular weights of peptides and nucleotides may have preceded the functioning of the current genetic code.

Chemical and biochemical investigations on the simplest RNA molecules in cells and in artificial systems should be undertaken in an effort to elucidate the fundamental mechanisms of the processes of biochemical information transfer from DNA to proteins via RNA. The minimal role required by the ribosome, the RNA, and the protein-containing body always involved in protein synthesis, needs to be assessed. Can information be transferred from DNA to protein via RNA in the absence of the ribosome or with a greatly reduced ribosome?

Research to determine the minimal chemical system to effect protein synthesis should be undertaken.

The nonenzymatic formations of long-chain amino acid polymers in the absence of nucleic acid information transfer is probably not relevant, since nucleic acids are required to transfer information to protein in all organisms. Thus, even if abiotic enzymes were formed, the central issue of how information for their formation is perpetuated would not have been approached. Information transfer via nucleic acids systems must have played a key role since the beginning of the formation of the cells. We recommend direct study of the origin of the information transfer system.

Cells are distinguished from other nonliving, microscopic spheres by their ability to create and maintain their own internal environment and to catalyze specific reactions that synthesize macromolecules continuously at faster rates than occur in the external milieu. The origin of life may have involved interdependent processes that would not occur alone and that therefore cannot really be studied in isolation, such as nucleic acid polymerization within lipid-protein sacs. Thus simultaneous study of several of these processes, an extremely difficult undertaking, may be not only relevant but requisite for progress in the field of chemical evolution. *We recommend that research into the polymerization and simultaneous aggregation of nucleic acid, protein, and lipid components be undertaken under conditions thought plausible for the Archean Earth.*

6

Early Evolution of Life

I. EVIDENCE FROM GEOLOGY AND GEOCHEMISTRY

The Oldest Rocks: The Archaen Aeon (3800 Million to 2500 Million Years Ago)*

The history of carbon and the history of life on Earth are so intertwined that the origin and early development of life may be regarded as an aspect of carbon chemistry and other light elements found in all living organisms, in association with liquid water.

There are three major methods of obtaining evidence for early life: (1) the abundance and quantity of reduced carbon present in ancient sedimentary rocks; (2) the presence of objects imbedded in these rocks, which are interpreted to be microfossils; and (3) the presence of stromatolites. Stromatolites are sedimentary carbonate or siliceous rocks, usually dome shaped and laminated, that are known to be the lithified remains of microbial communities.

Certain sedimentary rocks of Archean and early Proterozoic age contain microfossils (presumably remains of ancient bacteria) and geochemical properties putatively attributable to paleobiological activity such as stable carbon isotope ratios ($\delta^{13}C$) characteristic of subsequent biogenic carbon deposits. They also contain complex organic compounds trapped in the insoluble stable fraction known as kerogen; these are amenable to study by the methods of organic geochemistry.

This discussion is limited to evidence of life in the earliest Archean sedi-

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*For names and times of aeons see Table 7. For summary of evidence of pre-Phanerozoic life see Figure 1.

TABLE 7 Descriptions of Aeons

Approx. Age ($\times 10^9$ Years Ago)	Name of Aeon	Characteristics of Aeon
?–4.6	Chaotic Formation of Earth	
4.6–3.8	Hadean	No rock record; the Earth cools, and differentiates
3.8–2.5	Archean	Major tectonic activities, sparse microfossil and stromatolite remains (prokaryotic communities)
2.5–0.6	Proterozoic	Continental platforms, oceans, abundant stromatolites, and microfossils (prokaryotic communities)
0.6–Present	Phanerozoic	Abundant plant and animal communities

ments that have not undergone severe thermal or pressure alteration (metamorphism); during or before this time, life originated on the Earth. By the end of this period, life had evolved to a distinctly diversified level of prokaryotic (bacterial) organization.

The oldest known sedimentary rocks, known as the Isua supracrustal complex, are nearly 4 billion years old. They are exposed in southwest Greenland at the edge of the inland ice cap. Corresponding sediments outcrop in eastern Labrador. Although intensely metamorphosed, the Isua sequence contains a highly varied suite of sediments, some of which are germane to the question of the possible existence of life at the time of their deposition. Many of these sediments originally were carbon-rich shales in which the carbon has been metamorphosed to graphite. They are associated with banded iron formation (BIF), alternating layers of iron-rich and iron-poor minerals in a siliceous matrix. The presence of iron oxides in Isua banded-iron formations has suggested to some that oxygen was already produced by photosynthetic microorganisms. One argument, though not conclusive in itself, for a biogenic carbon cycle in Isua time lies in the significant degree of fractionation of the two stable isotopes of carbon, $\delta^{13}C$ and $\delta^{12}C$, as measured in the reduced carbon and the carbonate carbon from the same samples.

If the reduced carbon of the Isua sediments is of biological origin, it reinforces the somewhat startling conclusion that within only a few hundred millions of years after the differentiation of the Earth as a planet, life had originated. Unfortunately, the Isua sedimentary complex has been too intensively metamorphosed for the preservation of microfossils or of such structural information in the insoluble organic carbon. The possibility exists that other equally ancient sedimentary sequences of rocks may be found and that the original nature of the sediments can be inferred in spite of the subsequent metamorphoses.

We recommend continued research on the carbon, the banded iron formation, and other aspects of the Earth's most ancient rocks to determine whether life had originated by the time they were deposited.

The earliest evidence for a widespread biologically productive ecosystem can be inferred from two thick columns of diverse sediments: the Warawoona basis of Western Australia and the Swaziland system of Southern Africa. In 1980, impressive evidence in the form of microfossils and stromatolites was found in the Warawoona sediments dated 3.55×10^9 years ago. However, since the Swaziland work is longer established, we use it as our example. The volcanics and conglomerates comprising the Swaziland Sequence are found in the eastern Transvaal of the Republic of South Africa and adjacent Swaziland. The underlying volcanic units are dated at ca. 3.4×10^9 to 3.5×10^9 years. Certain sediments, in particular the carbon-rich cherts (microcrystalline quartz), contain preserved structures interpreted as fossil microorganisms. Certain biochemical pathways in extant living systems select the lighter stable isotopes of carbon (^{12}C relative to ^{13}C) and sulfur (^{32}S relative to ^{34}S). Therefore, studies of the stable carbon and sulfur isotopes in well-dated sedimentary rocks may yield evidence for ancient biological fractionation. The presence of locally abundant banded and iron-rich chert beds (BIF's) raises the question of whether these rocks imply the prior origin of biogenic oxygen production.

The Swaziland Sequence is an isolated block of rocks consisting of sediments and volcanic and other igneous rocks in which are intercalated organic-rich cherts and shales indicative of sediment deposition in shallow water in a subsiding basin. The entire sequence was injected and uplifted from below by several granitic bodies, which are dated at about 3×10^9 years. Fortuitously, the tectonic processes that uplifted the Swaziland Sequence resulted in very little thermal ($<275°C$) and structural alteration, so sediments are generally well preserved.

The Swaziland Sequence, although a conformable series of both sediments and igneous rocks, is divisible into three groups of Formations: (1) the lowermost Onverwacht Group (15,230 m in thickness), (2) the Fig Tree Group

(2150 m in thickness), and (3) the Moodies Group (3150 m in thickness). It is of interest to determine the time span during which the sequence formed.

The most convincing evidence that life had evolved is the presence of many tiny structures seen in rock thin sections and interpreted as microfossils. They fall into three distinct size classes of fairly well-defined modal distribution. They are embedded in carbon-rich cherts in the "Swartkoppie Zone" rocks that are transitional between the upper Onverwacht and the lower Fig Tree Groups. Some dozen or so reports have been published describing these microfossils from Onverwacht and Fig Tree cherts. The most reasonable interpretation of the reduced carbon of the Sheba Formation, a member of the Fig Tree Group containing carbon-rich shales, is that it represents organic carbon produced by photosynthetic microorganisms. If so, the Sheba Formation represents a major opportunity to estimate the productivity of a lower Archean basin. With the exception of the Archean sediments in northwestern Australia, the Sheba Formation is virtually unique among Archean rocks. Because it has rich gold-bearing strata in carbonaceous shales, the Sheba Formation has been intensively studied. The original basin was about 100 km x 40 km, with an average depth of 700 m, and is estimated to contain some 10^{10} tons of carbon. It is important to determine whether any of the carbon of the low Archaen sediments such as the Sheba Formation is of abiological origin. If reduced carbon was produced by photosynthetic processes, how much of the microbial photosynthesis was nonoxygenic versus how much was oxygenic? Cherts containing iron oxides including the BIF below the Sheba Formation indicate that oxygen was produced locally in the sediments. What was the source of this oxygen? The BIF in Fig Tree sediments is sufficient to form the basis of sustained commercial iron ore mining.

The view is gradually emerging, although there is much need for verification, that reduced carbon derived from dead organisms and probably from the generation of reduced gases by microbial activity has led to the concentration of economically valuable metals such as gold, uranium, and copper in carbonaceous sediments. A most striking example is to be found in the Late Archean sedimentary gold deposits of South Africa. In the Witwaterstrand and associated Transvaal gold fields some 2.5×10^9 to 2.6×10^9 years old, gravels derived from rivers were transported at the surface and deposited under anoxic atmospheric conditions. Both gold and detrital uraninite are concentrated in thin seams associated with reduced carbon in these sedimentary basins. The exact mechanisms of metal concentration are unknown, however; the association of uraninite-bearing minerals and gold with reduced carbon compounds and coal-like seams is so well established in the Witwaterstrand gold fields that these fluvial sediments are called the "carbon leader." Because they are so extensive, the total amount of gold in the carbonaceous conglomerate is immense; it provides a major repository of the earth's minable gold.

Exploration for fossils that permit the reconstruction of the nature of ecosystems of Archean organisms should be continued. Determination of the quantity and source of the carbon per unit rock volume per unit time in Archean basins and platform deposits should be attempted. The existence of coal-like sediments and occasional occurrence of gas and oil suggest that microbial communities were already well established. Organic matter from such ancient sediments provides material for organic geochemical assay of the kerogen fractions. Continued organic geochemical analyses may lead to identification of microbial ecosystems from which the organic compounds derived. Especially pertinent is the exploration of the possibility that economically important minerals (copper, gold, iron, uranium) were accumulated by processes unique in time that involved the activities of ancient microbial ecosystems.

We recommend continued global search for Archean biotas in favorable geologic formations such as unmetamorphosed (or low-grade metamorphosed) stromatolitic or banded cherts and carbonaceous shales. We also recommend geochemical and biochemical analysis of pre-Phanerozoic carbonaceous sediments, especially those in which recognizable fossils can be observed.

We recommend a program of research to determine the role, if any, of early life in the genesis of Archean carbon, gold, and iron-rich unmetamorphosed sediments. Continued efforts to obtain accurate radiogenic dates for these Precambrian rocks are also needed.

Intrinsic to these studies is research to develop a basis for interpreting the extent to which the carbon and sulfur isotope fractionation values obtained from kerogen and sulfides in Archean rocks are of biological origin. The extent to which the nature of Archean ecosystems can be inferred by detailed carbon and sulfur isotope and organic geochemical analyses of the carbon bonds in compounds comprising the kerogen fraction must also be determined.

Stable carbon and sulfur isotope studies of well-understood sedimentary carbon-rich deposits should be able to determine as precisely as possible the biological source of these two elements preserved in sediments as remnants of biological systems.

Stable carbon and sulfur isotope studies of the degradation products of organisms in recent sediments in well-characterized microbial communities and in laboratory pure cultures should be made. These studies should be made especially of prokaryotic organisms known to precipitate minerals. The lipid and nonlipid fractions, respectively, should be analyzed in order to identify the metabolic source of the organic matter in biosynthetic pathways.

Paleoenvironmental studies of pre-Phanrezoic microbiotas, i.e., the correlations of specific microbial ecosystems with the lithology, the sedimentary context, and the geochemistry of the rocks in which they occur, are needed.

Toward Modern Times: The Proterozoic Aeon (2500 Million to 600 Million Years Ago)

Although carbon-rich shales, microfossils, and stromatolites are known from Archean rocks, the degree of skepticism in acceptance of the biological origin of these increases with age of the rocks. However, the quantity and diversity of evidence for ancient life increases during the Proterozoic Aeon. For example, stromatolites, which are universally recognized as evidence of microbial life, become abundant during the Proterozoic. These laminated structures usually are produced by communities of photosynthetic microorganisms, whether composed of primarily spheroidal or filamentous forms or a mixture of both. One of the best examples of a well-developed stromatolitic and microfossiliferous sediment is the biota of the early proterozoic Gunflint Formation of Ontario, whose age is about 2×10^9 years. The Gunflint microbiota is of sufficient diversity to represent a "benchmark" of the level of evolution of microscopic life at a time not much later than halfway between the differentiation of our planet and the present. Recent analyses of the Gunflint assemblage reveal the presence of nearly 20 distinguishable groups of microorganisms, including those that were probably cyanobacteria (blue-green algae), budding bacteria, and filamentous iron bacteria. The Gunflint sediments include both silicified stromatolitic and nonstromatolitic lagoonal or basinal deposits that are thin but wide in areal extent. The diverse and abundant biota differ in the stromatolitic and nonstromatolitic facies. This indicates perhaps the evolution and diversification of ecosystems involving adaptations to varying environments that characterize later Proterozoic and Phanerozoic platform and continental marginal deposits. This sort of ecosystem diversification had probably occurred by 2×10^9 years ago. Recently, two new microbiotas of about the same age as the Gunflint have been discovered in Western Australia. Both contain well-preserved microfossils strikingly similar to those common in the Gunflint. This suggests that by Gunflint time certain prokaryotic photosynthetic communities of microorganisms may have already evolved worldwide.

The effect of biological processes, such as photosynthesis, and their impact on chemical and physical characteristics of the hydrosphere and atmosphere have long been known. The impact, especially of microbial life, on the lithosphere, in particular sedimentary rocks on a global basis, has, however, only recently been appreciated. Biogeology has primarily centered on the younger

Phanerozoic sediments, largely in connection with economic resource minerals of biological origin (phosphates, fossil fuels, and certain metallic ores associated with fossil reefs).

Current scientific acceptance of the very long history of life on Earth, extending back more than 3 billion years, draws renewed attention to numerous geobiological interrelationships only partially explored, such as the history of seawater and pre-Phanerozoic atmospheric changes associated with microbial respiration and photosynthesis. Biological activity directly affects light-element distribution, but the metallic elements iron and manganese, zinc, and many others involved in bioenergetic processes are also affected. The examples of copper and iron will suffice here.

As discussed in Chapter 3, metal ores are found in association with pre-Phanerozoic microbial carbonaceous matter. Approximately 30 percent of the Earth's known copper ores, primarily sulfides, occur in organic-rich Proterozoic sediments, wherein the copper was reduced from solution and precipitated in organic muds that were later altered to copper-rich shales. Whether the sedimentary banded-iron formations represent another example of the effects of biological activity on the lithosphere is not established. Worldwide layers of ferrous alternating with ferric iron deposits (BIF) have been interpreted to represent increasing concentrations of atmospheric photosynthetic oxygen about 2.0×10^9 to 2.2×10^9 years ago. More evidence both from the geological and biological record of this critical period of earth history is sorely needed.

Pre-Phanerozoic geobiology has only recently come into its own as a field of scientific research. The NASA biology program has played a crucial role in the origin of the discipline. The recognition of a worldwide microscopic record of life extending to greater than 3×10^9 years has altered our entire concept of the origin-of-life problem. Stromatolites are now accepted as trace fossils of abundant microbial life extending back to 3.5 billion years ago. Organic shales throughout the pre-Phanerozoic have recently been recognized as indicative of abundant microbial activity. From this new vantage point, exciting and important scientific problems emerge. Certain of these have been studied in detail, whereas others have been entirely neglected.

We recommend a vigorous program of research to reconstruct the ecosystems that made up the Proterozoic environment, especially those that led to unique and extensive surface structures, such as stromatolites, banded-iron formations, and stratiform metalliferous deposits.

There has been some suggestion that Proterozoic microfossils and stromatolites analogous to Phanerozoic body fossils such as trilobites and diatoms can be used as statigraphic markers and therefore for correlation of dates from remote regions.

We recommend that attempts be made to determine the validity of geolog-

ical correlation of microfossils and stromatolites on a worldwide basis both from pre-Phanerozoic and early Phanerozoic rocks.

Geological and biological data may be used to reconstruct the evolution of paleoecosystems through time. This is an immense and difficult task. To what extent is the increasing complexity of ecosystems an inevitable outcome of planetary evolution? For example, to what extent is the origin of complex behavior and intricate communication systems between social mammals a necessary outcome of evolutionary processes? These valid scientific questions fall in the domain of planetary biology and mainly involve evolution during the Phanerozoic Aeon. The question of the emergence of biological complexity, including social organizations and intelligence during the Phanerozoic Aeon is beyond the scope of our present document. The emergence of complex societies capable of extraterrestrial communication is an evolutionary biological phenomenon. Thus problems of the search for, and attempt to communicate with, extraterrestrial life lie at least in part within the province of planetary biology and chemical evolution. They can be considered aspects of the evolution of complex social organisms. Insofar as NASA contemplates attempts to detect intelligent extraterrestrial life, we recommend that the planetary biology community be represented in these deliberations.

II. EVIDENCE FROM STUDIES OF MACROMOLECULES

An understanding of carbon, its distribution, isotopic composition, chemistry, and especially its combination with H, O, N, S, and P to form macromolecules, is prerequisite to understanding the origin and evolution of life as a planetary phenomenon. However, the macromolecules themselves, once formed by living organisms, contain clues to their history. One of the astounding discoveries of molecular biology, especially work on the sequences of amino acids in proteins and of nucleotides in RNA and DNA is the great degree of conservatism of the macromolecules of living organisms. The molecular machinery of life is so universal and has changed so slowly that direct relationships between remotely related organisms can be deduced by comparisons of certain carefully chosen macromolecules (e.g., the ferredoxin in *E. coli* and adrenodoxin in cows). Thus based on advances in molecular biology, direct geochemical and geological studies of past life can now be complemented by techniques of molecular evolution.

Molecular evolution may be defined as the reconstruction of the evolutionary history of the cells of organisms and their subcellular components by the comparative study of biological molecules–especially the nucleic acids and protein polymers. All organisms are composed of cells, and each cell has at least several thousand kinds of macromolecules. In each cell, the sequence of amino acid residues in proteins and nucleotide bases in RNA's are genetically determined, that is, they are determined by the nucleotide base pair sequence in DNA's. Widely distributed proteins such as ferrodoxins and cytochromes used in respiratory processes found in extremely diverse organisms are functionally identical proteins. Since the primary sequences of monomers in these proteins differ often from each other in ways that can be related to inferrable mutations, evolutionary relations of the organisms in which they are found may be deducible directly from comparisons of the proteins. Molecular sequence similarities can be found in organisms thought to have diverged hundreds and even thousands of millions of years ago from common ancestors. These techniques have already been used to discern common ancestries in a number of species of organisms not formerly relatable. If organisms have extremely recent common ancestors, the sequence of amino acids in their proteins may not differ at all. A striking example of molecular conservation is the amino acid sequence of cytochrome C; the amino acid sequence in this respiratory protein is identical in chimpanzees and humans.

The promise of continued work in this field is immense. A clear and immediate objective is the elucidation of evolutionary relationships throughout the microbial world, including both nucleated (eukaryotic) microorganisms and bacteria. Because of the sparseness of the fossil record of microorganisms and because they diversified on the biochemical rather than the morphological level, knowledge of their evolution is rudimentary. The fossil record of animals and plants, from nearly 700 million years ago to the present is far more extensive. Therefore, techniques of molecular evolution are especially important in reconstruction of the early evolutionary history of life–microbial evolution. Crystallographic and sequence studies of proteins provide direct information on the nature of the evolutionary process, for example, they permit the assessment of the role of gene duplication in protein evolution. An understanding of the evolution of the replication system is greatly enhanced by direct-sequence study of the proteins and RNA's of the cell organelles such as the ribosomes involved in replication. Furthermore, by expanding our structural and chemical knowledge of macromolecules of cells thought to be primitive, such as methanogenic bacteria, we come closer to understanding the minimal system that displays the properties of life.

Detailed knowledge of microbial evolution combined with direct geological, geochemical, and microplanetological evidence is critical for understanding the major events that led to the origin and early diversification of living forms. *We recommend continuing studies of the origin and evolution of the earliest microbes as well as the effects they had in the past and continue to have on the atmosphere, hydrosphere, and sediment of the Earth.*

Molecular evolution is a recent scientific inquiry. The small amount of basic research in this area has been supported primarily by NASA in the context of the quest for greater understanding of the origin and early evolution of life. Most of the work on obtaining sequences of macromolecules has not been supported in a fundamental biological context. Rather the National Institutes of Health and the National Science Foundation have supported the work in order to achieve an understanding of particular proteins (such as hemoglobins and plasmogenins) that are considered important to particular human health problems. Indeed with the exception of the small program within NASA's Life Science Office, no government research support on the origin and evolution of life in relation to the Earth's surface has ever been formalized. The results obtained by the NASA-sponsored scientific program have significantly altered thinking about the origin and evolution of life. There needs, however, to be a closer interaction between disciplines such as general medicine, macromolecular chemistry, geochemistry, paleontology, microgeology, and organic chemistry. The lack of coordination has resulted in part from the failure of scientists and administrators to understand the antiquity and power of the interaction of the biota with the planet's surface. The Viking mission to Mars, comparisons of the surfaces and atmospheres of other planets with those of the Earth, and the recent influx of data from ancient rocks and molecular evolutionary studies have all greatly altered our perspective. Without the contributions of NASA in support of this science, these achievements would not have occurred.

We recommend continued support of the use of molecular data to determine early evolutionary trends. It is essential that data obtained using molecular methods with live organisms be evaluated in the context of studies of the sedimentary rock record.

We recommend that studies be undertaken to determine the nature of the simplest and smallest independent systems subject to evolutionary processes (minimal free-living cells). The spontaneous formation of such minimal systems under conditions thought plausible for the early Earth is the final goal of laboratory work designed to elucidate how life originated.

Appendix A: History of the Committee

This committee began, in 1973, as the Panel on Exobiology of the Space Science Board's Committee of Space Biology and Medicine (CSBM), under the chairmanship of N. H. Horowitz of the California Institute of Technology. It dealt primarily with the biological aspects of the Viking mission to Mars, which was launched in 1975 and landed in 1976. It also made recommendations in the context of development of policies concerning the protection of that and other planetary missions from contamination by Earth microorganisms (in *Recommendations of Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan*). With the need for interpretation of the Viking biology experiments, demands on the Exobiology Panel grew larger, and in 1973 the Panel was raised to independent committee status under the chairmanship of Peter Mazur of Oak Ridge National Laboratory, who chaired the committee from 1974 to 1977. In 1977, the Committee on Planetary Biology and Chemical Evolution (PBCE) published its first contribution: *Post-Viking Biological Investigation of Mars*. Earlier work published by the Committee on Space Biology and Medicine (CSBM) is listed below.

The original committee, the CSBM, is largely concerned with the scientific aspects of manned spaceflight, the effects of zero gravity on the development of organisms, and the response of living organisms to the space environment. This newer committee, the PBCE, on the other hand, is concerned with the origin and evolution of life as a planetary phenomenon. This concept is developed in the introduction of this report, which is concerned with the development of scientific strategy for planetary biology and chemical evolution for the 1980's.

Reports of Standing SSB Life-Sciences Committees

CSBM	Committee on Space Biology and Medicine, *Life Beyond the Earth's Environment: The Biology of Living Organisms in Space,* NAS, 1979.
CPBCE	Committee on Planetary Biology and Chemical Evolution, *Recommendations on Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan,* NAS, 1978.
CPBCE	Committee on Planetary Biology and Chemical Evolution, *Post-Viking Biological Explorations of Mars,* NAS, 1977.
CSBM	Committee on Space Biology and Medicine, "Space Biology," in *Report on Space Science 1975,* NAS, 1976.
	Committee on Space Biology and Medicine, Exobiology Panel, "Exobiology," in *Report on Space Science 1975,* NAS, 1976.
	Committee on Space Biology and Medicine, Exobiology Panel, "Biological Issues," in "Future Exploration of Mars," in *Opportunities and Choices in Space Science, 1974,* NAS, 1975.
	Committee on Space Biology and Medicine, Radiobiology, Advisory Panel, *HZE-Particle Effects in Manned Space Flight,* NAS, 1973.
	Committee on Space Biology and Medicine, Panel on Microbiological Problems of Manned Space Flight, *Infectious Diseases in Manned Space Flight: Probabilities and Countermeasures,* NAS, 1970.
CLS	Committee on Life Sciences, Panel on Management of Spacecraft Solid and Liquid Wastes, *Report of the Panel on Management of Solid and Liquid Wastes,* NAS-NRC, 1969.
	Committee on Life Sciences, Panel on Atmosphere Regeneration, *Report of the Panel on Atmosphere Regeneration,* NAS-NRC, 1969.
	Committee on Life Sciences, Space Radiation Study Panel, W. H. Langham, ed., *Radiobiological Factors in Manned Space Flight,* NAS-NRC, 1967.

Report of Ad Hoc Group

Space Science Board, "Life Sciences," Chapter 8 in *Scientific Uses of the Space Shuttle,* NAS, 1974.

Appendix B:

Basis for the Conclusion That There Is No Evidence for Current Life at Viking Sites

Our conclusion that no Viking data require a biological explanation and that there is no evidence for current life on Mars is based on the following points.

Absence of reduced carbon and nitrogen compounds. Reduced carbon- and nitrogen-containing compounds are necessary components of all known living terrestrial systems. No organic compounds, other than traces due to terrestrial contaminants were detected by the Viking gas chromatograph-mass spectrometer (GCMS), an instrument capable of detecting most small organic molecules when present in quantities to the extent of parts per million (ppm). Some compounds require higher concentrations for detection up to ppm. Even in the most barren terrestrial soils, mixtures of organic compounds are present in quantities between parts per billion and ppm. The highly destructive ultraviolet light flux at the Martian surface may account for the lack of organic compounds in the Viking samples, even those assumed to have been brought in by carbonaceous meteorites.

Lack of liquid water. Liquid water is a requisite for all known life. Consistent with the low temperatures and pressures at the planet's surface, Viking obtained no evidence for liquid water; nor is there evidence for any existing open bodies of liquid water, only for water vapor and ice.

Low temperatures. The regolith temperatures of Mars rarely, if ever, reach 0°C. The atmospheric temperatures are even lower. A putative Martian microbe at Viking sites would have two options to provide itself with an internal concentration of liquid water. It might lower the eutectic point by maintaining high salt concentration; to do so it would have to maintain multimolar salt concentration (-20°C requires greater than 5*M* NaCl concentration, a higher molarity than known for any earth organism with the possible exception of some obligately aerobic halophilic bacteria). Alternatively, to maintain a constant internal temperature near 0°C during growth it would have to expend huge amounts of energy.

High surface flux of ultraviolet radiation. The ultraviolet (UV) radiation flux at the Martian surface (0.4 J cm^{-2} min^{-1}) would be rapidly lethal to organisms composed of organic compounds, which tend to absorb strongly in the UV; for example, about a 0.1 J cm^{-2} min^{-1} UV-flux limit for survival of terrestrial unshielded microorganisms.

Adequate chemical explanations for the three Viking biology experiments. The positive signals from the three biology experiments can be understood on the basis of chemical principles. For example, the Gas Exchange Experiment (GEX) results can be understood as oxygen release by moistened peroxides or from iron oxide-containing clays. Several types of superoxides, all consistent with the properties of the surface, may be the sources of oxygen (Na_2O_2, K_2O_2, H_2O_2). The Label Release Experiment (LR) results may have been due to the use of formic acid as a reagent; this compound is easily oxidized in the presence of hydroperoxides and yields labeled carbon dioxide in approximately the ratio observed.

The Pyrolytic Release Experiment (PR) was designed to detect photosynthetic reduction of atmospheric carbon oxides into organic carbon under Martian conditions in the regolith. Martian regolith samples were irradiated at 320 nm in the presence of $^{14}CO_2$ and ^{14}CO and pyrolyzed at 625°C. This reduced carbon was then released as a "second peak." One explanation for the anomalously high second peak at Chryse may have been the availability of small amounts of engine ammonia as reductant. Other possible explanations for the observations are UV-induced organic synthesis from CO and H_2O_2 via production of hydroxyl radicals. However, in the PR experiment the reactants still generated statistically significant labeled pyrolysis products after heating to sterilization temperatures (175°C). Furthermore, water did not enhance the reaction and there was no direct correlation between height of second peak (quantity of reduced carbon) and exposure to light. Genuine biotic photosynthesis would have been light sensitive, stimulated by the addition of water, and abolished by sterilization. Horowitz *et al.** (1977) remarked, "There is evidence of considerable heterogeneity among different samples, but different aliquots from the same sample are remarkably uniform in their carbon-fixing capacity. In view of its thermal stability it is unlikely the reaction is biological." Thus a nonbiological explanation for the PR results is appropriate.

Absence of gas disequilibria. The Earth's atmosphere contains large quantities of gases such as methane, oxygen, nitrous oxide, and ammonia, which are

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*N. H. Horowitz, G. L. Hobby, and J. S. Hubbard, "Viking on Mars: the Carbon Assimilation Experiments," J. Geophys. Res. *82*, 4659–4662 (1977).

chemically mutually incompatible. Furthermore, such disequilibria are most conspicuous in those volatiles that interact with the biota (e.g., gases containing sulfur, nitrogen, carbon, oxygen, and hydrogen). There is direct evidence that these disequilibria have persisted over periods of millions of years–extraordinarily long in relation to the residence times of the gases. There is no doubt of the biogenicity of these disequilibria on Earth. At the same time, there is no evidence for comparable disequilibria phenomena in the Martian lower atmosphere. This may be due to our failure to achieve the necessary sensitivity to detect the relevant gases; on the other hand, CO_2, CO, N_2, and O_2 abundances detected on Mars can be reproduced by models that do not involve biological processes.

Might there be life at sites other than Utopia and Chryse? Any widespread distribution of life on Mars is unlikely, based on the ratio of reduced carbon in living biota on Earth relative to that dispersed in the sediment. Organic carbon, nitrogen, and sulfur compounds in the form of carbon-rich shales, muds, coal, petroleum, and the like are far more abundant by weight than those compounds in living organisms. The ratio of organic matter in the living biota to the quantity of organic matter in sediments is about 10^{-5}. Thus on Earth the vast quantity of organics is not in live organisms but in their corpses, food waste, and other remains. Although we have no estimate of the quantity of carbon in Mars present in comparable sediments, our experience with the sample testing at Chryse and Utopia, as well as orbiter imaging, make it unlikely that massive deposits of carbon-rich sedimentary rocks are abundant on Mars. Putative Martian organisms would have to recycle their carbon-containing remains with efficiencies approaching 100 percent. Alternatively, the putative Martian ecosystems are highly restricted and shielded. Experience on Earth has shown that the only ecosystem that has persisted through time is the entire biosphere of the Earth. Oases and islands on Earth are never closed systems. Their atmospheric, ground, water, and soil connections to the rest of the biosphere can be demonstrated.

The possibility of special oases on Mars cannot be entirely eliminated. The lack of the connection on Mars, due to the absence of flowing water, and the oxidizing potential of the surface, would prevent the development of a global distribution. Such oases would be highly specialized, shielded from irradiation and only marginally contribute to gas exchange. They would have to be able to regenerate continuously after being threatened by prolonged hostile conditions. Locating such putative oases would be extremely difficult. Examination of even 100 sites without the discovery of such oases would not exclude the possibility of their existence.

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