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A Strategy for Earth Science from Space in the
1980's. Part I: Solid Earth and Oceans

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A Strategy for Earth Science from Space in the 1980's Part I: Solid Earth and Oceans

Committee on Earth Sciences

Space Science Board

Assembly of Mathematical and Physical Sciences

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Part I: Solid Earth and Oceans

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This report has been reviewed by a group other than the authors according to 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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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* (1978); *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); *Strategy for Space Research in Gravitational Physics in the 1980's* (1981); and *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's* (1981). These strategy reports set scientific goals and priorities intended to maximize the scientific return on the nation's investment in space science.

With publication of this document, the Space Science Board's Committee on Earth Sciences (CES) has completed the first of a two-part strategy for the earth sciences from space. The level of effort required for this task dictated that it be done in two parts, i.e., the first part addressing solid-earth dynamics, continental geology, and ocean dynamics; the second part to address atmospheric circulation, global climate, global chemical cycles, and the Earth's hydrological cycle. Each strategy phase covers a period of approximately ten years, and when completed they should be regarded as an integrated plan for the earth sciences from space.

Like other Board science strategies, this document takes the position that

the strategy will be stated in terms of scientific objectives to be achieved over the time of the prescribed period, rather than in a series of recommended missions. It is the intent of these documents to provide a scientific baseline for guiding and evaluating the science content of specific missions and long-range mission planning.

The Board adopted this report as its policy position for the earth sciences from space in November 1981. It takes this opportunity to express its appreciation to the chairman and members of the CES for their sustained effort in seeing this difficult task to completion.

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

Contents

1. Introduction and Overview	1
2. State of Knowledge of the Planets	4
3. Scientific Goals for Earth Science	9
I. Global Atmospheric Circulation	11
II. Atmospheric and Climatic History	12
III. Ocean Dynamics	13
IV. Atmosphere-Ocean Interaction	13
V. Global Ice Budget and Hydrologic Cycle	14
VI. Major Chemical Cycles	15
VII. Plate Dynamics	16
VIII. History of the Earth's Crust	17
IX. Sedimentary Cycles	18
X. Internal Structure and Composition of the Earth	18
XI. Generation of the Earth's Magnetic Field	19
4. The Role of Space Measurements for Earth Science	21
5. Strategy for Earth Science from Space in the 1980's	23
I. Framework for the Strategy	23
II. Objectives for Solid-Earth Dynamics	26
III. Objectives for Continental Geology	40
IV. Objectives for Ocean Dynamics	71

6. Science Program Issues	85
I. Relation of Ground, Airborne, and Space Measurements	85
II. Scientific Instrumentation Development	86
III. Data Management and Analysis	90
IV. Theoretical and Laboratory Studies	91
7. Science Policy Considerations	95
8. A Look toward Completion of the Strategy for Earth Science from Space	99

1

Introduction and Overview

With man's first venture into space came an increased awareness that the Earth on which we live is a planet. Like the other planets of our solar system, the Earth owes its characteristics to processes that have interacted on a global scale. The terrestrial climate is a product of the transfer of energy and momentum within the Earth's atmosphere and global oceans. The land surface is continually being reshaped by convective flow in the Earth's interior, manifested in slow but unrelenting motions of large blocks of the Earth's surface. The Earth's magnetic field, generated by fluid motions in the dense metallic core, helps to shield the Earth's surface from the energetic plasmas streaming outward from the sun. Living organisms on the land, in the oceans, and in the air owe their continued survival to the balance of physical and chemical conditions in the Earth's surface and near-surface environment, conditions influenced in no small part by biological processes.

With the recognition that the solid earth, its oceans and atmosphere, and its life forms are governed by processes that act on a planetary scale has come an awareness that further understanding of these processes will require coordinated global observations and theories that integrate these observations. Many of the needed measurements can be made naturally and most efficiently from space. The view of the Earth from space is necessarily global in perspective. From space, remote observations can be obtained of the entire planet rapidly and in a unified fashion. The vantage point of space further provides a basis for studying on the Earth those processes common to other planets, including the evolution of planetary crusts, the dynamics of planetary atmospheres, and the generation of planetary magnetic fields.

The Space Science Board has requested that the Committee on Earth

Sciences develop a 10-year strategy for the scientific study of the Earth from space. The intent of this strategy is to provide a guideline to the development of long-range mission planning and to act as a reference for evaluating the science content of proposed programs of space measurements of the Earth over the next decade. For these purposes and in response to the Board's request, the Committee on Earth Sciences submits this report.

As documented below, the Committee believes that major steps toward further scientific understanding of the Earth can be made by space measurements. To provide a set of recommendations that is complementary to other strategy documents published by the Board, the Committee has elected to focus on the investigation of the physical and chemical characteristics of the solid earth, the oceans, and the lower atmosphere for the decade 1981 to 1990. The strategy for the study of life sciences from space for the next decade is given in the report of the Space Science Board Committee on Planetary Biology and Chemical Evolution, *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's* (National Academy Press, Washington, D.C., 1981). The corresponding strategy for the scientific study of the Earth's upper atmosphere, ionosphere, and magnetosphere is given in the report of the Committee on Solar and Space Physics, *Solar-System Space Physics in the 1980's: A Research Strategy* (National Academy of Sciences, Washington, D.C., 1980).

The complete strategy for the scientific study of the Earth from space over the next decade is complicated both by the diversity of scientific problems facing earth science and by the complex, interdisciplinary nature of many of these problems. For reasons of time and schedule, the Committee chose to present in this report only the first portion of its overall strategy: the strategy for the investigation from space of the solid earth and of its oceans. These areas of earth science were selected for this first strategy report because of programmatic urgency and because they are connected by several natural scientific links. Nonetheless, any division of earth science into separate groups is of necessity somewhat arbitrary, since many of the most profound scientific questions will inevitably cross disciplinary boundaries. Thus, the present strategy should be regarded as a first installment that treats at length a major component of earth science. Not included in this report are strategies for addressing the questions of atmospheric circulation, global climate, many aspects of atmosphere-ocean interaction, the Earth's water and ice budget, and major global chemical cycles. The Committee on Earth Sciences is currently in the process of preparing the complementary installment covering these remaining issues. A full and integrated strategy for the scientific study of the Earth from space will be complete once this second report is produced and stands together with the present document and with the Board strategies already completed for the life sciences and for the Earth's upper atmosphere, ionosphere, and magnetosphere.

For the purposes of detailing a strategy for investigating the solid earth and oceans from space, we have divided our discussion into three sections: solid-earth dynamics, continental geology, and ocean dynamics. While this division facilitates the presentation of scientific goals and approaches to address those goals, a number of scientific issues and measurement techniques span these subject areas. Along with the presentation of the individual strategies for each of the three scientific areas of this report, we relate the individual recommendations within an overall strategy for earth science from space.

For each major scientific problem area for earth science, we describe general strategic goals, and we identify objectives that can contribute fundamental advances toward these goals during the next decade and that can be accomplished only or most effectively by space measurements. For each objective, we present an evaluation of its scientific importance and a definition of the accuracy and scope of the measurements necessary to make a substantial scientific gain. On the basis of these evaluations, the objectives that will lead to the greatest scientific advances are enumerated for each problem area in order of priority. These primary objectives for the scientific study of the solid earth and the oceans should form the basis for defining future missions for the investigation of the Earth from space during the 1980's. In addition to the primary objectives, we present secondary objectives that would add to our scientific understanding of the Earth and that would enhance the value of future spacecraft missions. We also identify several scientific areas of fundamental importance, where space techniques cannot at present make an impact but for which the development of new measurement techniques holds substantial promise of providing important new information in the longer-term future.

Completion of this strategy carries with it a number of implications for the coordination of future ground and space measurements, for the orderly development of new instrumentation for space measurements, for the development of new techniques for the analysis and management of large quantities of data, and for the support of additional theoretical and laboratory work in areas of particular promise. We present specific recommendations in each of these areas as part of this report. Finally, the Committee has identified several issues of national policy for Earth-directed space science that should be considered in the implementation of this strategy.

2

State of Knowledge of the Planets

Of the nine planets in the solar system, the inner six have been encountered or orbited by spacecraft, and all have been studied to some extent through Earth-based observations. Our view of each of the planets has naturally been on a global scale, and our understanding of the complex processes that have shaped these objects and their environments has benefited from a synthesis of information on all the planets together. We know that the planets divide naturally into two classes on the basis of size, density, and position in the solar system. The major planets—Jupiter, Saturn, Uranus, and Neptune—contain most of the mass and angular momentum of the solar system, are of low mean density ($1\text{--}2\text{ g/cm}^3$), and range from 5 to 30 AU in distance from the sun. These large outer planets are rich in volatiles, especially hydrogen and helium, have low surface temperatures, and have well-developed satellite systems that mirror, in a fashion, the solar system itself. The inner planets—Mercury, Venus, Earth, and Mars—are by contrast smaller in diameter, higher in density ($4\text{--}5\text{ g/cm}^3$), and range from 0.4 to 1.5 AU in distance from the sun. These terrestrial planets are composed chiefly of rock and metal, are comparatively poor in volatiles, and have few satellites. The ninth planet, Pluto, which is 40 AU from the sun, is clearly different from the other outer planets, with its small mass and radius and the unusually large satellite-to-planet mass ratio of its single known moon.

Among the planets, the inner four and their satellites are best known. Though broadly similar in composition, the terrestrial planets vary in mean density from 5.4 g/cm^3 for Mercury to 3.9 g/cm^3 for Mars. The variation in planetary mean density with solar distance can be partly explained by a model for the proto-solar nebula in which the temperature and pressure de-

creased with distance from the nebular center and the chemistry of condensed material at any distance was dictated by equilibrium thermodynamics. The moons of the Earth and Mars, substantially lower in uncompressed density than the planets they orbit, are less easily explained by the simple nebular condensation model.

All the inner planets, including the Earth's moon, have undergone significant internal heating and differentiation. The oldest preserved rocks on the Earth are about 3.8 billion years old, and most of the Earth's surface—the ocean floor—is less than 0.2 billion years of age. In contrast, the moon has preserved some rocks dating back to an early episode of melting and crustal formation 4.5 billion years ago and contains no rocks younger than the period of volcanic flooding of the lunar maria from 3.9 billion to about 3.0 billion years ago. The moon has also recorded a period of intense meteor bombardment that ended about 3.8 billion years ago, a bombardment that produced many of the large impact basins on the moon and presumably also occurred on all the inner planets at about the same time. This assumed heavy bombardment of the inner solar system has provided a chronological reference marker that has been the basis for constructing the geologic history of Mars and Mercury and may serve a similar purpose for Venus.

The terrestrial planets differ substantially in the character of their atmospheres. Both Mercury and the moon are devoid of any stable atmosphere. The dominantly CO₂-rich atmosphere of Venus is nearly one hundred times more massive than the Earth's, while the CO₂-rich atmosphere of Mars is one hundred times less dense than that of the Earth. The abundances of several of the nonradiogenic noble gases in these three respective atmospheres roughly correlate with their atmospheric density. The large decrease in atmospheric mass with solar distance from Venus, to Earth, to Mars is apparently at variance with standard nebular condensation models in which the material from which the planets formed was progressively more volatile-rich with increasing distance from the center of the nebula. Venus and Earth have similar present abundances of nitrogen with respect to planetary mass, while Mars is relatively depleted. The Earth is unique among the planets in the large quantities of molecular oxygen in its atmosphere, thought to be a result of biological exchange of atmospheric gases. Venus is covered by a dense global blanket of clouds composed in part of sulfuric acid droplets. Cloud motions indicate a global wind pattern with a substantial height dependence to mean wind speed. Mars is known to have episodes of high-velocity winds that give rise to global dust storms. Mars also has climatological seasons, with cycling of CO₂ between the polar caps providing a major component of atmospheric circulation. The Earth and apparently Mars both have longer-term climatic changes, such as ice ages, whose origin is poorly understood.

The Earth is unique among the planets in the large quantities of free water

in its oceans, lakes, and rivers and in its atmosphere. The dynamics of the Earth's oceans play a large, but incompletely understood, role in the maintenance of the terrestrial climate. Water is present in the atmospheres of Mars and Venus, but is substantially less abundant. Water ice is also the chief component of the small residual polar caps on Mars. Mars shows evidence on its surface, however, of possible ancient large-scale flooding and fluvial erosion, suggesting both a denser atmosphere and abundant liquid water at some time in the Martian past. The present fate of that water is a major mystery; that substantial quantities of volatiles are held in a "permafrost" layer at some depth beneath the Martian surface is currently the most favored hypothesis.

The Earth also stands alone among the planets, so far as is known, in that its surface, atmosphere, and hydrosphere have provided an environment conducive to the development of life and the evolution of complex living organisms. These life forms have had a substantial influence on the chemistry of the atmosphere and the oceans and on the nature of major sedimentary rock units on the Earth's surface. Because the surface of Venus is so hot (750 K), Mars had long been thought to be the planet next to Earth most likely to harbor life. The absence of detectable organic molecules on the Martian surface and the apparently hostile surface chemical and physical environment suggest that living organisms are not present on Mars. Whether Mars was less hostile to the development of life during earlier times, when it may have had a denser atmosphere and flowing surface water, is an important but open question.

The Earth's surface is known to be in a state of continuing dynamical evolution. Crustal material is continually created at midocean ridges and destroyed beneath the deep-sea trenches, as the plates that make up the Earth's surface move in more or less steady relative motion. The formation of huge mountain belts, the development of chains of volcanoes, and the driving force behind many large earthquakes are linked to these plate motions. Neither the moon, nor Mercury, nor Mars shows evidence for global tectonics of such vigor or for the wholesale recycling of the surface into the interior. The surfaces of the moon and Mercury preserve a clear record of early heavy meteor bombardment and of limited ancient volcanism and tectonic features associated with that volcanism or with tidal spindown and global cooling. The surface of Mars also shows a record of heavy meteor bombardment, slightly softened by subsequent wind erosion, but demonstrates a more extended and extensive history of volcanism and tectonics, though still less than on the Earth. The Venusian surface, hidden by permanent clouds, is largely an enigma. Limited low-resolution Earth-based radar images and long-wavelength topographic data suggest a surface with both craters and large volcanoes, as on Mars, together with mountain belts as on Earth. The nature of the convective motions that drive plate tectonics on the Earth, the importance of such tectonic processes early in the Earth's history, and the causes of the major

differences in evolutionary style among the terrestrial planets are unanswered questions of major importance.

The Earth's interior is known to be layered, a product of global differentiation. At the Earth's center is a metallic core, largely fluid and in convective motion but with a small solid inner core. The core is surrounded by a mantle of ferromagnesian silicates, mostly solid and in very slow convective motion. The mantle is capped by a thin crust of igneous and metamorphic silicate rocks, generally overlain by a veneer of sedimentary material. Each of the other inner planets is thought to be similarly layered, but the evidence for this view varies. The moon is known to have distinct crust and mantle layers and is covered by a regolith layer that is continually "gardened" by repeated meteor impacts. Mars is thought to have a core because of its low moment of inertia and a crust because of the isostatic compensation of its surface topography. Mercury has a lunarlike regolith, but global-scale structural information is lacking. That Venus likely has a crust is revealed by long-wavelength topographic and gravity information and by the density and radioactivity measurements by Venera landers. The nature and distribution of the energy sources that produced global differentiation on each of the terrestrial planets are not well understood.

The Earth has a substantial magnetic field of internal origin, evidently produced by the action of a hydromagnetic dynamo sustained by the interaction of convective motions in the fluid core with the Earth's rotation. The field is dominantly dipolar, with a polarity that reverses at apparently random times, and has nondipole components that tend to show a systematic westward drift. The Earth's field extends through a volume of space many times larger than the planetary volume, forming an umbrella that shields the Earth from the flowing interplanetary plasma. Of the other inner planets, only Mercury has a magnetosphere comparable in character with that of the Earth, though much reduced in size. The moon shows evidence for a past magnetic field of substantial magnitude, now recorded in the remanent magnetism of lunar rocks and of large segments of the lunar crust. The origin of the ancient magnetic field of the moon is not known. Venus apparently has no internal magnetic field. The existence of a magnetic field in Mars is currently a matter of debate; if any field exists, it is small. Of the outer planets, at least Jupiter and Saturn have strong internal magnetic fields and have magnetospheres considerably larger in dimension than that of the Earth. The wide differences in the nature of planetary magnetic fields are not understood.

The history of the Earth thus shares many common threads with the histories of one or more of the other inner planets, including early global differentiation of crust and core, outgassing and evolution of the atmosphere, early bombardment of the surface by a heavy flux of meteoroids, and development of a global magnetic field and magnetosphere. The Earth has many attributes

not shared, however, with any other known planet, including its oceans, the oxidized state of its atmosphere, its tectonic plate motions and the consequent complex history of crustal deformation, and its life-forms. *A continuing challenge to the earth and planetary sciences is to account for the profoundly unique attributes of the Earth in the context of the common processes that have shaped the formation and evolution of the solar system.*

3

Scientific Goals for Earth Science

The primary scientific goals for the further investigation of the Earth are to determine the composition, structure, and dynamics of the solid planet, its oceans and atmosphere, and its surrounding envelope of charged particles and fields; to characterize the systems of living organisms and their interactions with their environment; and to understand the processes by which the Earth formed as a planet and evolved to its present state. These goals are both broad in scope and long term in nature. Progress toward achieving these goals contributes toward a fundamental understanding of the workings of our planet and toward a greater awareness of how the activities of man are coupled to the dynamical processes occurring in the land, sea, and air around him.

Earth science, by its very nature, is charged with societal goals that are equal in importance to the scientific goals. The Earth supplies man with much of the energy and all the raw materials that he consumes at an accelerating rate; a major goal of earth science is to characterize the global inventory of resources and to understand the process of resource emplacement. Variations in planetary climate in the geologic past have sometimes had drastic effects on the Earth's living organisms. Another major goal of earth science is to understand the roles of the oceans, the biomass, volcanic eruptions, extra-terrestrial effects, and man's activity on long-term variations in climate. Man is faced, too, with such life-threatening natural catastrophes as severe storms, floods, and great earthquakes. A further goal of earth science is to understand the processes leading to these hazards, to develop tools to predict their occurrence, and—in the more distant future—to discover procedures to prevent such catastrophes or at least to lessen their intensity.

Scientific investigation of the Earth has traditionally differed from that of the other planets for the obvious reason that our ability to make observations and measurements on the surface or in the atmosphere is not restricted in time or spatial position by the limitations of spaceflight. Our interest in earth processes has stemmed both from intellectual curiosity and from the large impact that many of these processes can have on our lives. The scientific study of the Earth may be said to date back several millenia; our observational data bases for many earth processes and phenomena extend both over long periods of time and to a high level of detail. Historically, this level of detail has presented earth science with both advantages and disadvantages. With the observational detail has come an awareness of the complexity of the Earth and of the many manifestations of its operative processes. At the same time, this detail has often obscured large-scale patterns to the observations, patterns that signify that some of these processes act on a global basis.

In spite of the long history of earth science, the general recognition that many phenomena on the Earth are linked by global-scale processes has occurred comparatively recently. Further advances in our understanding of these phenomena will benefit substantially from approaches that cross the boundaries between such traditional disciplines as geology, geophysics, geochemistry, oceanography, meteorology, aeronomy, biology, and space physics. The plate-tectonic revolution less than two decades ago led to an enormous leap in our understanding of the history of the Earth's crust, the relationship between continents and ocean basins, the origin of mountain belts, and the causes of volcanoes and earthquakes. The space age ushered in the discovery of the Earth's magnetosphere and radiation belts and the growing appreciation that solar, magnetospheric, and atmospheric phenomena are profoundly interconnected. Similarly recent has been the recognition that the Earth's climate is the result of a delicate balance among many processes, including the biological and nonbiological portions of the global CO₂ cycle, the distribution of land masses, the large-scale circulation of the oceans, the rate of major volcanic eruptions, and the orbital characteristics of the planet.

Coupled with this recent appreciation of the global scale of and the strong interactions among, as well as the global scale of, the many processes affecting the Earth and its environment has been the development of new tools and new approaches for studying the Earth. Deep drilling in the ocean basins and continents has led to new insight into crustal structure, the history of plate motions and deformations, and paleoclimate. Imaging from space has led to new ideas in continental tectonics. Large-scale or global observations and coordinated research programs have been initiated in seismology, in atmospheric research, and in physical and chemical oceanography.

Thus even as our understanding of the Earth has improved enormously in

recent years, so has our ability to recognize major gaps in our understanding and to apply the new research tools now available toward filling these gaps. In the sections to follow we briefly identify some of the primary scientific goals for making important new advances in each of several strongly interconnected problem areas in earth science. These goals can serve as a basis for formulating a strategy for earth science in the future, including the earth science that can be accomplished by measurements made in space.

I. GLOBAL ATMOSPHERIC CIRCULATION

The atmosphere nourishes, sustains, and protects life on this planet, by exchanging oxygen and carbon dioxide with the biota, selectively transmitting electromagnetic radiation from the sun, maintaining a balance of surface temperature, and helping to drive the hydrologic cycle. Despite the importance of the atmosphere, our understanding of its complex motions, and of the transported heat and water on a variety of time scales, falls far short of an ability to make accurate predictions. Severe weather disturbances such as hurricanes, thunderstorms, and tornados have devastated large areas. Droughts have often severely reduced crop yields in many parts of the world. Sufficiently accurate prediction of precipitation and storm tracks is still not possible in either the short or long term.

At midlatitudes, cyclones are the major source of precipitation as well as of extremes in local weather on a time scale of 3 to 5 days. These medium-scale low-pressure systems are strongly coupled to global planetary waves. In order to better predict their evolution and, consequently, local weather, we need a better knowledge of atmospheric phenomena ranging in scale from the dimensions of individual clouds to the entire globe. Improved observational data bases and more refined dynamical and numerical models are required.

Long-term (months to years) changes in local weather (climate variations) are significantly less well understood. There is hope, however, that some factors such as persistent "blocking highs" and storm tracks may be more predictable. There are strong indications that tropical-ocean-surface-temperature anomalies are correlated with seasonal climatic variations. The implication of such a correlation is that the temperature of the ocean surface has an important influence on the global atmospheric circulation. The nature of this coupling is not well understood.

On the time scales of years to decades, man's influence becomes important. Carbon dioxide added to the atmosphere over the last hundred years has led to a significant increase in its global concentration. As a result, an increase in surface air temperatures of several degrees in the next century has been

predicted. The carbon dioxide cycle and the roles of the biota and the ocean, however, are not well understood. Through alteration of the Earth's surface (e.g., urbanization, deforestation) man can also have a potentially significant impact on the reflectivity of the Earth's surface, thus changing the atmospheric heat balance and the long-term climate; these effects are similarly not well enough understood to develop an accurate predictive capability.

Man's potential for destroying the protective ozone layer is now recognized, and the possibility has stimulated a great deal of work on the upper atmosphere and in atmospheric chemistry. The reflective properties of this region influence the overall heat budget of the Earth and, therefore, may have an important effect on the global surface temperature.

II. ATMOSPHERIC AND CLIMATIC HISTORY

The geologic record indicates that important changes in the composition of the Earth's atmosphere and in the Earth's climate have occurred in the past. About 2 billion years ago the oxygen content of the Earth's atmosphere increased dramatically; this is thought to be due to an acceleration of photosynthetic activity by the Earth's life-forms. Chemical erosion processes accelerated, and the greater portion of sedimentary copper and iron mineral deposits were formed. Formation of other types of deposits ceased, most notably those involving mechanical transport of easily oxidized minerals such as uraninite and pyrite without chemical destruction by oxidation. More subtle changes in atmospheric composition may have occurred since 2 billions years ago.

Mean global temperatures have fluctuated considerably over geologic history. Under "normal" conditions, for instance, England would have a semi-tropical climate similar to that of Indonesia. Beginning about 40 million years ago, the world's climate began to become cooler. Permanent glaciers developed later in Antarctica and in Greenland. The reasons for this cooling are not known. Changes in solar-energy radiation or ocean circulation may have been involved.

Beginning about 2 million years ago, the climate had altered to the point where minor changes in the Earth's orbital parameters apparently triggered the development of glaciers that covered large areas of the land masses of North America and Europe every 90,000 years. The last Ice Age ended about 12,000 years ago with a rapid melting of glacial ice in North America, Scandinavia, and Siberia. The Earth's climate remains cooler than it has been over the majority of Earth's history, although warmer than either the period of the last glacial event or the average climate for the last 2 million years.

Neither the long-term climatic evolution nor the onsets of Ice Ages are well understood.

III. OCEAN DYNAMICS

Measurements of the poleward transport of heat in the atmosphere show that it carries only about one half to two thirds of the total necessary to balance the solar input. The rest presumably is accounted for by the oceans. The oceans, therefore, have a significant influence on climate, but the specific nature of the processes carrying the heat (as well as momentum, salt, and other properties) is known only qualitatively. Until recently the oceanographic observations necessary to address this problem have been obtained only in a fragmentary way and only in limited regions.

Detailed three-dimensional measurements of the horizontal and vertical circulation and of its time dependence and forcing by atmospheric winds and by surface heating and cooling are required on a global basis. A better understanding is also required of the role that turbulent processes play in the overall energy and momentum transfers. A major goal is to be able to predict accurately the future states of the ocean.

The oceanic general circulation is driven by the atmosphere through wind stress and surface heating and cooling. This time-dependent coupling is poorly understood at present, even on a regional basis. In order to approach the goal of understanding and predicting climatic variations, it is crucial that near-surface processes be globally observed and accurately modeled.

Superimposed on the general circulation are a variety of wavelike phenomena whose periods range from seconds to years and whose wavelengths range from centimeters to hundreds of kilometers. Waves can radiate energy and cause transport of heat, momentum, and other water properties and can contaminate observations of lower-frequency motions. It is vitally important to understand the generation and decay of such waves and their contributions toward the overall balance of energy and momentum. Tides are perhaps the best understood wave motion, but even they are not well understood on a global basis because their observation has generally been made along coastlines or within harbors, where severe distortions can occur.

IV. ATMOSPHERE-OCEAN INTERACTION

Much of the heat transported poleward by the oceans is added to the oceans in the tropics through direct solar heating and is removed at midlatitudes and high latitudes through exchange with the atmosphere. Bulk parameterization formulas based on idealized models and laboratory experiments are generally used to estimate this exchange. Theoretical models are crude and oversimplified, and only recently have there been exploratory efforts at a few selected sites in the ocean to understand the various processes that are acting

in a full three-dimensional sense within the atmospheric and oceanic boundary layers to transfer heat and momentum.

The wind is believed to be the major force directly driving the large-scale horizontal ocean flows and indirectly driving the swiftly moving western boundary currents that complete the circulation. Wind information typically comes from less-than-reliable ship reports. Long-term averages are generally required to give a meaningful global distribution, yet little is known of the monthly, seasonal, or longer-term variations in the wind stress or the response of the oceans. As in the process of heat transfer, the stress is inferred through empirical relationships between wind and wind stress drawn from idealized situations. Further, spatial derivatives of the wind stress are required for the ocean circulation problem, so that the typically poor spatial sampling of wind data makes present estimates of the wind stress of dubious predictive value.

V. GLOBAL ICE BUDGET AND HYDROLOGIC CYCLE

Permanent sea ice occurs in a variety of physical forms, primarily in the polar regions of the Earth, where it is formed both through direct freezing of surface waters and through calving from land-bound glaciers. Ice cover is a major factor in the global albedo of the Earth and has a strong influence on air-sea exchange in the polar regions, thus playing an important role in our long-term climate.

On the average, solar-heat input is strongest at the equator and drives a large meridional convective circulation in both the atmosphere and the oceans, which helps to redistribute this unequal heat input and ameliorate the climate of the temperate latitudes. The mechanisms by which this is accomplished are understood only in a qualitative sense; the effect of long-term changes in sea-ice cover on deep-water formation, one part of the convective circulation, is not known.

Sea ice and snow cover are important variables determining the amount of solar energy reflected back into space in polar regions. Latitudinal variations in the Earth's albedo in turn determine the atmospheric convective circulation and consequently the amount of heat moved from equator to pole. The processes that accommodate this heat flux influence both short-term weather and long-term climate.

The distribution of freshwater and ice on the Earth and its variations over time are important for understanding the planetary hydrologic cycle as well as for global water management. The hydrologic cycle is closely coupled to weather and climate, and the movement of water on the Earth's surface during floods and as part of shoreline processes can have pronounced effects on surficial landforms. Because the hydrologic cycle has traditionally been stud-

ied on scales no larger than the drainage system for a single river, a global perspective on this scientific problem area has typically been lacking. The global distribution of rainfall, for instance, and its seasonal and longer-term variations are not well known.

VI. MAJOR CHEMICAL CYCLES

Chemicals cycle through the atmosphere, hydrosphere, biomass, and part of the rock mass of the earth as a result of volcanic, weathering, erosional, plate tectonic, and biological processes. These cycles have usually been studied by mass-balance analysis. For example, inventories have been made of the rate of input of various chemical species to the world's oceans from rivers, sinks within the oceans have been identified, and, considering the mass of the world's oceans, the residence times of species within the oceans have been estimated. Similar attempts at mass balance have been made for the components of the atmosphere. The chemical reservoirs in the atmosphere, hydrosphere, biomass, and rock masses are coupled. For example, net oxygen is added to the atmosphere when the inventory of carbon is increased in buried sediments. Carbon is returned to the atmosphere as CO_2 by volcanic activity and by combustion of fossil fuels. Oxygen is lost when seawater interacts with rock as a result of hydrothermal circulation at midocean ridges, during oxidation of Fe^{2+} , C^0 , and S^{2-} in surface rocks and during combustion of fossil fuels. In general, the chemical composition of the atmosphere and the world's oceans must adjust so that the sources and sinks represented by affected biological and rock components are in overall balance.

Our knowledge of chemical cycles is at an early and rudimentary stage. This is largely the result of the global scale of the problem and the difficulty of defining the magnitude of all major sources and sinks. It is difficult enough to estimate the total volume of global volcanic outgassing, let alone to determine the typical composition of such outgassing. Nevertheless, major successes have been achieved. Until recently, for example, there was an unresolved discrepancy between the amount of Mg entering the world's oceans per year and the amount per year that could be removed by known sinks. It has recently been recognized that hydrothermal circulation at the world's ocean ridges provides the missing sink through fluid-rock interaction and precipitation of Mg.

Even our conceptual framework is probably oversimplified as it does not incorporate the variety of positive and negative feedbacks that occur in nature. As a result, this framework does not allow for the possibility of multiple steady states or oscillatory behavior or properly describe the nature of stability.

Chemical cycles take on added importance in assessing the potential impact of man-made contaminants on the long-term composition of the atmosphere and hydrosphere. This issue is made critical by the fact that small amounts of certain molecular species can have dramatic effects on the transparency of the atmosphere to electromagnetic radiation. Ozone and CO₂ are species of particular concern. Changes in the abundance of these species could strongly affect the solar flux, at the earth's surface, of life-damaging ultraviolet radiation as well as the global solar heat balance. Knowledge of the residence times and life cycles of these molecular species through the atmosphere, hydrosphere, biomass, and rock masses is a major scientific goal of critical importance to society.

VII. PLATE DYNAMICS

Since the mid-1960's, geology has been revolutionized by the theory of plate tectonics. According to this theory, the Earth's surface is divided into about 11 major and a similar number of minor plates, which behave as rigid units, are in continuous relative motion, and interact mainly at their edges. New plate material is created by ocean-ridge volcanism; old oceanic plate material is subducted or consumed at oceanic trenches. Many of the world's active volcanoes are associated with plate boundaries. Where plates are created or destroyed, or where plates move past one another in a strike-slip fashion, earthquakes occur. Earthquakes, which themselves indicate plate motion, outline the world's major plates.

The average relative motion of the Earth's plates over approximately million-year intervals is known for the last 200 million years from studies of magnetic lineations in oceanic plates. These plate motions are direct evidence for and are indicative of the general rates of convective motions in the Earth's viscous mantle. There are no oceanic plates older than approximately 200 million years; nearly all older oceanic crustal material has been subducted. Our knowledge of plate interaction prior to this time must rest on inference from continental geology.

Although we know the average relative velocities of the Earth's plates over times scales of approximately a million years, the Earth's magnetic field does not reverse polarity frequently enough to allow finer temporal resolution of the present rates of motion. As earthquakes attest, the motion of the plates at plate edges is episodic. We do not know, however, how stress and strain accumulate near plate edges. Nor do we know, as a more practical concern, whether diagnostic precursory effects before major earthquakes are general phenomena. It is believed that the episodic motions at plate boundaries become damped out with distance from the boundary by stress relaxation in

the viscous asthenosphere underlying the plates, so that the relative motions of plate interiors are steady; direct observations of plate motions over time scales of years are necessary to test these ideas.

A major goal in plate dynamics is to understand the driving mechanism for continued plate motions. The mechanism involves some form of thermal convection in the Earth's mantle, but the form of the motions is unknown at levels deeper than the plates themselves. We do not know the radial extent of the convection system involving the plates. Nor do we know the planform of the flow, that is, the pattern in plan view of upwelling and downwelling limbs of the convection system. Further, the relative contributions to the energy for convection from mantle radioactivity, heat from the core, and primordial heating (including core-mantle differentiation) are poorly known. The detailed pattern of the convective flow is thought to be highly sensitive to the viscosity of the Earth's mantle and to its spatial variations. The history of mantle convection is closely linked not only to the history of plate motions but also to the removal of heat from the Earth's interior and to the chemical evolution of the crust and mantle.

VIII. HISTORY OF THE EARTH'S CRUST

It is generally believed that the history of the Earth's crust back to at least Archean times (before 2.5 billion years ago) consists of events similar to those observed at present. That is, episodes of rifting, growth of new oceans, subduction of oceanic crust, and strike-slip deformation or collision of continental landmasses (such as in the Himalayas today) occurred in the past just as they are occurring now. The geologic record attests to such riftings and collisions, and substantial progress has been made in deducing the sequence of events whose integrated history is preserved, at least partially, in the geologic record. This is an area of extremely active and productive geologic research at present.

Some believe that prior to 2.5 billion years ago, mantle convection was more vigorous than at present and that the continents were, as a result, fragmented into smaller pieces. Landmasses might have been typically the size of island arcs such as Japan. In contrast, some scientists have suggested that the continental lithosphere was in fact uniformly distributed, with oceans covering the entire globe. Some areas must have been exposed to air, since "continental" or "shelf" sediments that require subaerial erosion for their genesis are observed in the oldest rocks. The further back we seek information, the more fragmented the geologic record, and the less constrained the synthesis of past processes or events. In this regard, the most fundamental question is probably whether there was a significant difference between Archean and post-Archean plate tectonics, and if so what the nature of this difference was.

IX. SEDIMENTARY CYCLES

Rocks above sea level on continents are exposed to unrelenting mechanical and chemical erosion. Sediments, the products of both erosion and chemical and biological precipitation, accumulate in continental depressions and along continental margins. If erosional processes continued unbalanced, the continents would ultimately erode below the level of low-tide wave action. The tectonic processes of mantle convection, continental drift, subduction, and continental collision transport the products of erosion back onto the continents, and thus act to maintain continental elevation above sea level.

The amount of continental surface flooded in past times reflects the relative volumes of ocean and continental rock, as well as the average height of continents above sea level, which is controlled by the relative rates of erosion and tectonism. Changes in continental shelf area parallel the orogenic cycles, which divide and punctuate geologic time. Determination of shelf area as a function of time can then tell us of past episodes of continental rifting and collision as well as of any long-term trends in the volume of water or continental crust. One important but poorly understood influence on global sea level is the volume of midocean ridges, which apparently has fluctuated in the past in response to global changes in plate recycling rates and planetary heat flow. Variations in the type and amount of sediment affect the chemical composition of the oceans, the atmosphere, and the biomass because the biosphere, sediments, oceans, and atmosphere act on linked chemical reservoirs. An increase in buried carbonate necessarily reflects a removal of CO_2 or C from the other reservoirs.

Sediments at the continental shorelines are subject to erosion by ocean waves and currents. The changes that occur here, where tectonic, fluvial, atmospheric, and oceanic processes meet, are typically studied only in local contexts. A global inventory of coastal sedimentary landforms and observations of their temporal behavior would help to tie these local studies to the geologic record of global-scale sedimentary processes associated with sea-level and climate changes.

X. INTERNAL STRUCTURE AND COMPOSITION OF THE EARTH

Seismic and gravity data indicate that the Earth's mantle is, to first order, remarkably uniform and homogeneous. Transitions to denser assemblages occur at approximately 400- and 600-km depth, but the chemical composition of the mantle appears to be approximately uniform. The dynamic response of the Earth's surface to the load redistribution occurring at the close of the last Ice Age (marked by approximately a 100-m increase in sea level and the re-

removal of approximately 3 km of ice from Canada, Scandinavia, and elsewhere) suggest that the Earth's mantle acts as a viscous fluid over geologic time scales. The mantle viscosity is sufficiently low that the mantle will convect strongly under the influence of any internally generated (radioactive) heat or in response to heat added at the base of the mantle from the core. The uppermost mantle underlying the surface plates—the asthenosphere—appears to be most fluid. Some have interpreted internal plate volcanism and geoid bulging, such as occurs at the Hawaiian Island chain, to be a surface manifestation of plumelike whole-mantle convection and have associated the fluid asthenosphere with the outwelling limbs of this convection. Others dispute this interpretation.

Subtle lateral variations in seismic properties indicate that inhomogeneities are present in the Earth's mantle. Many of these inhomogeneities are believed to be portions of subducted plate that have not yet been completely thermally or chemically resorbed into the mantle. The mantle is also known to be inhomogeneous in trace element and radionuclide abundances from chemical and isotopic studies of mantle-derived magmas. A major focus of current research is to determine whether these chemical inhomogeneities represent large-scale layering of the mantle or are of smaller characteristic dimensions and more uniformly distributed throughout the mantle volume; this question has profound implications for the differentiation history of the mantle and crust.

XI. GENERATION OF THE EARTH'S MAGNETIC FIELD

Seismic studies indicate that the outer core of the Earth is fluid and has radial distributions of density and seismic velocity similar to those of iron. Large, electrically conductive, rotating, turbulently convecting bodies, such as stars, generally have magnetic fields associated with them. Some of the energy in fluid convection tends naturally to cascade into a magnetic field. Reversals of the Earth's magnetic field, as well as the westward drift of irregularities in the field, support the hypothesis that the Earth's magnetic field is generated by turbulent convection of the outer core and by processes analogous to those operating in stars. Since Jupiter, Saturn, and Mercury also have internal magnetic fields, it is inferred that these planets, like the Earth, have convecting, electrically conductive interior regions.

The source of energy driving the convection of the outer core is, however, unknown. It could be latent heat of solidification from a growing inner core, but it is difficult to see how the inner core could solidify slowly enough to support a magnetic field throughout the Earth's history. The amount of heat

crossing the core-mantle boundary, important to theories of mantle convection, should be related to the nature and rate of outer-core convection and to generation of the Earth's magnetic field, but constraints from this perspective have not yet been established. The magnitude of this heat flux is not known at present.

4

The Role of Space Measurements for Earth Science

For the scientific investigation of planets other than the Earth, a phase of global exploration has generally preceded detailed study of the planetary atmosphere or surface. Global exploration has been conducted by orbiting spacecraft, while detailed studies have been conducted *in situ* with atmospheric probes and surface landers. The scientific study of the Earth, in contrast, has proceeded in the opposite direction, from detailed studies toward global syntheses. These global scientific syntheses are only in their formative stages, however, and many of the detailed ground, sea, and air observations cannot currently be placed within the context of planetary-scale processes. The phase of global exploration in the scientific study of the Earth is far from complete.

Measurements from orbiting spacecraft are the logical means by which to conduct global scientific exploration of the Earth. Orbital platforms by their very nature have a planetary perspective on the land, ocean, and atmospheric processes below. Platforms with polar or nearly polar orbits can give global coverage within a short period of observation time. Remote-sensing techniques can be applied to the land, oceans, or atmosphere with a globally consistent resolution and viewing geometry. An orbiting satellite can provide both wide-angle or synoptic views of the Earth and higher-resolution information on selected areas. A long-lived satellite can provide observations of time-varying phenomena, such as those associated with short-term weather systems, with seasonal changes, or with longer-term secular changes.

Recent technological developments have made it possible to consider a number of types of measurements from orbiting platforms that address important issues in earth science. Very precise measurements of distances over

baselines thousands of kilometers long are now possible using either radio interferometry or laser ranging to a satellite; such a measurement capability opens for the first time the possibility of measuring directly the relative motions of the Earth's tectonic plates on time scales of a few years. A wide variety of imaging systems has been developed, ranging in sensed wavelength from the visible to the microwave portion of the electromagnetic spectrum. Visible and near-infrared imagery play important roles in daily weather forecasting. Images of the land surface obtained from space are sensitive both to aspects of the composition of the surficial materials and to geologic structural features of a wide range of spatial scales; the opportunity is at hand to map in a uniform fashion the geologic units on all the exposed surface of the continents at a resolution sufficient to address major questions on the nature and evolution of continents. Infrared and microwave satellite sensors are now used routinely to deduce vertical temperature profiles for the global atmosphere. Techniques have also been developed to measure from space the concentrations of many important molecular species in the atmosphere and their variations with altitude. From space it is now possible to make precise measurements of surface elevation of both the oceans and the land masses, to determine the Earth's gravitational and magnetic fields from global scales down to wavelengths comparable to the spacecraft altitude, and to measure effectively the wind velocities at the surface of the oceans. The combined measurement of sea-surface elevation, oceanic wind stress, and global gravity will permit for the first time the realistic determination of the large-scale three-dimensional current patterns in the world's oceans.

In the foreseeable future, there are further technological advances that will permit both new types of measurements and observations at a sufficiently improved resolution to be sensitive to additional processes. Improvements in the accuracy and precision of space measurements of baseline vectors will permit observations of intraplate deformation, including the detailed response of the Earth to glacial unloading, and may lead to the recognition of precursory displacement or strain changes before large earthquakes. Active space-imaging systems in the visible and near infrared may lead to remote sensing of surface rock type with improved spectral and spatial resolution.

Within the next decade, space measurements can contribute fundamental improvements in our understanding of the Earth and its dynamic processes. With the continued development of new technological tools, the contributions to earth science from space can continue to be substantial long after the next decade as well. *We recommend that a vigorous program of space measurements be maintained as an essential element of the national effort in earth science for the 1980's.*

5

Strategy for Earth Science from Space in the 1980's

I. FRAMEWORK FOR THE STRATEGY

This report presents the first phase of an integrated strategy for earth science from space for the coming decade. Scientific topics treated at length in this first part of the strategy include the dynamics of the solid earth, the geologic structure and history of the continents, and the dynamics of the oceans. These three scientific problem areas are all of major importance for our understanding of the basic global processes that have shaped the Earth as well as for the knowledge that will contribute to our ability to deal with such major societal issues as natural resources, natural hazards, and future climate.

These scientific topics are also fundamental from a planetary perspective. The composition and structure of the land surface provide basic information on the geologic evolution of a planet. The dynamics of the surface and interior of a planet can be directly related to the distribution and transfer of planetary internal energy and to the tectonic and volcanic activity at and near the planetary surface. The terrestrial oceans are unique within the solar system; knowledge of their dynamics is essential if we are to understand the related problems, more common in a planetary context, of atmospheric dynamics and global climate.

In the area of solid-earth dynamics, such space techniques as satellite laser ranging and very-long-baseline radio interferometry offer the only tools to measure directly the present relative motions of the major tectonic plates. Because the plate velocities provide a framework for much of our current understanding of earthquakes, volcanism, and the origin of mountain belts, testing current concepts by direct measurement is of utmost importance. Space measurements can contribute in the next decade to an understanding

of the time-dependent deformation of the lithosphere near plate boundaries, to the planform of mantle convection as revealed in the gravity field, and to the irregularities in rotation rate and polar motion and their relationship to earthquakes. Over a time frame extending beyond the next decade, space techniques can be used to measure the horizontal and vertical motion within plate interiors, a topic of importance for understanding the rheology of the mantle and the state of stress in the lithosphere.

In the area of continental geology, space techniques offer the most efficient tools to map the distribution of surface rock types and of morphological and structural features in a global and uniform fashion. They also can provide a synoptic view of such dynamic geologic features as volcanoes and deserts and of the features associated with river and coastal-current systems and floods. The global distributions of rock type and of morphological and structural features are essential information for deciphering the history of the Earth's crust and for helping to characterize the geologic setting of areas of resource potential.

In the area of ocean dynamics, space techniques offer the only practical means to determine globally the surface boundary conditions for general circulation of the ocean, including the sea-surface slope and the wind stress. Space tracking of a large number of drifting stations can provide a direct measure of the near-surface circulation and can yield efficient synoptic determinations of subsurface properties necessary to understand the three-dimensional ocean circulation. Space measurements offer a straightforward means to monitor sea-surface temperature, important for both meteorology and ocean dynamics.

For solid-earth dynamics, continental geology, and ocean dynamics, therefore, space measurements can provide unique and important information that will substantially advance our levels of understanding. *The Committee regards solid-earth dynamics, continental geology, and ocean dynamics as areas of equal importance for a program of earth science from space for the decade 1981-1990.* The second and final phase in the complete strategy for earth science from space over the next decade will include scientific strategies for atmospheric circulation, climate, the water and ice budget, and major global chemical cycles and will address many scientific issues equal in importance to those treated in this report. The individual strategies in the second part of this report will be fully integrated both among themselves and with those of the present document.

The three areas, solid-earth dynamics, continental geology, and ocean dynamics, are linked through several scientific goals and objectives. The present surface of the solid earth is the product of many episodes of continental rifting, seafloor spreading, subduction and ocean closure, and continental collisions. The seafloor records the history of such processes only for the last 200

million years. The record of earth history and dynamics prior to 200 million years ago must be found in the mountain belts, the ancient shields and plateaus, and the rifts and sutures of the continents. Interpretation of structural features in such old mountain belts and rifts must be based on analogous features in the dynamically active mountain and rift systems of the present. The present motions of lithospheric blocks and the strains within plates are often closely associated with geologic structure. The Alpine-Himalayan belt, for example, is a broad zone of current deformation associated with the collision of several major continental masses with Eurasia. Characterization of the present dynamics of this zone will require an integration of both geodetic measurements and mapping of large-scale tectonically active structures. Even within generally stable portions of the plates, intraplate earthquakes attest to occasional nonrigid behavior. There is some evidence that areas of active intraplate deformation on continents may be localized to structurally distinctive "weak" zones that owe their origin to earlier episodes of tectonic activity.

In a broad sense, the large-scale circulation of the ocean is also at least partly a product of the instantaneous configuration of the seafloor. As the seafloor subsides with age, as continents drift relative to one another, and as global spreading rates vary, mean sea level can change, new avenues can be opened for major bottom currents, and the bottom boundary condition will slowly evolve. An understanding of ocean circulation, and its influence on climate, in the geologic past and in the future, is closely tied to an understanding of the changes in ocean bathymetry through time associated with plate dynamics.

The improved measurement of the global gravity field is important both as a tool to study mantle dynamics and as a necessary step in separating the effects of ocean currents and gravitational potential on sea-surface elevation. In addition, the measurement of gravity allows extension of geologic surface-unit definition through modeling to the third dimension. Measurement of the Earth's magnetic field from space provides information both on the dynamics of the Earth's core and on the distribution of crustal magnetic anomalies that are related to geologic structure and potentially to the subsurface temperature field. For all of these reasons, therefore, the individual scientific strategies for solid-earth dynamics, continental geology, and ocean dynamics collectively form a coherent first step in the formulation of an overall strategy for earth science from space for the 1980's.

For each of the three areas for which a detailed strategy is presented here, the Committee has identified scientific objectives of the highest priority that can be achieved by space measurements. The priority of each objective in this strategy reflects both its scientific importance and the feasibility for its accomplishment by space measurements during the 1980's. *Over the time frame of the next decade, progress toward achieving the stated scientific objectives*

for solid-earth dynamics, continental geology, and ocean dynamics should be balanced. The highest-priority objectives for each scientific area should be regarded as approximately equal in importance, and the achievement of a high-priority objective in one area is held to be of greater urgency than the achievement of a lower-priority objective in another area.

The strategy for earth science from space as presented in this report is conservatively paced, in recognition of the continuing need to strike a balance between major scientific advances and efficient use of national resources. Only those scientific objectives that are of fundamental importance and that can be achieved either uniquely or most effectively by space measurements are included in the strategy discussions that follow.

II. OBJECTIVES FOR SOLID-EARTH DYNAMICS

Introduction

At the high temperatures typical of the interiors of the terrestrial planets, the silicates that constitute the mantle behave as viscous fluids over geologic time scales. From our knowledge of the heat sources and the relations between viscosity and temperature in planetary interiors, it can be demonstrated theoretically that the internal evolution and the present temperature distribution of each of the terrestrial planets has likely been controlled by solid-state convection in the planetary mantle. For all the terrestrial planets except the Earth, however, direct observational confirmation of mantle convection is absent. For the Earth, the relative motions of tectonic plates provide unequivocal evidence for the convective motions of the interior.

The theory of plate tectonics has led to a dramatic increase in our understanding of a wide variety of geologic processes. According to that theory, the Earth's surface may be divided into a number of rigid plates that are in continuous relative motion and that interact only at plate edges. The relative motions of plates give rise to the great majority of earthquakes at the boundaries between plates. Zones of plate separation and plate convergence define the locus of most of the Earth's volcanic activity. Plate motions over extended periods of geologic time lead to the drifting of continents, the opening and closing of ocean basins, and the formation of great mountain belts. The geologic record contains evidence for plate interactions similar to those occurring today dating back billions of years.

Several of the fundamental assumptions of the plate-tectonic theory have not been tested directly. Though the directions of relative plate movements may be obtained directly from the trends of major plate-boundary faults and the direction of slip during earthquake faulting, the rates of plate motions

must be obtained indirectly from magnetic anomalies on the seafloor and the record of polarity reversals of the Earth's dipole magnetic field. These rates, which range from 1 to almost 20 cm/yr, have considerable predictive value over geologic time scales, although they are averages of the rates over the last few million years and they can be determined only across divergent plate boundaries or midocean ridges. Plate motions are episodic at plate boundaries, as evidenced by earthquakes. There are theoretical reasons to expect that this episodicity is damped out at distances greater than several hundred kilometers from the plate boundary by the effects of stress relaxation in the viscous asthenosphere beneath the plates so that the relative motion between the stable interiors of two plates is steady; this expectation, however, remains to be tested. Further, there are a number of small plates without a bounding midocean ridge; the relative velocities of these plates are poorly known. Finally, the assumption of plate rigidity is likely to break down in some intraplate regions and at some strain rates; while some of these regions have been identified on the basis of earthquake activity, neither the full suite of such regions nor their strain rates are known.

The driving mechanism for plate motions is thought to be mantle convection, but the form of that convection and the aspects of the flow most important for maintaining plate movements are not known. We do not know, for instance, whether the convective system that includes the plates as upper boundary layers extends to the core-mantle boundary or is limited to the upper mantle; the answer to this question depends on the radial distribution of viscosity in the mantle and on chemical differences, if any, between the upper and lower mantles. The planform of mantle convection, the pattern of flow velocities at each depth in the mantle, is not known below the level of the plates. Thus, the relationship of regions of upwelling and downwelling to the locations and types of plate boundaries or to zones of intraplate volcanism and faulting are poorly understood. Theoretical and laboratory studies suggest that the planform of mantle convection is closely related to the radial extent of the convection system involving the plates and that the planform can be discerned in the surface pattern of gravity, topography, and heat flow, once the effects of the lithosphere on these quantities are removed. This promising line of research is in its infancy, and both further theoretical studies and globally distributed measurements are needed.

A poorly understood process in solid-earth dynamics is the deformation of plate interiors. Some continental regions are undergoing active rifting and extension; we do not know the cause of such rifting, its relationship to mantle convection, or the conditions under which rifting leads to continental breakup and the creation of a new ocean by seafloor spreading. Large areas of continents have been slowly uplifted by 1000 m or more as broad plateaus; broad areas have also subsided at varying rates to become intracontinental basins.

The origin of these slow but long continuing vertical movements within plates is not generally understood.

Because of the role of viscosity and its spatial variations in controlling the dynamics of the solid earth, independent measures of mantle viscosity are extremely important. The radial distribution of viscosity in the mantle has been estimated from the response of the earth to the melting of the great ice sheets at the close of the last Ice Age. The most critical data for determining the Earth's viscosity profile are the rates of vertical motions in regions within a few thousand kilometers of the edges of the areas of major glaciation during the last Ice Age. Unfortunately, existing measurements of such motions by two conventional geodetic techniques are limited in spatial extent and are contradictory. Independent measurements, capable of detecting motions as small as a few millimeters per year, are necessary to resolve the disagreement.

Another process sensitive to the viscous properties of the mantle is the time-dependent deformation that follows a major earthquake over periods of months to years. The postseismic deformation has been determined for only a few large earthquakes along plate boundaries, and then only for restricted regions. More complete data sets for additional earthquakes are needed. We do not know, in addition, whether large earthquakes may be preceded by detectable deformation, a vital question for possible earthquake prediction. Nor do we know the relative importance of episodic slip by large earthquakes and of more or less steady motion by aseismic creep for the major fault zones.

Temporal variations in the distribution of mass within the Earth can lead to changes in the planetary inertia tensor and thus to changes in rotation rate and pole position. Torques exerted on the crust and mantle by atmospheric winds or by fluid motions at the top of the core can also change the angular momentum of the solid parts of the Earth. Changes in the length of day have been shown to be correlated with global zonal winds and with seasonal effects in the atmosphere. A variety of other correlations have been proposed among changes in the Earth's angular velocity vector, changes in the Earth's magnetic field, variations in atmospheric winds or climate, and large earthquakes, but the causal relationships, if any, are not understood. Variations in the amplitude of the Earth's free nutation, or the Chandler wobble, indicate that a source of energy must exist to excite this motion. Excitation of the Chandler wobble both by atmospheric sources and by large earthquakes has been proposed. The known earthquakes are insufficient as a source of excitation, but there may exist "slow" or "silent" earthquakes that involve large displacements at rates too low to be detectable by seismometers. Such "silent" earthquakes need not be closely related in space or time to observed earthquakes. Accurate determination of pole positions and the temporal relationship between large shifts in pole path and major earthquakes can help to resolve these questions.

Observations of changes in lengths of geodetic baselines with time can be made with such space techniques as very-long-baseline radio interferometry (VLBI) and satellite laser ranging to accuracies of a few centimeters per year. Such techniques offer a unique opportunity to observe plate motion directly over short time periods, a result that would contribute fundamentally to our understanding of plate kinematics and of the forces driving plate motions. The same techniques can be applied to the problems of time-dependent deformation in seismic zones, which substantially enhance our knowledge of earthquakes and their recurrence times, and of variations in earth rotation and polar motion. Over a somewhat longer time frame, space geodetic measurements will be of sufficient accuracy to detect vertical motions within plates and to infer from these observations the rheology of the mantle. With space measurements it is possible to measure the Earth's global gravity field and to discern the signature in the gravity field of the planform of mantle convection. Thus, space measurements over the next decade can have a profound impact on our understanding of solid-earth dynamics.

Scientific Objectives

The primary science objectives for the study of solid-earth dynamics from space for the next decade, in order of priority, are as follows:

- 1. To measure the present rates of motion between the stable portions of the Earth's major tectonic plates;*
- 2. To measure time-dependent deformation in a number of the major worldwide seismic zones using space techniques;*
- 3. To measure the Earth's gravitational field from global scales to wavelengths of 200 km or less;*
- 4. To measure variations in the Earth's rotation rate and polar motion with increased accuracy;*
- 5. To initiate the determination of large-scale vertical and horizontal motions in the interiors of the Earth's major tectonic plates.*

Determination of the present motions of the Earth's major plates is of the highest priority because it provides an overall test of the fundamental assumptions of the theory of plate tectonics. Space techniques provide the only means for such measurement, and present technology is expected to permit measurements to the necessary accuracy. Measurement of time-dependent deformation in seismic zones is also of first-order scientific importance for the determination of the mechanical behavior of the crust and mantle in such regions and for an understanding of the recurrence times of major earthquakes. This objective is also of strong social significance, as information from such

measurements may lead to earthquake prediction. Space techniques provide the only accurate method to make frequent observations of deformation over broad regions around fault zones and across plate boundaries that are partly or wholly submarine. *The first two scientific objectives, measurement of plate motions and measurement of deformation in seismic zones, are approximately equal in importance, and we recommend strongly that both objectives be achieved in the next decade.*

Determination of the Earth's gravity field over a wide range of spatial scales is of importance for solid-earth dynamics because it is likely to provide direct information on the planform of mantle convection. As discussed in other sections, improvement in the resolution and coverage of gravitational field measurements is essential to the determination of the general circulation of the oceans and would also provide useful data on deep crustal structure. Mapping of the Earth's gravitational field at a consistent resolution on a global scale is best accomplished by space techniques. *Because the measurement of global gravity is a primary objective for both solid-earth dynamics and ocean dynamics and is an important secondary objective for continental geology, the determination of an improved gravitational field through space measurement should be an objective of highest priority for the 1980's.*

Determination of variations in the Earth's rotation rate and polar motion with an accuracy greater than can be achieved with conventional astronomical techniques is a necessary step in the measurement with space techniques of changes in orientation of long baselines, an important step in the determination of plate motions and of deformation in seismic zones. In addition, this objective will provide new information on the extent of slow coseismic deformation, will help to resolve the contribution of earthquakes to excitation of the Chandler wobble, and will provide a constraint on global zonal winds that is independent of meteorological measurements.

Vertical motions within plates are of prime scientific significance as they can yield direct information on the viscosity structure of the mantle. Because the accuracy required to measure vertical motions is likely to be beyond measurement capabilities for the next decade, however, this objective is given a comparatively lower priority. Horizontal deformation within plates will be determined to some extent in the process of measuring the motion between the interiors of the major plates, so that monitoring of horizontal intraplate deformation in specific regions has reduced priority as a distinct objective. It is nevertheless important for both vertical and horizontal motion to initiate measurements in the next decade in order to establish a reference base against which measurements of intraplate deformation can be made in the following decade.

The Earth's scalar magnetic field has been mapped by the POGO satellites and the vector magnetic field by Magsat. The further measurement from space of the Earth's magnetic field during the next decade is at present re-

garded as secondary to the objectives enumerated above because these two magnetic surveys have recently been carried out and because the scientific implications of these data have not yet been fully evaluated. We recommend that NASA continue to support the analysis of data from these two missions to obtain a global description of the Earth's field and of its changes over the time between the two sets of measurements to assess whether time variations in the magnetic field observed from space can constrain models for flow in the fluid core and to ascertain whether geomagnetic sounding of the upper mantle using natural variations in the external field is practical from space. The Committee requests that it be informed of the results of these studies as they are completed, so that fundamental questions emerging from the analyses can be evaluated in terms of the overall strategy.

1. *To measure the present rates of motion between the stable portions of the Earth's major tectonic plates.*

A direct determination of the relative velocities between the major plates will test and extend the kinematic theory of plate tectonics. Such measurement will determine whether the plate velocities over time scales of years are equal to the velocities averaged over millions of years as inferred from seafloor magnetic anomalies. These measurements will permit the relative motions across the major convergent and strike-slip boundaries to be obtained directly rather than from the assumption of plate rigidity. In addition, the relative motions of those plates whose velocities relative to adjacent plates are currently poorly known, such as the Caribbean and Philippine plates, can be measured accurately for the first time.

MEASUREMENT REQUIREMENTS. To determine the present rates of motion between the Earth's major plates, an accuracy of at least 1 cm/yr at a high level of confidence is required. Such an accuracy level is needed in order to obtain useful information on the relative motions of the slower-moving plates. For example, the probable motion of the North American plate with respect to the Eurasian plate is only about 2 cm/yr. Measurements must be made at four or five widely distributed points in each major plate wherever possible in order to ensure that the motion between the major stable portions of the plates are being measured and that the results will not be contaminated by deformation within the plates.

For most of the major plates, the long-term average rates of relative motion are known from marine magnetic anomaly patterns and other geologic and geophysical observations. The main scientific problem can be formulated in terms of testing the null hypothesis that the present rates in the 1980's are equal to the long-term average rates. In order to obtain a valid test of a null hypothesis, it is necessary that a high degree of confidence be established for the measured rates of motion.

The specification of confidence limits for the determination of plate motions, and for the measurement of other geodetic variables as discussed below, is made difficult by the fact that systematic rather than random errors limit the accuracy of measurements of baseline lengths and orientations by the techniques currently used in VLBI and satellite laser ranging. Purely statistical treatment of such measurements, assuming normally distributed errors with zero means, can in fact lead to faulty inferences if the effects of systematic errors are not properly considered. To achieve the highest priority objectives for solid-earth dynamics as detailed in this report, *we recommend that all the specified measurement accuracies for the determination of plate motions and of time-dependent deformation in seismic zones be achieved at least at the 95 percent confidence level.* To establish a 95 percent confidence interval, a great deal of attention must be given both to possible sources of systematic errors in the measurements and to possible deficiencies in the models used to analyze the data. All plausible sources of error should be included in the error budget, and explanations must be given for how the estimated limits on the individual sources of error were established or why particular probability distributions can be expected to characterize the individual errors. Some sources of systematic or model error will have estimated probability distributions that are far from Gaussian in the wings, and the effects of the wings may strongly influence the determination of 95 percent confidence intervals. Thus the ratio of the widths of the 95 and 70 percent confidence intervals can be substantially larger than the value of about 2 that holds for Gaussian distributions. *The Committee urges that NASA assess carefully the possible sources of systematic error in the measurements and in the physical models used to determine lengths and orientations of baselines and that every effort be devoted to reducing those errors to levels consistent with the measurement accuracies specified in this report.* Proper ("blind") comparison of the measurement results from independent techniques will be an essential step in this effort.

2. To measure time-dependent deformation in a number of the major worldwide seismic zones by space techniques.

The measurement of deformation in major seismic zones will define the distribution of strain across plate boundaries and will resolve the relative importance of earthquakes and slow aseismic creep in plate-boundary motion. The vertical and horizontal deformation following a large earthquake can be used to infer the nature of mantle viscous processes in the vicinity of the fault region. The important question of whether earthquakes are generally preceded by diagnostic tectonic deformation can be answered only by conducting measurements of deformation on a variety of time scales in areas of high seismic risk.

MEASUREMENT REQUIREMENTS. The first step in the measurement of plate-boundary deformation should be to establish a reference grid against

which motions can be measured in a number of major seismic zones in the western hemisphere and the western Pacific. The segments of each boundary selected should include seismic regions in which, on the basis of seismic studies, there is a reasonable probability that a major earthquake will occur within the next decade. The network of base points should be broad enough to span the width of plate-boundary deformation.

In the case of strike-slip boundaries, for instance, shear-strain accumulation may be distributed across a network of faults, as in California, or more uniformly across a crustal volume, as in New Zealand. Hence, a number of stations at distances from the plate boundary of up to at least several hundred kilometers will be required to define the nature of shear at any point along the boundary and to be sure that the total slip has been measured. The spacing between geodetic control points should range from roughly 30 km near the fault trace to perhaps 100 km at large distances. The measurement accuracy required for relative position is 2 cm in each coordinate at the 95 percent confidence level. For initial epoch (i.e., initial time) measurements, somewhat poorer accuracy would still be quite useful in view of the expected size of displacements during and after large earthquakes. Measurements in a number of major seismic zones are recommended because the probability of a great earthquake in any one area during a given decade is low.

We further recommend that a resurvey of the initial epoch base network be made at least two or three times within the next decade to determine how strain is accumulating along each boundary zone. This will identify areas of high earthquake risk and will also give a measure of the distance that time and space-varying strain penetrates into plate interiors and will thus help to determine the asthenospheric viscosity.

Measurement accuracies of 1 cm/yr at the 95 percent confidence level will be required to test whether plate-boundary slip rates differ from the expected long-term plate motions. Accuracies of 0.5 cm/yr will be needed to define even coarsely the shear distribution across fault systems.

For societal reasons, it is important to have as much warning as possible of the time and place of occurrence of a major earthquake. Space techniques, such as satellite ranging or radio interferometry using either natural or satellite-generated signals, offer a means of monitoring large areas of particular social concern for the precursory motions that may precede a large earthquake. We recommend the establishment of denser networks of reference points in areas of particular earthquake concern and the measurement of deformation in these areas on approximately a monthly basis. The required measurement accuracy is 2 cm in each coordinate at the 95 percent confidence level. We do not know the time scales for anomalous tectonic motions before large earthquakes or whether such precursory motions are a general phenomenon. Any anomalous deformation would provide a timely alert system so that other instruments of different types could be installed in the

affected area. If no precursory motions were detected before a large earthquake using monthly observations, then more nearly continuous observation methods would be necessary to determine whether preseismic motions occur on shorter time scales.

The limited information available at present suggests that tectonic movements that occur a few hours to a few days before a large earthquake might be the most likely ones to provide a useful basis for earthquake prediction. The size of the area over which movements occur may be small, less than a few tens of kilometers in dimension. On such time and distance scales, both space and land techniques can be used to measure deformation to comparable accuracy. We recommend that an evaluation be made of the capability of space geodetic techniques for the continuous measurement of deformation in a seismic zone and that an assessment then be made of the relative advantages and economics of ground and space techniques for such continuous observations.

A large earthquake in the next decade in an accessible area would represent a major "target of opportunity" for measuring the postseismic deformation over a broad zone and for inferring from those measurements the viscous properties of the asthenosphere. The deformation should be measured as soon as possible following the earthquake to distances of at least 200 km from the fault plane and should be repeated at monthly intervals for as long as detectable motions persist. To accomplish such measurements, we recommend the development of a mobile space surveying capability that can be rapidly deployed in the event of a large earthquake within the epoch grid. Such a capability should include high-mobility space geodetic stations that can be available on short notice, along with the means for transporting the stations quickly to the possible areas of interest. Measurement accuracies of 2 cm in each coordinate at the 95 percent confidence level are required for most of the postseismic measurement period. Somewhat poorer accuracy would be quite useful for the initial postseismic measurements, in view of the large expected rates of motion.

For most convergent and divergent plate boundaries, at most one side of the boundary is above sea level, except for a few cases where suitable islands exist. Variations in tectonic motions along the land side of such a boundary can be instructive, but observations of variations across the boundary are required to define fully the time-dependent deformation associated with cycles of earthquakes and episodes of plate motion. We therefore recommend the development of methods for measuring the motion of the seafloor beneath several kilometers of ocean water and the determination of initial epoch positions of a number of points on the seafloor along plate boundaries in the western hemisphere and western Pacific. The sites should be chosen along plate boundaries with the highest expected rates of convergence or divergence. Position measurement accuracies of 10 cm or better are required.

3. *To measure the Earth's gravitational field from global scales to wavelengths of 200 km or less.*

Although it is generally agreed that the Earth's lithospheric plates are driven by some form of thermal convection, neither the planform nor the radial extent of this convection system is known at present. It has recently been suggested that convection in the mantle may occur on several scales. One scale that is directly observable is that associated with the motions of the plates themselves (for the Pacific plate the horizontal scale is 10^4 km). Another smaller scale suggested by laboratory and numerical experiments is one with dimensions of the order of the depth to the base of the convecting layer.

The planform of convection in the Earth's mantle should be visible in geologic and geophysical observations on the Earth's surface, such as topography, gravity anomalies, and heat flow. The principal problem is that the thermal and mechanical properties of the plates themselves tend to obscure the effects of deeper-seated processes such as convection. Nonetheless, mantle convection is expected to be discernible, at least in oceanic regions, in a correlation between long-wavelength ($\lambda \geq 1000$ km) gravity anomalies and long-wavelength topographic anomalies. On the basis of theoretical studies of mantle convection, this correlation would be expected to vary as a function of wavelength and should provide important new information on the planform of convection, the depth to the base of the upper-mantle convection system, and the viscosity structure of the mantle.

There is little currently known, however, of the correlation between long-wavelength gravity and topography anomalies as a function of wavelength on the Earth's surface. The main problem is that there currently does not exist a global gravity field of sufficient accuracy and resolution. While gravity measurements in land areas are of adequate coverage in North America, Europe, India, and Australia, they are sparse in South America, Africa, and Eastern Asia. Coverage of gravity measurements in oceanic areas is also poor over the oceans south of about 30° S, although it is good elsewhere.

At shorter wavelengths, gravity anomalies arise from the redistribution of mass associated with such geologic processes as basin formation, mountain building, and volcanism. Gravity anomalies, if coupled with topographic data of comparable resolution, can therefore help to determine both the subsurface structure and the state of equilibrium of the Earth's crust and upper mantle. In ice-covered regions, gravity anomalies can be used to outline buried basement structure.

Short-wavelength gravity anomalies also provide information on the mechanical properties of the Earth's lithosphere for time scales greater than about 10^6 years. The lithosphere responds to geologic loads such as sea-mounts, volcanic islands, and sediments in a manner similar to that of a thin elastic plate overlying a weak fluid foundation. By comparing observed gravity anomalies to model calculations it has been possible to estimate the

effective rigidity of the lithosphere and to demonstrate its variation with crustal age. This continuing area of research is providing new information on the rheology and state of stress in the Earth's lithosphere.

Preliminary studies indicate that it should be possible from space in the next decade to determine the global gravity field to a resolution of 200 km with an accuracy of better than 3 mgal. Thus, space measurements can provide information on such basic questions in geodynamics as the planform of convection in the Earth's mantle and are the only feasible means during the next decade of determining the gravity field in such poorly surveyed regions of the continents and oceans as the zone of continent-continent collision in Asia or the plate boundaries and seamount chains of the southern oceans. Space techniques, in addition, will provide gravity-field information at similar resolution and accuracy over land and oceans, a situation not possible using present methods of measurement. These data will be particularly useful for studies of the global mass balance of divergent and convergent plate margin zones and of planetary isostasy. Topographic data for poorly surveyed land areas will be necessary in order to interpret the gravity data; land topographic information of sufficient resolution and accuracy will be obtained as part of the objectives for continental geology, given later in this report.

MEASUREMENT REQUIREMENTS. Theoretical models of an elastic plate overlying a convecting layer indicate the resolution and accuracy limits on the gravity field that are likely to provide information on the form and viscosity structure of convection in the mantle. Small-scale convection is believed to have a characteristic length scale determined by the depth of the convection. For convection confined to the upper mantle (700-km depth) this would give an approximate lower wavelength limit of 700 km. There is not really an upper limit for the wavelength relevant to mantle convection. However, a wavelength range of 700 to about 3000 km would include the possibilities of both upper- and whole-mantle convection. Better resolution would greatly improve knowledge of the details of the flow patterns. For example, over portions of the oceans the properties of the plates themselves contribute little to the observed gravity field for wavelengths greater than about 200 km, although they may contribute to the topography.

It is difficult to put precise values on the required accuracy of the gravity-field measurements. Terrestrial measurements indicate that in the central Pacific Ocean the gravity field changes by 10 to 20 mgal over regions of unusually shallow seafloor around the southeastern end of the Hawaiian Ridge and the Line Islands. Since these gravity and depth anomalies may be maintained by some form of convection, accuracies of between 2.5 and 5 mgal would be required to define them adequately. Although it is not precisely known how the gravity field may vary over other topographic anomalies in

the oceans or over the continents, it is likely that a horizontal resolution of 200 km (full wavelength) and an accuracy of 2.5 mgal will be required in order to define satisfactorily the gravity field that may be attributed to convection.

4. To measure variations in the Earth's rotation and polar motion with increased accuracy.

Accurate measurements of polar motion and of variations in the Earth's rotation rate are needed in support of the measurements of plate motions and deformation in seismic zones by space techniques. For experiment durations of 2 days to 1 week for the determination of a site position, errors in the Earth's rotation and polar motion may cause comparable errors in the resulting coordinates.

The mechanisms responsible for variations in the Earth's rotation and polar motion are also of fundamental interest in themselves. Annual variations in pole position are thought to be caused primarily by seasonal shifts in atmospheric mass and changes in groundwater distribution, including snow and ice. Changes in the Earth's rotation rate over periods of up to a few years are believed to be due mainly to changes in the zonal winds. The dominant source of excitation of the Chandler wobble and the mechanism and rate of its damping, however, are not known. Meteorological effects may be the primary source of excitation, but whether they can account for the total observed amplitude, a question that depends on the damping rate, is uncertain. Torques on the base of the mantle due to turbulent motions in the fluid core have also been suggested as a source of excitation both for the Chandler wobble and for variations in rotation rate at periods in excess of a few years. Great earthquakes theoretically can cause sudden changes in the rate and direction of polar motion, which produce differences of a few centimeters in pole position after a few months. "Silent" earthquakes and slow pre-seismic or post-seismic movements may also help to excite the Chandler wobble. If fault motions are a significant source of excitation, then changes in the Chandler wobble would provide information on large aseismic fault motions that would be difficult to detect in other ways. Also, the contributions of any pre-seismic or post-seismic motions occurring over periods of weeks or more to the total seismic displacement for a great earthquake would be determinable.

Present astronomical measurements of latitude can determine the pole position to an accuracy of approximately half a meter if observations are averaged over 5 days. This measurement accuracy is not sufficient to determine if there is a correlation between large earthquakes and excitation of the Chandler wobble or to define the rate of damping of the wobble. Determination of the pole position to ± 3 cm by space-geodetic techniques should be sufficient to resolve these questions.

Differences in the Earth's angular orientation in space with respect to a reference system rotating at a uniform rate can currently be determined to an accuracy of about 2 msec of time, or roughly 1 m at the equator. This accuracy, derived from conventional astronomical observations at over 50 sites during a 5-day averaging period, is adequate to observe the annual and longer-term variations in rotation rate but is not sufficiently small to observe irregular variations at periods of a month or less. Measurements with 3-cm accuracy for a single day, in concert with worldwide meteorological measurements, should give new information about how rapidly the angular momentum in the zonal winds can be transferred to the solid earth.

MEASUREMENT REQUIREMENTS. Monitoring the pole position to ± 3 -cm accuracy at a 95 percent confidence level with a 2- to 5-day integration time is required to achieve the objective of measuring polar motion. This requirement appears to be achievable in the near future both with satellite laser-range measurements and with long-baseline radio interferometry, provided that worldwide networks of stations are used. Although the great Chilean earthquake of 1960 may have caused a change in the position of the mean pole of 50 cm or more, most large earthquakes are expected to give changes of only 10 cm or less. There is no expected change in the instantaneous pole position but only a change in the pole path at the time of the earthquake. Even for a large earthquake, the time necessary for the displacement between the new path and the original path to reach a magnitude of 3 cm may be as long as 2 months. This means that a measurement integration time as short as 1 day probably is not needed for pole-position determination. However, the accuracy and confidence level for the measurements must be as high as possible in order to be able to observe reliably the effects of the several large earthquakes likely to occur during the 1980's. Isolating these events from the effect of meteorological or other sources of change in polar motion will be difficult even with highly accurate measurements.

The requirement for monitoring deviations of the Earth's angular orientation from that expected for uniform rotation is 3-cm accuracy (0.06 msec of time) at the 70 percent confidence level for a 1-day integration time. From the results of the First GARP (Global Atmospheric Research Program) Global Experiment, it appears plausible that 3-cm variations from uniform rotation may be present over periods of about 2 days. A measurement integration time as short as 1 day thus is necessary in order to determine the time history and frequency of short-period torques on the Earth due to atmospheric winds.

5. To initiate the determination of large-scale vertical and horizontal motions in the interiors of the Earth's major tectonic plates.

VERTICAL MOVEMENTS

Large-scale vertical movements are thought to be caused by either tectonic forces or events involving large-scale load redistributions. One such event oc-

curred about 10,000 years ago when major glaciers in Canada, Scandinavia, and Siberia melted. Others are associated with the transport of sediments in rivers to the continental shelves and slopes and the erosion and weathering of continental regions. Vertical uplift at present is either measured by precise leveling surveys or deduced from long-term sea-level measurements at tide-gauge stations. Vertical uplift rates in excess of 1 cm/yr have been reported from leveling data for some areas in the eastern United States. There are serious disagreements between the results of leveling surveys and those from tide-gauge data, which indicate substantially smaller rates of uplift, severely hampering efforts to understand the geologic implications of such measurements.

Vertical movements related to postglacial load redistributions are particularly significant because they directly reflect the rheology of the mantle. The maximum rates of postglacial uplift occur in the central parts of areas deglaciated. Central Canada and central Fennoscandia are currently rising at about 1 cm/yr. The rates of central uplift are not particularly useful in constraining mantle viscosity, however. The pattern of present uplift or subsidence in areas peripheral to those deglaciated, on the other hand, is diagnostic of such aspects of mantle rheology as radial variations in viscosity and linear versus nonlinear flow laws. Determination of the peripheral uplift or subsidence pattern by space techniques in locations unrestricted to coastal areas would permit an improved determination of the radial viscosity profile in the Earth's mantle and an estimation of lateral variations in mantle viscosity. Accuracies for vertical rates of motion of about 0.1 cm/yr would be required.

MEASUREMENT REQUIREMENTS. The first measurement priority for vertical uplift in plate interiors should be to verify or refute by space-geodetic techniques the large rates of vertical uplift reported from the results of precise leveling measurements; ± 0.3 cm/yr accuracies are required. If these large rates of uplift are confirmed, their time variability should be assessed. If large rates of uplift are not generally observed, then the highest-priority measurement for vertical intraplate motions is to determine the pattern of uplift and subsidence peripheral to areas recently deglaciated to ± 0.1 cm/yr accuracy. The use of absolute gravimeters should be assessed as a possible adjunct to space-geodetic techniques.

The accuracies required for this measurement objective are unlikely to be available in the next decade. For baselines less than 1000 km in length, distance measurements of ± 2 cm at the 95 percent confidence level are feasible using space techniques. At longer baseline lengths, the uncertainties may increase. Vertical uplift uncertainties are more difficult to estimate and are likely to be larger. Thus the 95 percent confidence interval for the difference between two vector baseline measurements is expected to be about ± 4 cm in each coordinate. If these measurements were made over a 10-year period, the uncertainty in the rate of uplift at any point would be ± 0.4 cm/yr. This

accuracy is only barely adequate to begin addressing the questions of vertical uplift outlined above. For this reason vertical uplift measurements cannot be given high priority for the next decade, although they would be given high priority if measurement accuracies were 5 times greater than they are at present. It is expected, however, that measurement accuracy will improve with time, and even if this does not occur, data of the necessary accuracy could be obtained over a period of several decades. Because of the scientific importance of the pattern and magnitude of subsidence in certain tectonic areas and peripheral to deglaciated regions, it is recommended that measurements be initiated at benchmarks established along several lines in the continental United States and Alaska. In decades following the next, these benchmarks should be resurveyed using space techniques and the vertical motion determined with the ± 0.1 cm/yr accuracy required.

HORIZONTAL STRAIN

Determination of the motion of the Earth's major plates, the highest-priority objective, will require the demonstration that several long baselines within each plate are constant at measurement accuracies of 1 cm/yr. At smaller rates of change for many long intraplate baselines, internal deformation is strongly suspected on the basis of seismic and geologic evidence. Continental rifts occur, for example, in eastern Africa and in the western part of North America. Intraplate deformation has also been documented in Alaska, Asia, and the central Indian Ocean. Major earthquakes occur for poorly understood reasons in some intracontinental regions far removed from plate boundaries, such as the New Madrid seismic zone in the United States. Whether strain in such regions is episodic or steady, and whether it continues monotonically for geologically long times, is not known.

MEASUREMENT REQUIREMENTS. To study the processes of intraplate horizontal deformation, a greater measurement accuracy (0.1 cm/yr) is required than for the measurement of plate velocities and of deformation in plate-boundary zones because the rates of internal plate deformations are expected to be substantially smaller than the motions of the plates themselves. Thus unless measurements of plate stability indicate that intraplate strain changes substantially more rapidly than expected, it will be sufficient within the next decade to establish epoch baselines across several major zones in which horizontal deformation is indicated by geologic information, so that the rates of intraplate deformation can be determined in succeeding decades.

III. OBJECTIVES FOR CONTINENTAL GEOLOGY

Introduction

The Earth's crust can be conceptually divided into three parts. One part consists of the solid rocks exposed at the surface of the continents and on the

floors of the oceans. The nature of these rocks, and their structural and stratigraphic relationships, have permitted geologists to infer the physical and chemical properties of the crust to depths of a few kilometers. The deeper crustal rocks comprise a second part. Geophysical methods have been employed to define the base of the crust and the general nature of the deep crust and underlying mantle, but the detailed configuration and composition of deep crust, particularly on the continents, is not known. A third part of the Earth's crust is the thin veneer of soils, sediments, water, and ice, which are the agents or products of the erosion and modification of the Earth's crustal surface. In terms of planetary volume, this third outer part is inconsequential. When viewed from its surface or from space, however, this outer veneer takes on extreme significance, because it holds the clues to the nature and rates of processes that have been operating to form and modify the Earth's crust throughout its history. In many parts of the Earth, it is also a mask that must be penetrated to understand the nature of the underlying solid rock.

In the last two decades, we have experienced a profound revolution in our perception of the Earth, owing first to the exploration of the ocean basins and the development of the theory of plate tectonics and second to the exploration of the planets and the global views and comparisons of these bodies. We know that the continents and ocean basins are underlain by two types of crust that differ fundamentally in terms of composition, structure, age, and mode of origin. Masses of continental and oceanic crust are embedded in the lithospheric plates. The major aspects of the Earth's tectonic processes and the geologic structures they create are now known to be related to the relative motion and interaction of these plates. The present ocean basins are comparatively well understood in terms of the formation of new oceanic crust and lithosphere by the process of seafloor spreading. Two decades ago, folded mountain belts (Alps, Appalachians, Andes) were viewed independently of other major geologic features. Plate-tectonic theory provided the framework in which mountain building can be understood as a product of plate convergence and continental collision. The general classification of volcanic deposits in terms of edifice shape and deposit geometry (e.g., flood basalt, stratovolcano, shield volcano) has matured into an understanding of the location, composition, and style of volcanism relative to divergent and convergent plate boundaries. Clues to the formation and growth of continents have been provided by the nature of processes currently active at plate convergence zones. Although most tectonic and volcanic activity occurs at or near the boundaries of the plates, significant activity is often localized in intraplate regions; the relationship of this activity to plate tectonics or to sublithospheric processes, however, is not well understood.

The understanding of many of the processes responsible for the thin, outer veneer of the crust has also progressed. Concentrated field studies of specific features (rivers, glaciers, active volcanoes) have provided a few well-

known examples in which the basic processes and rates are becoming known. Studies of present sedimentary and tectonic environments, unified by plate-tectonic theory, have permitted the construction of a framework in which the environments represented by ancient crustal rocks can be reconstructed and interpreted.

Despite our improved understanding in the last two decades of the global interlinking of geologic processes on the Earth, we nonetheless find ourselves facing a series of fundamental, significant, and challenging geologic questions as we enter the next decade. One of the most fundamental questions is when plate tectonics first became the major process shaping the Earth's crust. At issue in this question is the Earth's heat budget, the history of mantle convection, and the dynamical evolution of the crust. The ocean basins preserve only the most recent 200 million years of plate-tectonic history. The record of the first 95 percent of Earth history is to be found in the continents. We have not yet characterized the rocks and structures of the continents well enough, however, to extrapolate confidently present tectonic processes back into early Earth history.

We do not fully understand the chemical and physical processes that have controlled the generation and evolution of the continents. The present configuration of plates and their interaction provides clues to many of those processes. Zones of active continental collision are characterized by structural features and rock types that can be recognized in the ancient sutures marking the continental collision zones of the past. Zones of continental rifting and separation, and of rift systems that failed to lead to continental drift, can also be identified. It appears that a region of large-scale deformation during one geologic era can act as a locus for deformation during later tectonic events. A major question for continental tectonics is the mechanism by which large interior regions within each of the continents became stabilized against major deformation for billions of years. The volumetric growth of continental crust with time is also poorly understood. Recent mapping of rocks in western North America, for instance, has revealed a series of small fragments of island-arc and continental material that were derived from elsewhere and were subsequently accreted onto the continent. The degree to which this aspect of continental growth has operated on a global scale is poorly known because our knowledge of the composition, structure, and distribution of continental rock units over much of the planet is incomplete.

The nature and controlling mechanism of intraplate volcanic and tectonic processes are poorly understood. Planetary exploration has shown that Mercury, Mars, and the moon are characterized by a single global lithospheric plate, in contrast to the multiple tectonic plates on the earth. Intraplate volcanism and tectonics are common to all the terrestrial planets, and a study of these phenomena on a planetary basis may prove fruitful for understanding

their role for the Earth. The relative importance of intraplate and plate boundary activity, for instance, is poorly known for the first half of earth history—the Archean—when the global heat flux was much greater than at present. Venus, with its higher surface temperature and presumably thinner lithosphere than the Earth's, is regarded by some as a testing ground for tectonic theories of the Earth's Archean.

Knowledge of specific time-variable geologic processes within the global system is also fragmentary. For example, certain types of volcanoes are found in association with specific plate boundaries, and we recognize the general cause-and-effect relationships. However, we do not understand why these structures occur at some places along a boundary but not at others. A major contribution to this understanding would be a comprehensive global inventory of volcanic structures and their geologic characteristics. A similar situation exists for other landforms and structures (such as glacial, fluvial, eolian, permafrost, and tectonic features), which precludes a complete understanding of these processes in terms of a global system.

The rates and scales at which major geologic processes operate to modify the landscape are incompletely understood. Determination of these quantities requires observations over both a long term and a global scale. For example, in the past few decades, major floods occurring only every century or so in many parts of the earth go largely unstudied because of their isolated and ephemeral nature; the role of major floods in the global budget of continental erosion and deposition is therefore poorly known. Such information on global geomorphic processes is essential to the understanding of the rates of change of our landscape, such as the migration of deserts, and to the assessment of the hazards represented by geologic activity such as volcanic eruptions.

Geologic studies have shown that mineral and petrochemical resources do not occur randomly in the Earth's crust. Known locations have been extensively studied in order to document the mode of occurrence of the resources and to attempt to understand their processes of emplacement. At present, our understanding of resource location is often based largely on empirical correlations. A major challenge for the next decade is to develop a global framework for understanding resource location and emplacement that has predictive capability.

The Committee concludes that answers to these fundamental questions are commonly linked to an understanding of the origin, evolution, composition, and structure of the shallow continental crust. Since the distribution of this crust is global, we can expect to achieve major advances in understanding crustal dynamics and evolution only if a strategy for investigation adopts a similar scale and builds on the framework established by the plate-tectonic theory.

The advent of instrumented platforms in polar orbit has provided a significant new approach to crustal studies since all the continents can be sensed repeatedly over a relatively short time scale. This technique allows a standardized base for continuous observation and uniform measurements of all land masses, including the very remote areas, which would result in a substantial improvement in the current geologic maps of the continents. Further, a variety of platform instrumentation can provide information at different wavelengths to maximize the information derived from data analysis and interpretation. A range of synoptic resolutions will provide viewing fields much larger than obtainable by aircraft as well as high-resolution capability for smaller fields. Lastly, orbiting platforms are uniquely capable of repeating measurements where previous cloud coverage, seasonal changes, or temporal events make additional observations necessary. Space platforms can provide a substantial contribution and complement to ground-based and airborne investigations and can have a major impact on our understanding of the continental crust.

Scientific Objectives

The primary scientific objectives for the study of continental geology from space for the next decade, in order of priority, are

1. *To determine the global distribution and composition of continental rock units,*
2. *To determine the morphology and structural fabric of the Earth's land surface,*
3. *To measure temporal changes in geologic conditions at the Earth's surface.*

The first two objectives are complementary, are approximately equal in importance, and should be accomplished in a balanced and interactive fashion. Their priority reflects our expectation that knowledge of the global distribution of composition and structure will provide linking information to the history of continental crust. The third objective requires as a first step that the present distributions of rock units, and their composition and structure, be established.

The objectives for continental geology are all long term in nature. Achievement of the objectives will not be fully accomplished in a single step, but substantial progress toward these objectives and fundamental improvements in scientific understanding can be achieved during the next decade.

An obvious societal goal is to understand the global distribution and geologic context of the Earth's mineral, metal, and energy resources. Achieving

this goal requires understanding the basic processes that are responsible for these deposits. The processes that lead to the formation of ore deposits are often expressions of global phenomena. Some metal deposits, for example, result from hydrothermal activity associated with divergent plate boundaries. While space observations are not likely to lead directly to new discoveries of resources, space measurements combined with airborne and ground observations can lead to an improved understanding of the geologic setting and formative processes for resource emplacement.

Measurement Requirements

In attempting to discern the physical and chemical properties of a planet and the dynamics of its operative processes, no single type of measurement or observation satisfactorily and fully suffices. The primary scientific objectives for continental geology are no exception to this rule. For each of the stated objectives, there are several research tools that can contribute toward the achievement of the objective. The measurement requirements for the area of continental geology thus are based on the expectation that progress toward each primary objective will occur by a variety of global measurements, each type of which will address a different aspect of the overall objective.

The Committee has reviewed the state of the art of techniques for remote sensing in geology. Certain techniques and measurements are sufficiently well defined to be applied in space, and their potential for advancing geologic understanding and for geologic applications is such that they should be applied at an early opportunity. Other methods have been developed through the laboratory stage but have not been fully tested in a field environment. Still other promising techniques for remote sensing are at an earlier conceptual or definition stage. Because of the different degrees of development of potentially useful remote-sensing tools, *the program of research necessary to achieve the scientific objectives for continental geology must strike a balance among space measurements using proven remote-sensing methods, development of space-measurement systems employing techniques shown to be useful in laboratory and field experiments, and additional laboratory and field work to test the promise for remote sensing of new types of measurement.*

1. *To determine the global distribution and composition of continental rock units.*

Rock compositions indicate the sources and compositions of their parent materials and the basic processes responsible for their formation. The distribution of rock units indicates the extent to which these formation and modification processes operated and the direction and magnitude of crustal deformation. Such deformation is indicative of the kind and extent of dynamic processes in the Earth's crust.

The determination of the distribution and composition of major rock units on the continents ideally involves not only the discrimination and boundary definition of the various rock units but also the measurement of the abundances of major elements and principal minerals in the individual rock types. While the complete specification of chemistry and mineralogy of continental rock types will probably never be achievable from space, a substantial advance would result from the ability to sense remotely the major rock-forming minerals of the continental crust (feldspar, pyroxene, quartz, olivine, carbonates, and their weathering products, particularly clays) and to be able to distinguish variations of a few weight percent or less in the abundances of silicon and other major cations. In addition, it would be desirable to be able to sense the distribution and composition of a number of less abundant rock and mineral types, such as hydrothermal alteration products, because of their association with zones of mineralization.

Many, if not all, of these rock and mineral types can be sensed remotely from space using techniques either well developed or currently envisaged. Techniques for the remote sensing of rock type can be divided into two classes: those that measure mineralogy directly and those that measure morphological expression or bulk properties from which rock-type information can be inferred.

The techniques that directly measure the mineralogy of the surface materials depend on electronic and molecular absorption or re-emission of energy from the sun. There are currently several problems in applying these techniques. Absorption and scattering in the atmosphere block entire spectral regions and also reduce scene contrast in atmospheric "windows." In the mid-infrared region, thermal emission from the atmosphere and variations in surface temperature complicate the measurement. Detector sensitivity and the absolute energy level at the desired wavelengths are the primary factors limiting bandwidth and spatial resolution; this is particularly true for spacecraft operations where the velocity of the measuring device is dictated by the spacecraft altitude. Vegetation contaminates and blocks measurement of surface material, although there are indications that the spectrum and other properties of vegetation itself will yield some information on the underlying rock type. Even when no vegetation exists, the surface material is usually a product of weathering, and the unweathered rock type often must be inferred from an understanding of weathering processes.

At visible and very-near-infrared wavelengths in the electromagnetic spectrum, a variety of Fe^{2+} - and Fe^{3+} -bearing rocks and minerals can be distinguished. Mafic minerals such as pyroxene and olivine have strong Fe^{2+} absorptions near $1 \mu\text{m}$ (Figure 1). The spectrum continuum shape (color) at visible and near-infrared wavelengths has been shown to contain compositional information even when well-defined absorption bands are not found.

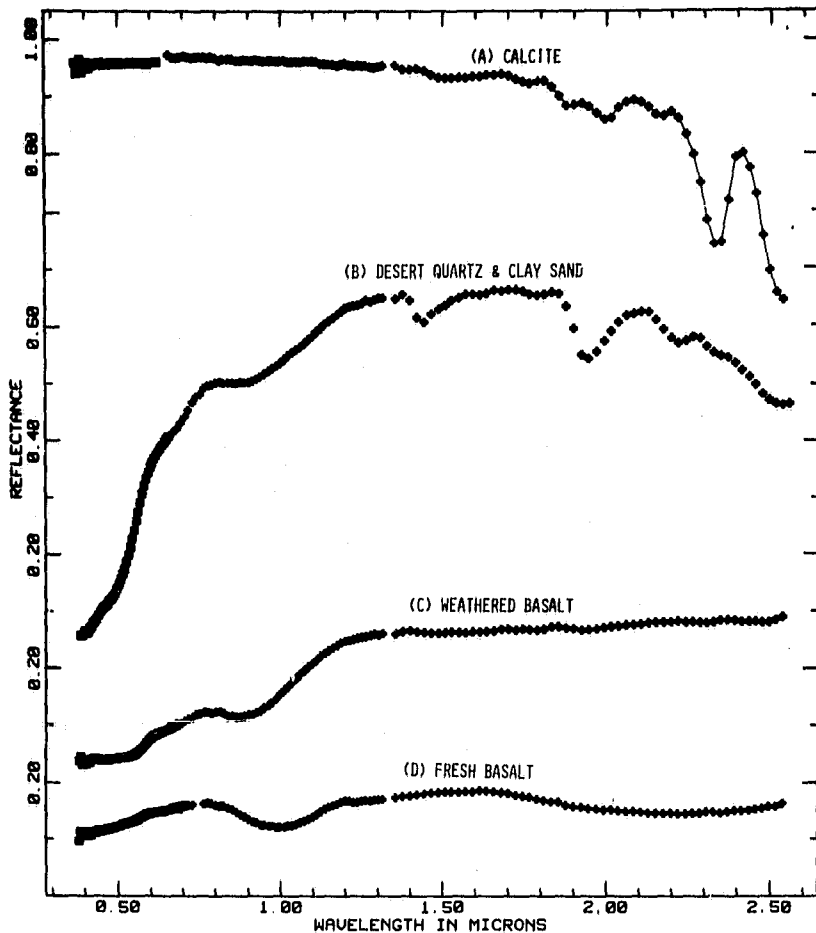
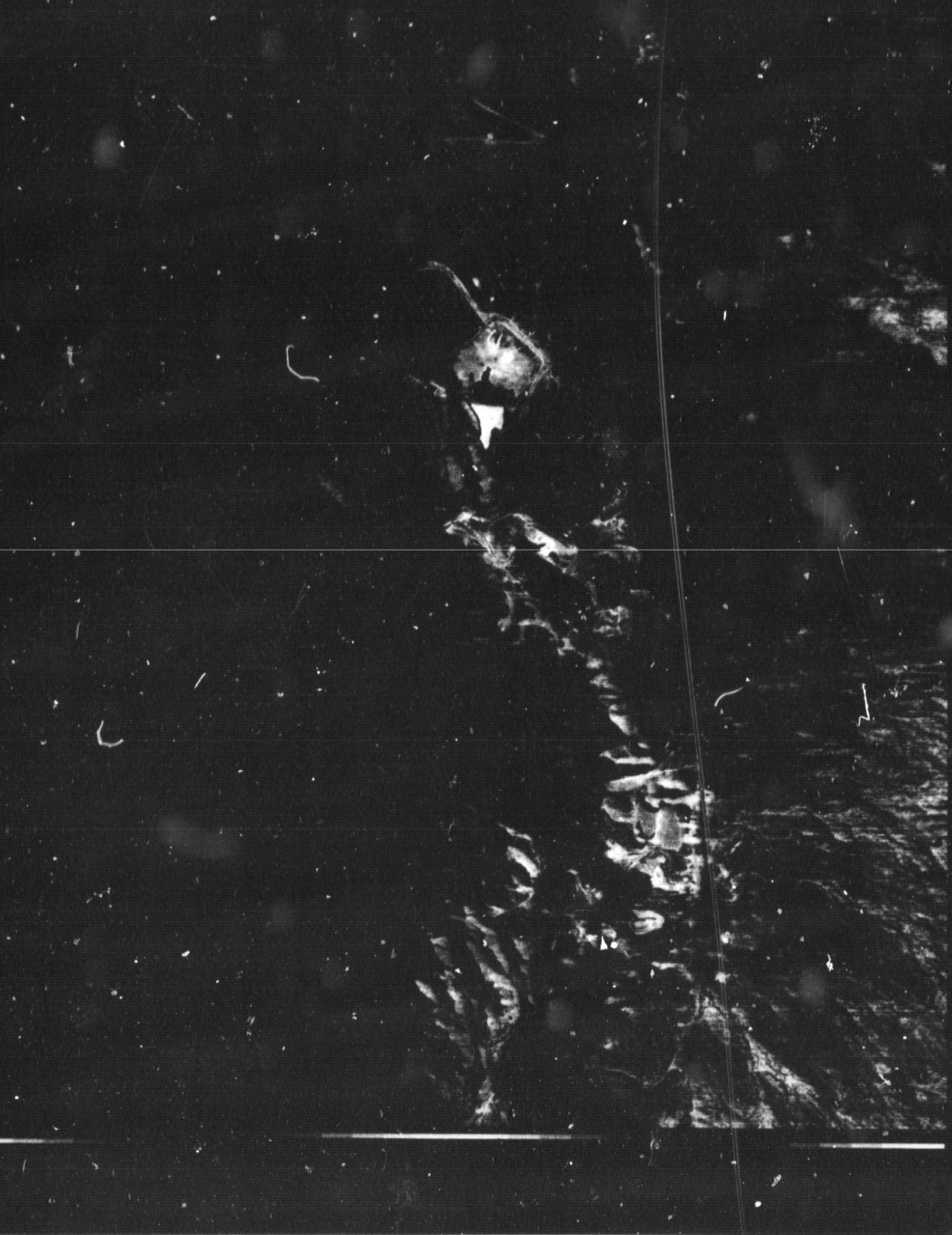


FIGURE 1 The spectral reflectance as measured in the laboratory of four naturally occurring terrestrial rocks. Electronic and molecular absorption bands are evident in this spectral region, where reflected sunlight is the dominant contribution. Spectrum A is for a calcite sample and shows the carbonate molecule bands in the 2.0–2.5 μm spectral region. These bands are different for different carbonate minerals. Spectrum B is for a mixture of clay and iron-bearing quartz sands from central Egypt. The Fe^{3+} absorptions from the oxidized iron is evident in the visible spectral region, and Al-OH absorptions are present at 2.25 μm . Water absorptions appear at 1.45 and 1.95 μm . Spectra C and D are for more and less weathered olivine basalts, respectively, from Kilauea, Hawaii. The oxidized iron (Fe^{3+}) absorption is more evident in spectrum C. An Fe^{2+} absorption toward the ultraviolet portion of the spectrum (near 0.4 μm) is evident in both spectra, as is the Fe^{2+} absorption, due to olivine and pyroxene near 1.0 μm . These spectra are quite different from one another, and the absorption bands yield diagnostic information on mineralogy, especially when the spectra are displayed and analyzed on an expanded scale.

48

FIGURE 2 Multispectral image of the porphyry copper test site in Silver Bell, Arizona. The image is a color ratio composite, with ratios $1.6 \mu\text{m}/2.2 \mu\text{m}$, $0.66 \mu\text{m}/0.56 \mu\text{m}$, and $0.83 \mu\text{m}/1.15 \mu\text{m}$ displayed as red, green, and blue, respectively. These ratios were selected to define areas of mineralogy associated with hydrothermal alteration zones. Areas with high iron content are green, areas with high clay content are red; where both occur, the image displays yellow-orange. The yellow-orange and pink areas identify intensely altered rocks and open pits associated with the copper-molybdenum mineralization. They correspond accurately to alteration zones mapped from months of field and laboratory work. The area shown has dimensions $11 \text{ km} \times 16 \text{ km}$.



Fe^{3+} -rich deposits, particularly hydrothermally altered materials, have been mapped from space using Landsat multispectral scanner images.

The solar-reflected infrared region, 1–3 μm , provides more diagnostic spectral information about the composition of minerals and rocks than does the visible region. There are strong atmospheric absorption bands at 1.4 and 1.9 μm due to water vapor, but the adjacent spectral regions are well suited for remote sensing from space (Figure 2). The region around 1.6 μm exhibits the highest reflectance for most rocks because it is nearly midway between the ultraviolet-visible iron absorption bands and a strong fundamental OH vibration at 2.74 μm . The region from 2 to 2.5 μm contains a number of diagnostic absorption bands for hydrated silicates and for carbonates.

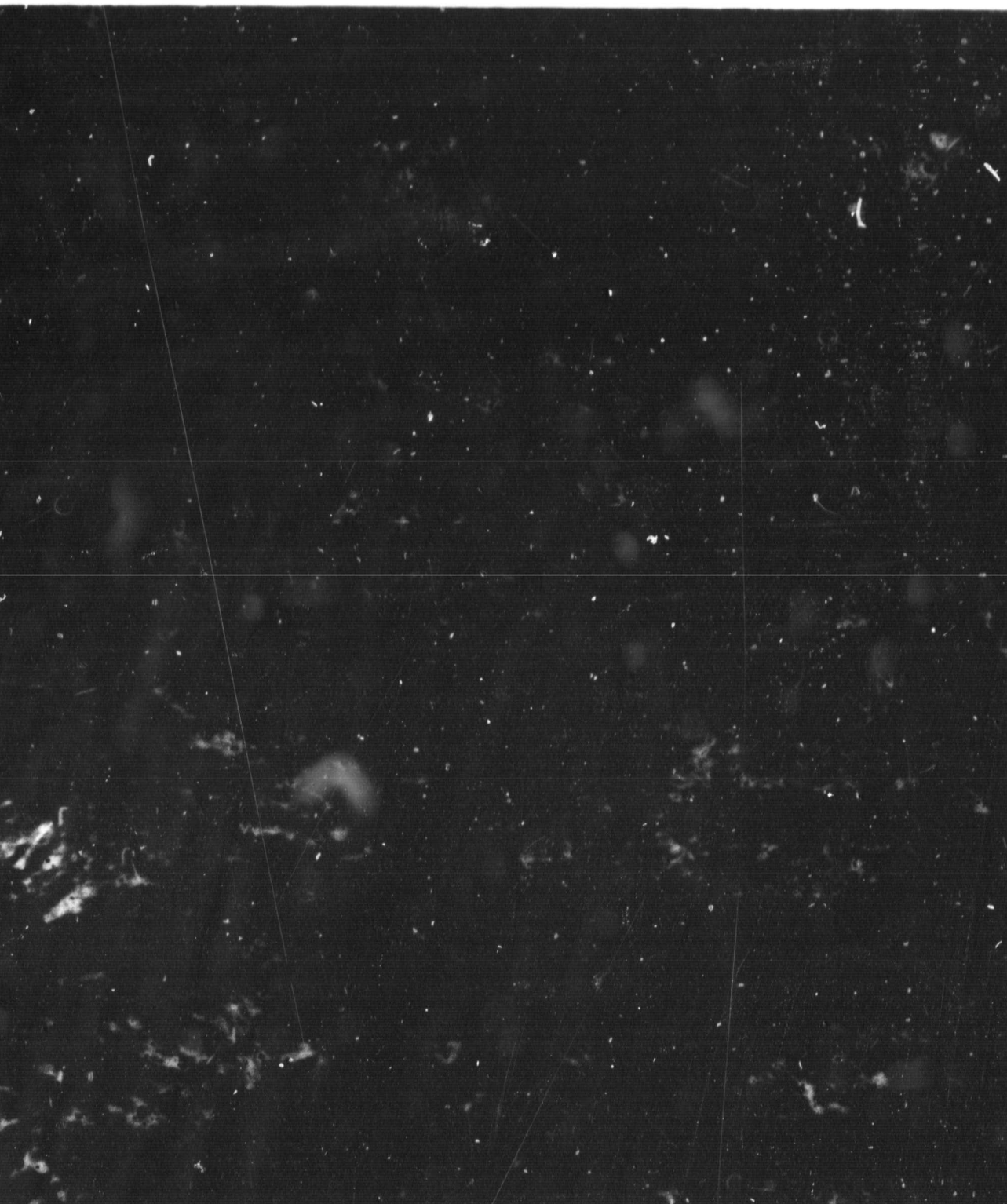
Considering the state of instrument and technique readiness, the Committee recommends that global imaging in the 1.5–1.8 μm and 2.1–2.4 μm bands, as well as bands in the shorter-wavelength regions of the visible and near infrared, be conducted at the earliest opportunity. These passbands will provide new, first-order compositional information not available by other techniques in the near term. The measurements should be made with a digital imaging system to permit optimum information return using image-processing techniques.

The Committee is informed of and impressed by a number of additional instrument concepts whose wavelength regimes and measurement precisions could substantially increase the capability for determining rock composition from space. These concepts are listed below in an approximate order of priority that reflects their current level of development and their potential to address systematically the primary science objective within the period of this strategy. The order also indicates an increasing level of instrument complexity leading to greater combined capability for rock-unit discrimination. The Committee urges NASA to support vigorously the continued development of these instrumental types at a pace commensurate with the fulfillment of this strategy by the end of the decade.

The 2.0–2.5 μm spectral region is of particular interest because it contains narrow, highly diagnostic spectral absorption bands for hydrated silicates, important as both weathering and hydrothermal alteration products, and for carbonates. The Al-OH band at 2.2 μm has been used in the laboratory to identify some clays. The potential of the carbonate absorptions is less well defined but could be equally important. A set of narrow passbands appropriate for detecting the Al-OH absorption from space has been selected, and a Shuttle experiment (the Shuttle Multispectral Infrared Radiometer) is scheduled to test the concept. The Committee requests that it be informed of the results of this experiment so that it may better assess the impact of this narrow multiband approach for a future mapping capability.

The mid-infrared region from 8 to 14 μm is especially important because

FIGURE 3 Color-composite image of the East Tintic Mountains, Utah. Six channels of multispectral mid-infrared (8 to 14 μm) aircraft scanner data were acquired. This area has high relief and moderate vegetation and consists mainly of Tertiary silicic igneous rocks and Paleozoic quartzite and carbonate rocks that have been locally hydrothermally altered. These digital-image data were computer processed to create a color-composite image based on principal component transformations. Color differences in this image are related to the spectral differences in the surface material. When combined with a visible and near-infrared color-composite image from a previous flight, with limited field checking, it is possible to discriminate several rock types, depending primarily on their silica content. A, B, quartzite; C, D, E, interbedded sandstone, limestone, quartzite, shale, dolomite, and chert; F, silicified rocks; G, mine areas; H, Dragon mine; I, argillized rocks; J, quartz latite and quartz monzonite; K, latite and monzonite; L, vegetated areas; M, calcific quartz latite; N, O, carbonate rocks; P, hydrothermal dolomite; Q, mine tailings and ponds.



spectral emittance variations provide a basis for distinguishing silicate and nonsilicate rocks and also for discerning small differences in the silica content of rock, a basic index for determining rock type. Laboratory measurements, theoretical calculations, and an airborne study have shown that a few passbands in this spectral region can distinguish silica content and, therefore, important silicate rock types (Figure 3). The scientific return from this technique is likely to be as high as for any other method of sensing rock type remotely. The early state of development and the complexity of the technique have been considered in determining the relative priority of this task.

In the visible and near-infrared spectral regions to $2.5 \mu\text{m}$, the photometric precision of spectral reflectance measurements of the Earth's surface have not been generally sufficient to reveal most of the mineralogical information present. Weathering and mixing reduce spectral contrasts. Current techniques measure principally changes in the spectrum continuum but cannot resolve, for instance, the diagnostic electronic transition bands of most Fe^{2+} -bearing minerals between 0.9 and $1.1 \mu\text{m}$. These bands are being used successfully to map mineralogy on the lunar surface, where the required photometric precision of better than 1 percent has been achieved. Preliminary laboratory studies of naturally occurring terrestrial surface materials have shown important spectral features when this photometric precision is achieved. To achieve this precision in terrestrial applications, calibration techniques must be developed to remove atmospheric effects. As precision improves and spectral features become better defined, higher spectral resolution to a limit of about $\Delta\lambda/\lambda \approx 0.01$ will be required. The Committee recommends continued development of the capability to image at radiometric precisions of better than 1 percent, using many narrow bands with a spectral resolution of about $0.01 \mu\text{m}$ in the visible and near-infrared regions. This capability will permit the remote sensing of most of the abundant rock-forming minerals of the continental crust.

Indirect indications of rock type can also be derived from textural and bulk properties of surface material over a wide range of spatial scales. The weathering history and environmental conditions are at least as important as the rock type in controlling these properties. Identification of specific rock type from such remote observations is not always possible without ground truth, because the same rock type may have different properties under different weathering conditions. Distinguishing between units of differing rock type, however, is more readily accomplished even when specific rock types cannot be determined.

Theoretical models and airborne experiments indicate that additional information about textural and bulk surface properties can be obtained by using multifrequency, multipolarization radar images. Simultaneous observation, at two or more frequencies, of the polarized and depolarized components can permit the characterization of surface roughness units and surface cover

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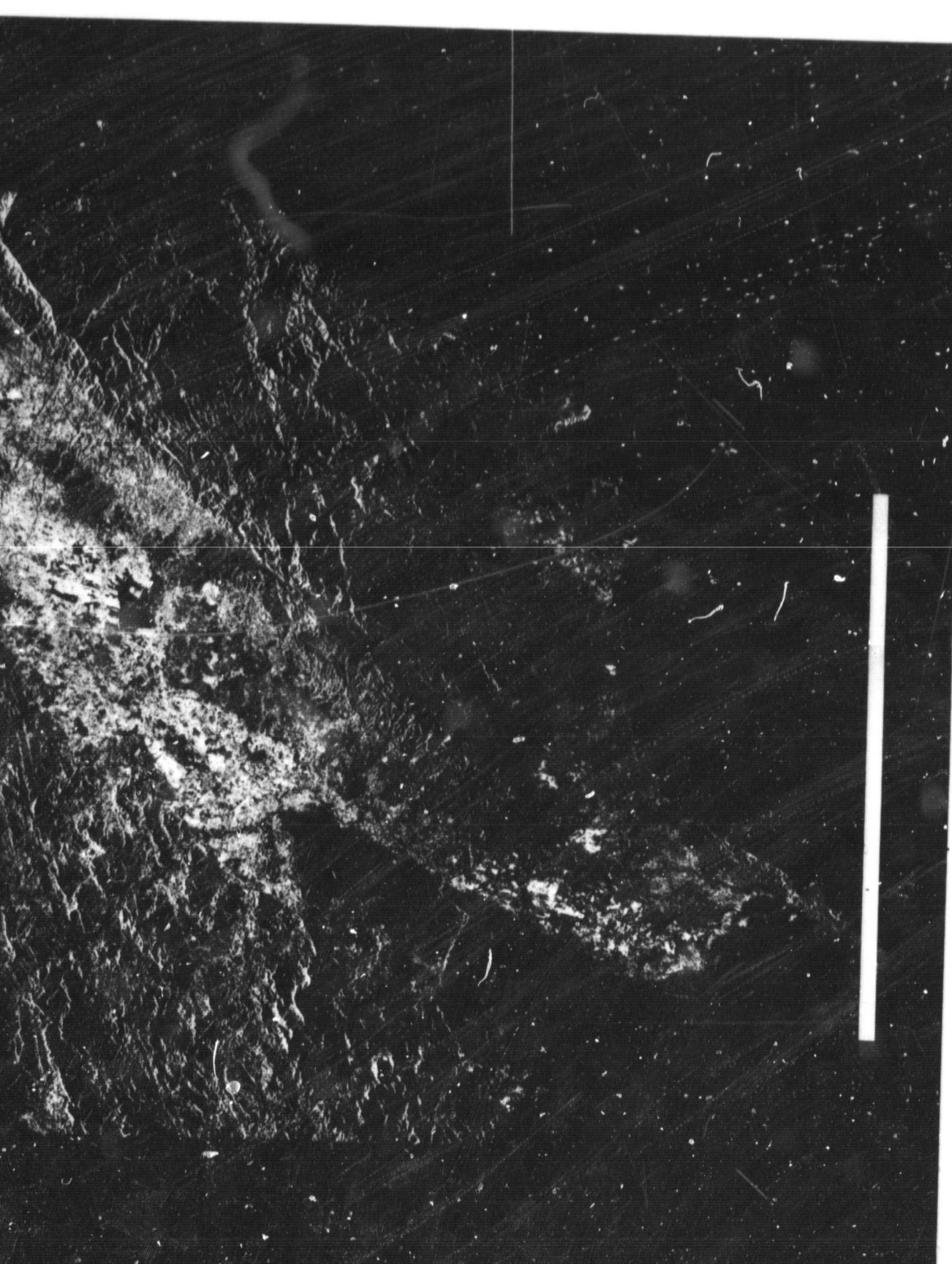
The image is a Seasat radar scan of the northern Dominican Republic. It shows a 100 km by 100 km area with 25-meter resolution. The radar illumination is from the top. The image is divided into three main regions: a fine-textured karst area in the lower left, a rugged mountainous area in the upper left and right, and a flat alluvial plain in the middle. Curvilinear shapes in the lower right indicate beach terraces.

FIGURE 4 Seasat radar image of the northern region of the Dominican Republic. Three major geologic units of different age are visible on the image as a result of their topographic texture. The tertiary limestones give rise to a characteristic karst topography. This unit can be seen at the lower left of the image as the area with very fine texture. Cretaceous and older volcanic, sedimentary, and plutonic rocks underlie the region of the rugged mountainous topography at the far upper left and right side of the image. The flat-lying region across the middle of the image corresponds to the Recent alluvial plain of Rio Yuna. The curvilinear shapes around the peninsula in the lower right portion of the image correspond to beach terraces resulting from the uplift of that region. This image covers a 100 km \times 100 km region with 25-m resolution. North is toward the right of the image. Radar illumination is from the top.



units as well as the separation of surface scattering from volume scattering. Rock-type discrimination has been possible from images obtained by the synthetic-aperture radar on Seasat (Figure 4), and a similar radar-imaging experiment is planned for the Space Shuttle. We recommend that development of a flexible spaceborne radar system, with multipolarization and multifrequency capability, be developed to determine the extent to which such a radar capability can effectively discriminate rock types and rock units on a global basis.

One of the most useful bulk physical properties measurable from space is thermal inertia because of its direct relation to the ability of surface material to conduct heat into and out of the interior. The thermal inertia is primarily sensitive to changes in surface density and thermal conductivity, and the properties controlling these parameters are mainly rock type, soil moisture, and the degree of compaction of the surface material. Observation of the diurnal (or seasonal) temperature cycle of a surface can yield the average thermal inertia in the top several centimeters (or several meters) of the underlying material.

Recent thermal inertia measurements (Figure 5) indicate the discrimination potential of combining thermal inertia mapping and visible wavelength imaging. Thermal inertia is complementary to such surface properties as spectral reflectance and emissivity. With thermal inertia measurements, rocks with similar reflectance but different thermal properties, such as limestone and dolomite, can be distinguished. Further, it has been possible with thermal data to distinguish bedrock from alluvium and to discriminate among several different spectrally bland, dark volcanic rocks on the basis of their thermal properties. It is clear, however, that in order to achieve the maximum benefit from techniques combining thermal inertia and other measurements, the resolutions will have to be comparable. For example, thermal inertia measurements combined with Landsat-type multispectral data will have to achieve resolutions of less than 100 m.

Currently available results show that remote sensing from space can differentiate a number of rock types and can distinguish among at least some constituent mineralogies. New techniques providing additional data over a wider spectral range will considerably improve our diagnostic capability, based on recent research and on ground and aircraft field tests.

A key question is how much of the continental land surface is available to mapping of rock type from space. Vegetation and clouds limit the areal coverage of the exposed landmass using the visible and IR portions of the electromagnetic spectrum, where rock type and mineralogical discrimination potential is best documented. Rock type is most easily determined for the 20 percent of continental area that is mostly free of vegetation; in such regions rock outcrops or weathering products may be viewed directly at most times of year. Additional areas, where the vegetation cover is only partial or seasonal,

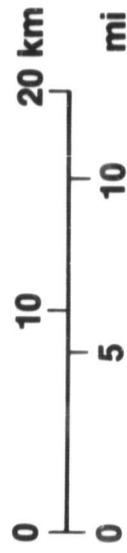
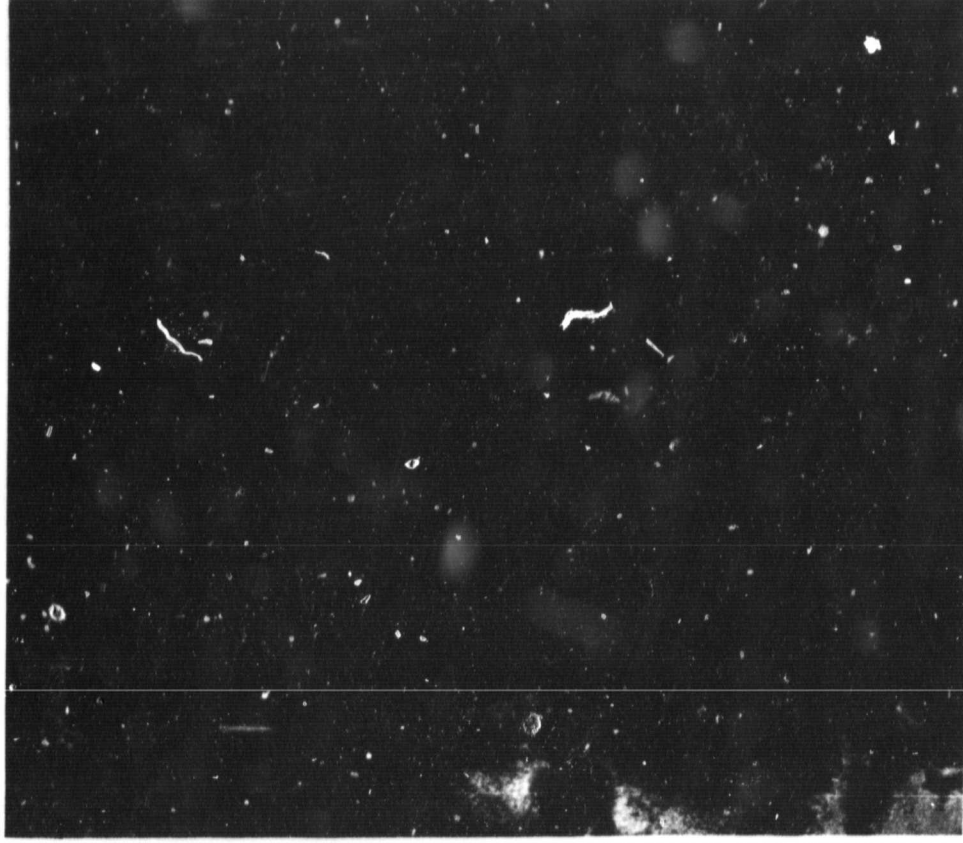
FIGURE 5 HCMM (Heat Capacity Mapping Mission) and Landsat images of an area near Pisgah, California, at the same scale. The HCMM image is a combination of visible (green), day IR (blue), and night IR (red). All three components were complemented, so areas that are either cold or have low albedo appear bright (colored). For example, Lavis Lake playa is red because it has high albedo (dark in green), is warm during the day (dark in blue), and cold at night (bright in red). The Landsat image is a principal-component composite, chosen to maximize separability of units. Landsat obviously provides more detail (80-m versus 500-m resolution); however, many of the bedrock units have similar appearances on Landsat images. On the HCMM image these rocks can be delineated and distinguished (but not identified). For example, the biotite quartz monzonite in the south-central edge of the image and the lava flows look similarly dark on the Landsat image but are orange and green, respectively, on the HCMM image, because of differences in thermal properties, even though they are both spectrally dark. Similarly, the pahoehoe and aa flows of Pisgah (center) are more easily separable on the HCMM image because of their differing thermal properties. The separation between bedrock (on the left, just above center) and alluvium derived from that bedrock (shed northward from the bedrock) is much sharper in the HCMM image, again because of different thermal properties. Similar spectral properties of bedrock and derived alluvium mask this contact on the Landsat image.

PISGAH, CALIFORNIA TEST SITE

HCMM



LANDSAT



DAY IR (BLUE) + NIGHT IR (RED)
+ VISIBLE (GREEN). ALL COMPLEMENTED

PRINCIPAL COMPONENTS
COMPOSITE

(IMAGE CENTER: 34°40'N, 116°25'W)

can be usefully surveyed. It appears that rock type can be inferred in some cases even in heavily vegetated areas, using the effects of soil chemistry on vegetation and the general land morphology, but the extent to which inferential techniques can be applied is not yet known. Rock-type maps of even the most easily observed 20 percent of the continent would represent a substantial advance over existing information. Most areas of the continents can be viewed free of clouds at some time, but sufficient repetitive observations are required.

To be generally useful, the spatial resolution for all of these remote-sensing techniques should be less than the smallest horizontal dimension of the major continental rock units. At the same time, the resolution must be compatible with existing technology for sensors and for the transmission and processing of data. In view of these needs, a horizontal resolution of 30 m for spectral and radar measurements and of 100 m for thermal inertia measurements appears to be required to make a significant contribution toward determining the global distribution and composition of continental rock units and, at the same time, to be technologically achievable either currently or in the near future. The resolution in terms of rock type and mineralogy is much more difficult to specify because it depends on the particular geologic problem that would be addressed using the remotely sensed data. In many cases it would be sufficient to distinguish only among major lithologies (e.g., sandstone, limestone, shale, granite, basalt), while in other cases small variations in lithology or mineralogy can be important.

2. To determine the morphology and structural fabric of the Earth's land surface.

One of the most significant keys to unraveling the geologic and tectonic evolution of the continental crust lies in the geometry of structural features at and beneath the Earth's surface and the spatial relationships among them. Such structural features, which range in size from continental scale to morphologic indicators a few centimeters in dimension, are controlled by past and present tectonic deformation, rock properties, and erosional factors. It is a major challenge to distinguish among the various structural features, discern their relative age relationships, and interpret in a global context the dynamical geologic processes that created them. Since most areas of the Earth's land surface are covered by weathering products and vegetation, surface structure must often be inferred from morphologic texture. Areas of dense vegetation are frequently inaccessible and in many cases represent areas of the Earth's surface where the least geologic data are available. Space provides a vantage for determining structure for all continental areas. Such global coverage is essential for testing tectonic models, for comparing the tectonic history of specific geologic settings, and for comparing geologic structures on Earth to those of other planets.

The synoptic view of continental structural features afforded by space has played an essential role in the development of current ideas on continental tectonics. Landsat images provided key information in support of the recent conclusion that the north-south convergence of India and Eurasia is partially accommodated by large displacements on prominent east-west trending strike-slip faults in China and Mongolia. With this observation came the general recognition that the collision of two continental land masses leads not only to the development of a major mountain belt such as the Himalayas but also to a broad zone of intracontinental deformation localized on major faults at distances of up to 2000 km from the plate suture zone. On the basis of this new understanding of the tectonics accompanying continental collisions, further study of space images of recent and ancient suture zones within the continents and of the structural features in the surrounding areas is likely to be an extremely fruitful area of research for the next decade.

Space imaging has contributed as well to an improved understanding of other surface processes and features. Space observations of regions in north Africa sculpted by wind erosion led to new ideas on the relative roles of eolian and fluvial erosional processes in deserts. Images from Earth orbit have aided in the study of the drainage systems of large rivers and of the dynamics and geologic effects of glaciers in inaccessible regions. Landsat photographs have been used to identify previously unknown craters of probable impact origin.

The space images to date of surface structural and physiographic features on the continents have been two dimensional. A major improvement in our ability to detect and to recognize such features, as well as to understand the history of the continental crust, would result from information on the third dimension—topography—at a horizontal resolution comparable with that of existing and planned two-dimensional images. The most useful form for such information in structural and morphologic studies is a three-dimensional image. Such a representation can be obtained either by direct stereo imaging or by generating a stereo image from digital topographic data. *The Committee recommends that digital topographic data be acquired of all land surfaces as a primary means to determine the morphology and structural fabric of the continental crust.* Horizontal spatial resolution should be 30 m or less, and topographic heights should be measured to an accuracy of 10 m or better.

In cloud-free regions, topographic data can best be obtained with a scanning laser altimeter or a line scanner with a stereo configuration. A scanning laser altimeter can provide digital topographic data directly, and stereo images can be derived from such data by computer. Such an instrument would also measure the surface reflectivity at normal incidence, data that can

be processed to yield reflectivity images at the laser wavelength. These images would complement other measurements of continental rock types.

As indicated earlier, cloud coverage in many areas, particularly in tropical regions, limits the viewing at visible and infrared wavelengths; for such regions, topographic data can be obtained with radar stereo imaging. The high sensitivity of radar scattering from natural surfaces to variations in the surface attitude, combined with the fact that the observation geometry can be completely controlled by the observer, makes the imaging radar a powerful tool for determining structure and surface morphology. Radar images of the surface can be obtained in any weather. Radar sensors, with their high sensitivity to variations in canopy-top attitude and the capability of some penetration through vegetation, are also better suited to measurement of physiography in vegetated regions. This is well illustrated in Figures 4 and 6, which show radar images in regions with almost complete vegetation cover. To allow the construction of stereo images from radar data, it is essential to acquire radar images of a given terrain with at least two depression angles. Two viewing directions can be automatically acquired during ascending and descending orbital passes.

Overall, the determination of the morphology and structural fabric of the continents can best be achieved by a combination of digital topographic data and digital images in the visible and near-infrared regions. If the digital topographic data are obtained by laser altimetry or by stereo imaging at visible and near-infrared wavelengths, then the acquisition of digital radar images should be regarded as an important complementary measurement objective that is the best method for acquiring morphologic information in cloud-covered regions. Digital radar images would also provide considerable primary information on continental landforms if digital topographic data were not available.

Determining the morphology and structure of continental crust as expressed at the Earth's surface allows inferences to be drawn on the deep structure of the crust, which is also a three-dimensional problem. Measurements of the Earth's gravity field, in concert with topographic data, will permit an understanding at depth of the structural features mapped on the surface. *Therefore, determination of the gravity field from space in the poorly surveyed regions of the continents is an important secondary objective for continental geology.*

Magnetic-field measurements from space can also aid in defining the deep structure of rock units with an induced or remanent magnetization. We recommend that NASA continue to support the analysis of Magsat data to determine the extent to which space measurements of magnetic fields can contribute to an understanding of the geologic structure and evolution of

FIGURE 6 Seasat radar image of folded sedimentary rocks in the Appalachian Valley and Ridge Province, south-central Pennsylvania. The rock layers have been compressed into tight synclinal and anticlinal folds, and differential resistance to weathering and erosion have led to the valley and ridge physiography. The Susquehanna River cuts across structure, creating major water gaps in the ridges. Metamorphic and igneous rocks underlie the landforms at lower left. Triassic basin rocks occur below the surface of the area across the bottom. Image area is approximately 100 km x 80 km. Radar illumination is from the top.



the crust. The Committee requests that it be informed of the results of such studies.

3. To measure temporal changes in geologic conditions at the Earth's surface.

On geologic time scales, the surface and landforms of the continents are continually modified by the processes of erosion and deposition, uplift and subsidence, volcanism and faulting, and the movement of water and ice. These fundamental processes have shaped the surface of the Earth throughout the history of the planet. Most of these processes are activated or modulated by the same internal forces that have determined the chemical composition and physical structure of the continental crust. This subtle relationship operates at global scales and suggests that over geologic time scales the growth, development, and modification of continents is cyclical in nature. The effects of these processes must be understood if we are to unravel the tectonic evolution of the crust and all the major factors controlling the origin and history of the continents. The important geologic processes that modify the continental landscape are not well understood, however, globally or on time scales of years to centuries. We do not fully know, for instance, the relative roles and the global relationships between the continuing erosion and deposition by wind, rainfall, rivers, and coastal currents and the rare but catastrophic effects of major storms and floods. We do not know the global budget of volcanic activity and its relation to global heat flow, mass transfer of erupted and displaced material, mass transfer of magma within the Earth, and the cumulative effects of volcanic dust and debris on terrestrial climate. Much of our ignorance on these issues stems from our incomplete information on the magnitudes and rates of occurrence of the largest storms, floods, eruptions, and other intense but short-term geologic phenomena.

The time scales for geologic processes span a wide range. Earthquakes, landslides, explosive volcanism, and flash floods occur over periods of several minutes to hours. Tropical storm erosion, lava flows, regional floods, estuarine circulation, and playa lake variations occur on time scales of hours to days or weeks. Glacial flow, stream and wind erosion, and shoreline changes occur over times measured in months to years. The opening and closing of an ocean basin can span a period of hundreds of millions of years. These phenomena also operate over spatial scales ranging from several meters to regions with dimensions of thousands of kilometers.

Surface and aerial observations have provided useful data concerning small- and moderate-magnitude geologic phenomena of high and intermediate frequency, respectively. Knowledge of large-magnitude, rare phenomena remains inadequate. Events during the past decade have emphasized that these phenomena, however, are precisely those with maximum impact on

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modern society; the Mount St. Helens eruptions and the flooding of the eastern United States by the tropical storm Agnes are two examples. Whether these phenomena are those with the maximum cumulative impact on the continents is an open question.

The high-magnitude geologic phenomena of interest may have return periods of decades or centuries. In the next decade, such a rare event may not occur at any particular location on the planet. However, an orbital platform can allow the substitution of space for time in the evaluation of rare, high-magnitude events. The repeated observation of the entire planet can provide vital information for the regional study of those phenomena that occur within selected volcanic, climatic, tectonic, and geomorphic regimes. This information may at a later stage form the basis for prediction within those regimes.

Existing hydrologic data-collection systems illustrate the limitations of surface monitoring of geologic hazards. The predominant concentration of stream-gauging stations on the planet occurs in humid-temperate regions, such as Europe and the eastern United States. However, these are precisely the regions of minimum hydrologic variability. The world's arid, savanna, and tropical regions are undersampled, even though these areas experience immense fluctuations in streamflow and sheetflow. A global program of orbital observations would allow the unbiased comparison of hydrologic regions for such large-scale phenomena as floods, droughts, and glacial mass balances. Great floods are especially understudied in regions that have low-density sampling networks.

Phenomena of very short duration can be studied effectively by a temporal sensing schedule of much longer duration than the event under observation. Long-term stress to vegetation, for example, can serve as a surrogate measure of short-term magnitude of geologic catastrophes. The tree fall of a volcanic blast, the destruction of flood-plain vegetation, and the burial with sand of marsh grass by hurricane washover are examples of geobotanical indicators of event magnitude. Research on such indicators is only in its infancy and deserves continued support.

In addition to short-duration geologic hazards, several chronic problems to society require global observations, best achieved from orbital platforms. These variations include increases in the arid regions of the world, advancing and retreating glaciers, long-term changes in the level of lakes, changing weather patterns, and water budgets. Many of these variations must have occurred in the past and are recurring because of natural rather than man-made influences. It is crucial to understand these natural variations in the context of man's impact so that we can intelligently minimize our effect on the Earth without unduly curtailing our activities. The fact that many of these processes occur on nearly global scales suggests that their variation will

be most effectively addressed from Earth orbit. In this way, for example, changes in the size of the polar cap, freshwater systems, arid regions, and CO₂ content of the atmosphere can be assessed simultaneously on a global scale.

To measure adequately the temporal changes in geologic conditions at the Earth's surface, repeated imaging in several bands in the visible and near infrared will be necessary. Radar imaging would be a valuable additional source of information in cloud-covered regions, for instance during episodes of major flooding. The orbital sensors should achieve a ground resolution of 30 m or less and a scene repeatability period of 2 days to 1 week. It should be noted that these measurement requirements and accuracies are compatible with those specified for the other primary objectives to determine the composition, distribution, and structure of continental rocks. An attractive additional option with multipurpose application would be the ability to modify the orbital sensing system in real time, by increasing ground resolution or by adjusting spectral sensing bands, to study a specific phenomenon of interest, presumably one that was detected by the system operating in its planetwide monitoring mode.

The data storage and transmission problems of a long-term global observation program for earth-surface geologic processes are substantial but can be approached through several options. Local emplaced sensors and satellite relay systems can be used to trigger various modes of orbital sensing. The orbital sensing system can be programmed to recognize key scene changes requiring sensing and data transmission to ground stations. System flexibility should be conserved to allow modification as more is learned about the critical signature changes associated with significant geologic changes.

IV. OBJECTIVES FOR OCEAN DYNAMICS

Introduction

Modern oceanography is usually dated from the time of the British *Challenger* Expedition, which began in 1872. Since then, considerable knowledge has been gained of the gross properties and circulation of the oceans. We know, from hydrographic work, the large-scale distribution of chemical properties and the existence and size of the major current systems. With moored instrumentation, we have learned that superimposed upon the large-scale, long-term mean flows there is a complex time variability whose frequency-wavenumber spectrum is known in outline. Under the impact of the electronics and computer revolutions, knowledge of the detailed dynamics of the oceans has vastly increased, and we have reason to believe that substantial additional progress will occur.

For life on the Earth, the most important effect of large-scale movement of water is the moderation of global climate. Temperature extremes well beyond the present variations would be the norm for vast areas of the Earth if the oceans did not exist. The ocean is thought to provide this ameliorating effect by carrying a large fraction of the heat supply from the equator to the poles, thus limiting the large temperature variations that would occur, and by acting as a large capacity heat sink, thereby reducing the potential seasonal temperature ranges. At present, however, we lack real measures of the amount of heat carried poleward by the oceans.

Because of this strong bond between the oceans and global climate, the question arises as to whether some feature of the ocean is changing to a degree that is effecting commensurate changes in climate on the continents. There is no way of addressing this question, as the present climatic state of the oceans is known only in the most primitive terms.

The global oceans also play a role in determining the abundance of carbon dioxide and its potentially catastrophic effect on climate. The oceans absorb some of the carbon dioxide from the atmosphere, reducing atmospheric heating rates. When the atmosphere is heated, the oceans will also respond to these increased temperatures. We cannot predict either the magnitudes or the rates of these exchanges, over the short and long term, without first acquiring a better knowledge of the large-scale water circulation and its response to changing atmospheric conditions.

The oceans are a global phenomenon. The tools available to the oceanographer have, however, been best suited to studying the ocean at a few discrete points or, in rare instances, in a small region. Recent work has begun to show that the ocean must eventually be studied in its entirety if it is ever to be understood. There are many physical and dynamical analogies between the oceans and atmosphere. Meteorologists have long recognized that the study of the atmosphere requires a global observation network. The existing observational base for the atmosphere is indeed truly global, combining ground-based radiosonde stations with satellite measurements. It is only the presence of this network that permits studies of large-scale dynamics, weather forecasts, and studies of climatic variability. Most of the fundamental problems to be solved in understanding the dynamics of the world oceans require a similar global network.

LARGE-SCALE OCEANIC CIRCULATION

The large-scale circulation of the ocean is driven directly and indirectly by the wind field, and by atmospheric heating at the equator and cooling near the poles. If there were no continents, the resulting flow would be dominated by strong zonal flows with a much weaker meridional convective component, such as is seen in the atmosphere. Except for the Antarctic Circumpolar

Current, these tendencies for zonal systems are interrupted by continental boundaries, and instead we find ocean-basin scale gyrelike flows with a strong east-west asymmetry; relatively weak interior flows are returned in strong western boundary currents, a consequence of the spherical geometry of the rotating Earth. The spatial scales involved in the resulting circulation run from about 30 km up to the size of the largest ocean basins, or about 10,000 km. A fundamental feature of the ocean is that it is vertically stratified, and thus the flow of water is a function of depth as well as geographic position. Superimposed on the time-averaged flows are a variety of time-dependent processes, which render the determination of the average extremely difficult and which also contribute dynamically to the large-scale mean distribution of properties. From the past decade of work, it is known that over great areas of the ocean, this variability (often called mesoscale variability or "eddies") can have energy levels one or more orders of magnitude greater than that of the mean flow.

Through turbulent eddy stresses, the field of variability is capable of generating time-averaged movement of the various fields. These fields include passive tracers such as tritium, dynamically active tracers such as heat and salt, and dynamical quantities such as momentum and energy. Because these different tracers can be transmitted and mixed differently, the general circulation of the ocean cannot be defined uniquely.

THE GEOSTROPHIC RELATIONSHIP

Generally speaking, water movements having spatial scales greater than 30 km and time scales longer than a day are in geostrophic balance to a good first approximation. This important relationship represents a balance between the Coriolis force and the pressure forces. Because the Earth rotates, water parcels in the northern hemisphere tend to be deflected toward the right of their trajectories (because of the Coriolis force). In an ocean in nearly steady state, this force is balanced by the pressure forces so that water trajectories tend to lie along lines of constant pressure. An analogy can be drawn to the atmosphere, where air circulation is around the highs and lows, rather than flowing from high pressure to low pressure. Knowledge of the internal pressure field permits calculation of horizontal currents. Internal pressure gradients arise both through horizontal changes in density and through changes in elevation of the sea surface. Traditionally, the pressure field is computed from shipboard measurements of water density in which the sea-surface contribution is missing, a depth-independent factor that has not, until recently, been a directly measurable quantity. Instead, its effect on the geostrophically derived currents is usually inferred through some assumption about a depth at which the currents might vanish.

Most large-scale motion in the sea is what oceanographers term "quasi-

geostrophic," meaning simply that the motion is not exactly geostrophic. Perfect geostrophic balance does not permit any time evolution or any forces to act in the direction of flow, implying that there are no sources or sinks of energy and momentum. But both in theory and practice, the deviations from geostrophy required to produce the necessary fluxes are very small and not normally observable by direct measurement.

Because the ocean is a complex turbulent fluid, the different geostrophic scales are linked together both kinematically and dynamically. For example, the very intense flows associated with western boundary currents (the Gulf Stream and Kuroshio) have a cross-stream scale of order 100 km; but the return flows, which are required to conserve mass, seem to occur from this 100-km scale on up to the scale of ocean basins. Thus, a determination of the 100-km scales of flow can strongly constrain the large scales, and vice versa.

There are dynamical links as well. In fact, a useful definition of a turbulent fluid is that there should exist strong flows of energy from one spatial and temporal scale to others. More specifically, scales on the order of several tens of kilometers, the mesoscale (including both a temporally varying part and one that might be described as "standing eddies"), contribute fluxes of momentum, energy, and heat that provide some of the pathways not found in the simple time-averaged fields.

OBSERVATIONAL PROBLEMS

Historically, oceanographers have had to observe the world's oceans from a few slow, expensive ships. In more recent years, *in situ* measuring systems have been developed that are able to last for a year or longer, but these latter instruments are far too few and expensive to make measurements over the entire globe with adequate resolution.

Over the past 100 years of shipboard and *in situ* measurements, a gross quantitative picture of the large-scale circulation of the ocean has been acquired, based on the geostrophic relationship. There are two extremely serious problems with the resulting "classical" picture. First, because of the difficulty of sampling a global fluid from a ship, all observations have to be lumped together as though they were contemporaneous ("synoptic"). The problem is mitigated somewhat by the relatively high energies of low-frequency motions, but, as noted above, the smaller scales are dynamically and kinematically related to the larger scales.

The other major problem, as discussed earlier, is the lack of knowledge of the contribution to the pressure field made by the elevation of the sea surface. This depth-independent contribution is usually estimated on the basis of an educated guess that at some great depth in the ocean there is a level at which the absolute velocity vanishes, reducing the problem to the notorious "level-of-no-motion" controversy. Although some progress has been made

recently in dealing with this problem, there is no generally accepted procedure that has been applied (or is applicable with existing data) to the global problem.

As a consequence of these difficulties, existing pictures of the general ocean circulation are at best semiquantitative. The lack of a quantitative picture is one of the greatest stumbling blocks to progress in understanding the ocean circulation and its role in transporting heat and in ameliorating the effects of increases in atmospheric CO₂.

It is possible that one could determine the absolute flow fields and time-averaged quantities by deploying modern recording current meters in the ocean. To measure circulation changes on spatial scales on the order of 100 km or less, however, would require an impossibly large number of spatially independent observations. Further, in most regions of the ocean the energy of the temporal variability exceeds that of the time-averaged variability by one or more orders of magnitude, with a structure requiring several years of data to obtain a stable, mean velocity.

The discovery of this intense eddy field, which dominates the velocity records, means that one must attempt to understand its character globally. As noted above, the time-dependent fields can have time-averaged effects through the nonlinear equations of motion. With existing equipment, a fragmentary picture of this global variability for short periods of time in restricted regions of the oceans has been obtained.

On short time scales there are other important flows that manifest themselves as surface pressure gradients without geostrophic balance. Among these are tsunamis, which are long gravity waves, storm surges, and tides. Storm surges and tsunamis are shallow-water phenomena of great social importance along coasts and large lakes. Tides are global phenomena that until recently were observed in highly restricted locations—tidal stations along coasts and even inside estuaries. The recent development of deep-sea pressure gauges has helped to clarify the picture of how tides progress around the globe, and accurate measurements of sea-surface elevation on a global basis from space should make a substantial contribution. Tidal dissipation influences the ocean circulation and is important in the evolution of the Earth-moon system. Tides in the solid Earth are sensitive functions of the physical properties of the crust, mantle, and core. The tidal signal also appears in measurements of gravity, tilt, and strain; and improved knowledge of the tides will result in more accurate measurements of these quantities. For astronomy and for space-geodetic measurements, the tides are an important factor in station locations in three dimensions relative to Earth's center, the Earth's moment of inertia and hence the length of the day, the secular retardation of the rotation of Earth, measurements of polar motion, satellite positions, and the deceleration of the lunar longitude.

THE GENERAL CIRCULATION AND CLIMATE

Calculations of the flux of heat from the equator to poles suggest that the ocean carries an amount of heat equal in importance to that carried by the atmosphere. But this calculation is based purely on atmospheric observations; the value of the oceanic heat flux is calculated as a residual that cannot be found in the atmosphere. How the heat might be carried in the ocean—in large-scale wind-driven gyres, as an eddy heat flux, in the upper stress-driven layer, or in deep equatorward flows of water formed in polar sinking regions—is unknown. Because the ocean thus plays a major role in ameliorating global pole-to-equator temperature contrast, slight changes in the meridional transport of heat in the ocean could lead to large apparent climatic fluctuations. A determination of the form of the meridional heat flux and its changes requires a long-term global data base. Such a data base is prohibitively expensive and impractical, using the conventional point observation tools. Satellite-based measuring systems seem the only reasonable alternative.

The influence of oceanic circulation on climate is ultimately governed by exchange processes at the sea surface, another area of intensive research in present-day oceanography. The two media are closely coupled; to better understand the general circulation we must also better know the manner in which momentum, heat, and freshwater are transferred to it from the atmosphere.

Not only are these processes fundamentally important in the time-averaged sense but also at a wide range of time scales. For instance, it has been shown that the Pacific sea-surface temperature can have an influence on the weather experienced over North America on time scales of weeks to years. Western boundary currents have been shown to be the return flow of water forced to circulate in great gyres by the wind stress exerted on the ocean surface. We do not yet know how the observed annual periodicity of these boundary currents is related to the annual cycle in the atmospheric circulation.

The direct interaction between the ocean and atmosphere occurs at the surface of the sea. Under a wide variety of conditions, one observes a nearly homogeneous, or mixed, layer at the sea surface. This layer is a manifestation of the erosion of the stratification by the stress exerted by the wind and through heat loss to the atmosphere. Detailed understanding of the structure and evolution of the mixed layer globally would permit much greater understanding of the role of the ocean in maintaining and changing climate. A great deal of effort has gone into the development of a number of theoretical and numerical models of the processes that exchange heat and momentum between ocean and atmosphere, and a number of large intensive experiments have been carried out to test the validity of these models. While progress is being made, these processes have yet to be understood on a global basis. Scientific issues in this area will be addressed in the second phase of this strategy.

Scientific Objectives

We have emphasized the need for improved understanding of the ocean's general circulation from a global perspective. Measurements from space are inherently constrained to observations at or near the sea surface. On this basis we give a ranked set of scientific objectives in which the order is established both from the importance of the measurement and from its feasibility.

The primary scientific objectives for the study of ocean dynamics from space for the next decade, in order of priority, are

1. (a) *To measure the time-variable sea-surface elevation;*
(b) *To measure the time-independent sea-surface elevation relative to the geoid;*
2. *To determine the oceanic wind stress;*
3. *To measure directly the near-surface circulation;*
4. *To measure subsurface ocean properties;*
5. *To measure sea-surface temperature.*

The measurements of sea-surface elevation and wind stress are related and together determine the surface boundary conditions on the ocean. In principle, at least, with these measurements it should be possible to solve numerically the dynamical equations to obtain the interior motions (using appropriate bottom boundary conditions) and to verify the results obtained with the direct measurement of near-surface circulation and subsurface properties. Although the achievement of only one of the objectives 1(a), 1(b), or 2 by itself would greatly advance knowledge of the ocean, and independent efforts toward each should be made, the interdependence of the objectives is such that we believe that efforts should be made to achieve all three at nearly the same very high priority.

Measurement of the sea-surface elevation from space will give, for the first time, the distribution of geostrophic surface currents, which, combined with traditional hydrographic sections, will allow computation of three-dimensional current fields uncomplicated by the usual need to choose a reference level. This information is virtually impossible to obtain by any other means and should have a considerable impact on our understanding of the general circulation. The measurement of the time-independent elevation requires the additional measurement of the Earth's gravity field—a measurement that appears at this time to be less accurate than that of the surface elevation on spatial scales shorter than about 200 km and for this reason only is rated slightly less important. Wind stress is probably the most important force driving the general circulation, and its measurement by satellite appears possible with useful accuracy. Wind-stress observations are available on a more or less global basis from ship reports, but the sampling and accuracy

are nonuniform in quality. Satellite observations should permit a better understanding of the coupling between the general circulation and the wind field. Direct measurement of the near-surface circulation will serve to test models for the circulation based on sea-surface elevation and wind-stress measurements and will, because of the different spatial sampling and distribution of errors, provide independent information on the circulation as well. Such measurements have been made in limited regions by tracking drogued buoys from space with interesting results. However, a number of scientific and technical questions must be answered before such tools can be deployed in quantities useful for looking at the global circulation. Measurement of subsurface properties is extremely important for understanding their relationship to such surface measurements as elevation, wind stress, and temperature. A global program of such subsurface measurements can best be accomplished by transmitting data to one or more satellites; the transmission of such data across the air-sea interface poses a technological challenge, but we believe it to be feasible. Measurement of sea-surface temperature is a primary objective for both ocean dynamics and meteorology, and its priority for oceanography reflects the view that such measurements appear to be limited in their scientific utility, primarily because of the lack of correlation between the temperature of the thin ocean-surface skin measured by satellite techniques and the interior motions.

1. (a) *To measure the time-variable sea-surface elevation.*

The past decade of physical oceanography has shown that the ocean is time variable on all spatial scales ranging upward from the Rossby deformation radius (about 30 km) to scales equal in dimension to entire ocean basins. Particular attention has been paid to the so-called mesoscale variability, of spatial dimensions of order 100 km and time scales of months. For many purposes, this mesoscale variability may be regarded as the oceanographic equivalent of atmospheric weather systems. As with the atmosphere, a detailed description of these motions and of their dynamics is necessary for understanding the larger-scale movement of fluid. In addition, the oceanic motions must be sampled adequately to prevent aliasing of the longer space and time scales.

Understanding the dynamics of the circulation and of its variability requires some means of determination of the global distribution of the variability and its characteristic scales and intensities. Because the ocean is fundamentally a turbulent fluid, the relations between different scales of motion and resultant energy transformations require observation of the complete spectrum of fluctuations.

This form of oceanic variability may be shown to be nearly geostrophic in character. Much of this variability may thus be found by measuring the

changes with time of the slope of the sea surface relative to the geoid. We believe that altimeter measurement from satellite is the most efficient technique for obtaining a global picture. The regional oceanographic experiments of the past decade suggest that through most of the frequency-wavenumber spectrum there are comparatively simple relationships between the surface geostrophic pressure fluctuations and the structures in the mass field at depth.

Study of the kinematics of time variability of the ocean does not require a highly accurate geoid, and the short-lived Seasat demonstrated that, over spatial scales of at least several hundred kilometers and less, the resolution obtained, of order 5 cm, is adequate to describe the variability on those scales.

Determination of the full range of oceanic variability is impossible without altimetric measurements taken over a time span sufficient to sample the significant frequencies. But the low-frequency cutoff, if any, is unknown. Experiment lifetimes of approximately 5 years or more will permit at least a beginning answer to the climatically important question of whether there exists real interannual large-scale variability.

The measurement requirements for the determination of the variable slope of the ocean surface thus follow from existing studies of the general circulation of the ocean and from the scientific issues to be addressed. Ocean elevation should be measured with a system resolution of 5 cm over continuous tracks spanning the major ocean basins. The cross-track spacing should be 50 km or less. Measurements in any given location should be repeated at intervals of 10 days or less. And the continuous duration of the measurements should be at least 5 years.

We know of no technological reason that would prevent achievement of this objective. The resolution and accuracy requirements imply that a large number of parameters, ranging from orbital radius to atmospheric pressure load and wave height, must be determined with even greater equivalent accuracy on all scales. These requirements appear attainable with existing technology and physical models.

1. (b) *To measure the time-independent sea-surface elevation relative to the geoid.*

Our present picture of the time-averaged general circulation has resulted mainly from analyses using hydrographic observations. Measurements of temperature and salinity (conductivity), converted to density, allow computation of horizontal pressure gradients, assuming that one knows the sea-surface elevation. This pressure gradient then must balance the Coriolis force if the flow is slow, steady, and frictionless, the so-called geostrophic balance. In this way the velocity field is calculated indirectly and is contingent on

knowing the pressure head resulting from the distortion of the free surface. In the past this has been an unknown quantity that could be inferred by directly measuring the velocity at some reference depth or making a subjective judgment as to where the velocity might be zero. Direct measurements of mean current are relatively few in the ocean, and oceanographers have generally had to resort to a more subjective route that leads to ambiguous pictures of the general circulation. Accurate measurements of the sea-surface elevation by altimetry would be of enormous value to these studies and consequently to estimates of the fluxes of heat and freshwater. Knowledge of the absolute (i.e., total) current field is also required to understand the time-variable part because the two current systems interact through the equations of motion.

Determination of absolute ocean currents from altimetry requires knowledge of the oceanic geoid because the surface geostrophic current is inferred from the relative slope of the sea surface and the gravitational equipotential field. In the absence of an adequate geoid estimate, altimetry is confined to studies of the time-variable components of the ocean circulation. But the determination of the flow fields with periods approaching the lifetimes of altimetry experiments and longer, which are of interest in climatological studies and for understanding the dynamics of the variability, requires knowledge of the absolute flow fields.

Apart from the direct use of an improved geoid for computing absolute ocean currents, there are additional benefits from improved gravity determinations. One of the components of satellite orbit uncertainty is the imperfect knowledge of the gravity field at satellite altitude. Further, regional geoids constructed from shipboard gravity data, which will always remain important for specific oceanographic problems, would be greatly improved if the surrounding global geoid were known with much greater accuracy than it is at present. The measurement of the Earth's global gravity field is also a primary objective for solid-earth dynamics and an important secondary objective for continental geology.

As noted above, the low-frequency (including the time mean) ocean circulation contains important energetic spatial scales as small as the Rossby radius of deformation (30 km). No single foreseeable satellite determination of the Earth's gravity field will provide sufficiently accurate knowledge of the geoid on spatial scales this short. Nonetheless, current estimates of the improvement in knowledge of the ocean circulation obtainable from feasible space measurements of gravity combined with altimetric mapping suggest that the results will be important and useful despite the failure to encompass the complete geoidal wavenumber spectrum. Steps should be taken to quantify more precisely the contribution that realistically obtainable gravity information will make toward solving the reference velocity problem and, con-

sequently, toward determining more accurately the mass and heat flux in the ocean. Possible approaches are to simulate the introduction of smoothed gravity-field information in hydrographic section inversion schemes, in simple analytical models, or in basin-scale, eddy-resolving numerical models of the general circulation.

The requirements on the altimetry necessary to specify total ocean currents are equivalent to those required for the time-variable circulation. We expect that a substantial scientific impact would result from gravity measurements capable of determining geoidal heights to 5-cm accuracy from global scales to wavelengths of 200 km or less.

2. To determine the oceanic wind stress.

The ocean circulation, both average and time varying, is driven by a variety of processes at the air-sea interface. These processes include the wind stress, evaporation and precipitation, and the exchange of sensible heat. Of these, the wind stress is of primary importance both because it directly drives the circulation and because it is an important parameter in the indirect calculation of air-sea heat exchange.

Preliminary results from the scatterometer flown on Seasat suggest that it is feasible to determine the oceanic wind stress with accuracies and sampling coverage far greater than are now available. The accuracy desired is the equivalent of 0.1 dyne/cm^2 stress down to spatial scales including most of the wind-stress variance. With regard to this latter point, it should be noted that the dynamically important quantity over most of the ocean is not the wind stress itself but rather its curl, the vorticity forcing term. Because the wind is, to a good approximation, in equilibrium with the surface wave field, radar backscattering measurements of the surface roughness, in principle, permit the determination of the wind stress. Scatterometer technology should be evaluated in view of the above requirements for wind-stress accuracy. The potential use of synthetic-aperture radar for measurement of wind stress should also be explored.

The wind stress should be determined simultaneously with altimetry. Such observations would permit the first direct tests of the theories relating the wind stress and its fluctuations to inferred mean flows and their fluctuations in the ocean.

3. To measure directly the near-surface circulation.

The general circulation of the ocean consists of the geostrophic plus the nongeostrophic parts; the near-surface velocity field is the sum of the geostrophic part, determinable from altimetry, plus a stress-driven portion that is not seen by the altimeter because it does not generate surface-pressure gradients to first order. This stress-dominated region must be measured and

understood in conjunction with the wind-stress field as it is the dynamical region that couples the wind with the geostrophic field. In addition, the stress-dominated layer carries important contributions to the heat flux and other oceanic properties.

In principle, at least, knowledge of both the sea-surface elevation (i.e., the geostrophic velocity) and the wind stress should allow computation of the current field within the stress-dominated layer. In practice, however, this region is turbulent and requires parameterization of the turbulent exchanges, an area of active scientific investigation at present. Direct measurements of the currents in this region are an important check on the models. These measurements will be most useful if performed over the same time period as the measurements of sea-surface elevation and wind stress.

For many years, drifting surface buoys, normally "drogued" to some depth below the surface, have been deployed for the purpose of determining water velocity. These buoys have been tracked remotely either by ships or satellites. In a purely technical sense, the method is fairly well developed. The ability to deploy large numbers of inexpensive drifters over large regions of the ocean for determining total surface velocity is an attractive one.

The requirements to be placed on such a system of tracked buoys for the objective of determining globally the near-surface circulation need to be defined more clearly than they are at present. In particular, quantitative estimates are needed of the numbers of such drifters required to compute the oceanographically relevant parameters and to understand the degree to which the inevitable measurement errors (due to windage and water slippage) jeopardize the entire idea. An engineering program should be established to construct such drifters with high survivability and known slippage and windage rates and to reduce the cost of both drifters and communication links.

At present, therefore, we cannot explicitly state system measurement accuracies. We recommend that a thorough definition of the measurement requirements for direct determination of near-surface ocean circulation be undertaken so that this attractive technology can be exploited.

4. To measure subsurface oceanic properties.

At best, direct measurements from space provide information on properties related to the oceanic surface boundary conditions. As with the study of any other fluid system, understanding of the ocean requires a knowledge of the three-dimensional fluid. Conventionally, such information is obtained by lowering instruments from ships into the water depths and by mooring internally recording instruments for later retrieval by ships. The properties measured in this way are various, ranging from the dynamical ones of density and velocity to chemical tracers of water movement such as tritium and oxygen. In addition, there exist subsurface drifters that behave analogously to the

surface drifters described above. These are now tracked either acoustically from shore stations or ships or by internally recording moored acoustic sensors.

If it were possible to solve the engineering problems of relaying subsurface information across the air-sea interface to satellite transmission systems, one could revolutionize the problem of measuring and understanding the ocean. The problems are formidable, involving as they do the necessity of reaching the sea surface in ocean depths of the order of 5000 m and of then penetrating this extremely high-stress interface adequately to transmit at required data rates. Such a system would be useful only if it were cheap enough to be deployed in large numbers. The capability of making such measurements from both drifting buoys and moored systems should be explored.

With a trans-sea-surface capability, one would be able to contemplate real-time three-dimensional oceanic measurements for the first time in a useful way (e.g., with floats, acoustic tomography, and conventional moored data). In addition, the entire economics and strategy of *in situ* measurements in remote locations would change; instruments are frequently less expensive than the cost of ships that retrieve them but are recovered at present only because the data are internally recorded.

5. To measure sea-surface temperature.

Sea-surface temperature measured from space by IR techniques and more recently by passive microwave has been available for many years. Sea-surface temperature is a component in the computation of air-sea exchanges and is useful for the tracking of certain kinds of large-scale oceanographic features. However, the satellite measurement is of a very thin skin at the sea surface whose coupling with temperature fluctuations a few meters deeper is poorly understood and believed to be weak. We note that measurement of temperature is likely to remain of more urgent interest to meteorologists who require lower thermal boundary conditions on their atmospheric models than to oceanographers.

The currently available accuracy of 1.5°C appears to be adequate for detection of surface fronts, major boundary currents, and large amplitude eddies. Studies should continue to be directed toward improving the measurement accuracy and resolution.

FUTURE MEASUREMENT SYSTEMS

All the items listed above can be related to technology that is either available or for which enough work has been done that they appear possible with some additional development.

A number of important physical parameters exist, however, for which we

do not have a sound basis for estimating even their feasibility. We do not mean to imply that these parameters are less important than those already listed, merely that they first require a serious effort to define measurement accuracies and a technical basis for their determination. Chief among these are overocean evaporation and precipitation and all the elements involved in the computation of air-sea transfers of heat. The instruments required to make these measurements adequately are now unknown.

We also suggest the continued study of existing data sets such as that from the synthetic-aperture radar (SAR). It seems clear that the information content of this type of measurement must be very high; but it is not now possible to see clearly exactly what this information is, how it would be used, and what its impact could be. The widespread observation of internal waves by SAR are intriguing, and we can speculate that, for example, a wind-stress measurement might ultimately be more accurately done with a SAR rather than a scatterometer.

6

Science Program Issues

I. RELATION OF GROUND, AIRBORNE, AND SPACE MEASUREMENTS

Earth science has classically been conducted from measurements made on the ground and from seagoing ships, more recently from aircraft and rockets, and only most recently from space. It is hardly necessary to affirm that the space measurements required to fulfill this strategy are based on the current state of scientific understanding achieved through this heritage of ground and airborne measurements and that the results of such space investigations must be fully integrated with the information from those ground and airborne measurements to make the greatest scientific advance. We have the ability on the Earth, in contrast to the other terrestrial planets, to conduct a variety of intensive ground and airborne investigations of a duration, resolution, and coverage limited only by our resources. This ability does not detract from our need for the large-scale, global view of earth processes that space observations can readily provide. Rather, it affords us the opportunity to target these intensive ground and airborne studies at least partly on the basis of the synoptic view provided from space.

Several of the primary scientific objectives of this strategy can be accomplished only with a closely coordinated program of ground and space measurements. In the area of solid-earth dynamics, the determinations of tectonic-plate motions, of deformation near seismic zones, of variations in earth rotation and polar motion, and of intraplate deformation are all accomplished by the measurement, using satellite laser ranging or radio interferometry, of vector baselines between two or more simultaneously operating ground stations. In the area of ocean dynamics, the direct measurement

of near-surface ocean circulation requires the simultaneous tracking by satellite of large numbers of surface buoys; and the global measurement of subsurface ocean properties requires a network of subsurface instrument systems that telemeter a variety of sensed data to a satellite for transmission to ground. While the strategy for continental geology does not call for simultaneous space and ground measurements, an essential step in the validation of the remote-sensing tools needed to carry out the strategy is the use of ground truth to test inferences made from space observations. The standard procedure for the development of remote-sensing instruments for use in space generally includes laboratory demonstrations, field application, and finally validation in airborne experiments.

Thus on both scientific and strategic grounds, *a coordination of space, airborne, and ground measurements and an integration of the results from all types of experiments should be indispensable aspects of a global program of earth science. We recommend that sufficient planning and resources be devoted to ensure that the ground and airborne measurements necessary to accomplish this strategy can be conducted in the next decade.*

II. SCIENTIFIC INSTRUMENTATION DEVELOPMENT

Over the period to which this global strategy is directed, we expect that NASA will maintain its role in carrying out supporting research and development programs, especially for the development of flight instrumentation and mission techniques that precede initiation of operational systems. The Committee is seriously concerned, however, that the level of support for and the substance of the instrument development programs at NASA are inadequate to support the strategy and its primary objectives and measurement accuracies contained in this report. This conclusion is not a reflection on NASA's capability; to a large extent it is attributable to the relatively recent beginnings being made by the agency to justify and develop a balanced, long-term remote-sensing program for earth sciences. Nonetheless, it is a clear indication that a major supporting element of this science strategy, and of the mission planning that grows out of it, needs attention and at the earliest opportunity. Further, it is essential that an instrumentation development program be coordinated to the implementation of the science strategy, beginning with instrumentation conceptual development that anticipates and focuses on the longer-range measurement issues and ending with the testing of dedicated flight-ready hardware. This implies that long lead times, of the order of the strategy decade, are required and, therefore, that a development program cannot be contingent on or overly dependent on approval of a specific mission.

From the solar-system perspective, the Committee recognizes that the science objectives in this strategy, and its successors, have analogs with those for exploration of the other planets. As a consequence, we expect a growing commonality in measurement techniques, precisions, and requirements and the instrumentation concepts to fulfill these measurement criteria. The Committee recommends that NASA periodically review the various levels of instrument development in both the planetary-exploration and earth-science programs to identify those activities in one program that can be used to address objectives for the other by either direct application or adaptation.

The Committee has identified several key instrument issues that have emerged in construction of the strategy. Up to the present, no sensors have been flown successfully in space that were developed specifically for determining the composition and structure of the Earth's exposed land masses. What has been learned from space, and some indication of its potential, has been derived from data obtained with sensors designed for other purposes. Consequently, *there is an immediate need to begin a dedicated instrument-development program in order to address the science objectives for study of the continents.*

The measurement requirements and instrument concepts described in the strategy for continental geology are sufficiently advanced in their development so that the Committee can foresee their utility in carrying out the science objectives for investigating continents. This expectation is based on the premise of an orderly program of instrument development. Beyond the period addressed by this strategy, we can anticipate that subsequent science objectives for the study of continents will be based on improved capabilities for measuring the composition of surface rock types and for inferring subsurface structure. To address these objectives, the Committee believes that the following instrumentation concepts should be supported.

There is a transition region of the electromagnetic spectrum between 2.5 and 5 μm where both reflected sunlight and emitted thermal radiation contribute to the spectral signature of the Earth's surface. This spectral region contains diagnostic information for nitrates, sulfates, carbonates, and some silicates. This region has not been adequately investigated for surface material identification from space, however, because of the low-energy flux available from the surface and because of the difficulty in separating the solar-reflected and the surface-emitted components of the spectra. The potential for deriving rock-type information in the 2.5- to 5- μm spectral region is high; the development of both instrumentation and analysis concepts required to achieve this potential should be supported.

Rocks, minerals, and vegetation luminesce under irradiation by solar blue and ultraviolet light. Field and airborne work has shown that luminescence can be detected remotely by measuring the changes in the depth of Fraun-

hofer lines in the solar spectrum reflected from the Earth's surface caused by the superimposed broadband luminescence spectrum. Differences in the amount and the spectrum of luminescence among rock types and among vegetation types, as they are affected by soil chemistry, seem to allow mapping of some rock-type units. This technique would provide information entirely different from other remote-sensing methods, and it appears useful to a wide variety of remote-sensing applications. The work done in this area has been sufficient only to show promise; considerable field and airborne studies using several Fraunhofer lines simultaneously are needed to demonstrate the value of this method for rock-type discrimination from space.

The standard imaging techniques in the visible and midinfrared to near-infrared portions of the spectrum are passive, employing solar radiation or emitted thermal radiation. Active illumination of one surface element at a time using lasers appears to promise a significant improvement over standard techniques in the capability for rock-type discrimination in these spectral regions. One advantage of active imaging is the potential for operating at night, when extraneous radiation scattered into the instrumental field of view is much reduced. Further, the surface and atmosphere are generally colder at night, reducing background thermal emission, and cloud cover is usually less. Another advantage is the ability to control the power, spectral content, duration, and direction of the laser light source. All of these parameters can aid in discriminating against unwanted radiation. The intensity of the laser illumination required is well below that harmful or even detectable by the unaided human eye. An active imaging system will require a laser with a high peak power to obtain sufficient signal return from space, a high pulse repetition rate to be able to cover a wide swath with sufficient resolution, a high efficiency for power consumption, and tunability to provide multispectral coverage. No such laser exists at present. The state of laser technology is continuously improving, however, and the Committee expects that, with sufficient research support, lasers appropriate for active imaging from space will be available by the end of the decade.

Any remote-sensing technique that can provide a global or even regional capability for subsurface electromagnetic sounding would be extremely valuable for continental investigations. Electromagnetic sounders have been used from surface vehicles and airborne platforms with a limited amount of success in specific locations. The most dramatic success was achieved in Greenland and Antarctica, where airborne sounders were used to penetrate through more than a kilometer of ice and obtain profiles of the depth to bedrock. We recommend that an investigation be conducted to assess whether electromagnetic techniques can be used from space to achieve subsurface sounding of the upper layers of the continental crust.

The primary objectives for solid-earth and ocean dynamics require no fundamentally new instrument concepts, though not all of these concepts have been fully developed. The issue in these discipline areas is primarily one of high accuracies with accompanying high confidence levels. This situation is especially the case for altimetric measurements and satellite tracking systems. The current NASA satellite tracking system cannot provide the required accuracies specified earlier. *We recommend that NASA improve its satellite tracking systems to achieve the accuracies required by this strategy; the necessary system upgrading must be undertaken in the early 1980's in order to address the primary scientific objectives for solid-earth and ocean dynamics.*

The Committee urges NASA and other relevant agencies to assess critically the various techniques proposed to achieve the recommended high accuracies in altimetry measurements, satellite orbit determinations, long-baseline measurements, and geoid determinations. Among the techniques that indicate promise for attaining these accuracy levels are an improved satellite tracking system at two or more frequencies in the microwave band to correct for ionospheric effects; water-vapor radiometers to reduce substantially the tropospheric propagation correction due to atmospheric water vapor on satellite tracking and on radio interferometric measurements of baseline lengths; the use of Global Positioning System satellites to determine distances between ground stations for intermediate-length baselines (tens to hundreds of kilometers); the use of short (subnanosecond)-pulse lasers to determine very accurate distances from a ground reference point to an orbiting satellite; satellite-to-satellite Doppler measurements to improve the horizontal resolution of the global gravity field; and acoustic interferometry to determine accurately the position of sites on the seafloor. The Committee requests that it be regularly informed of the results of these technique assessments.

Lastly, during the development of this strategy, the Committee became increasingly aware that there is a large segment of the earth-science community that has little or no involvement in earth-science research from space. Undertaking a global program designed to carry out this strategy clearly will require a much larger participation from this community than is currently apparent. There are sufficient precedents in other areas of space science that strongly indicate that close and sustained cooperation between NASA and the scientific community can be achieved. As one means to build to this level of participation, we suggest that NASA demonstrate its intentions through active enlistment and support of available expertise to develop an appropriate experimental and instrumental protocol to address program goals.

III. DATA MANAGEMENT AND ANALYSIS

Implementation of the scientific objectives and measurements of this strategy will give rise to a new set of data problems that are the result of the generally increasing complexity of measurements and magnitude of data over the period to which the strategy is directed and the global nature of the strategy. Adoption of this strategy will impose the significant requirement that the data chain from observation to interpretation must be well conceived and effective.

An overview of the measurement requirements specified in the discipline areas indicates a number of common related data issues. It is apparent to the Committee that over the next 10 to 15 years the increase in data volume will be due largely to meeting measurement requirements for higher spatial and spectral resolutions, repetitive measurements, measurement of long-duration phenomena, and measurement of many short-duration phenomena with large-scale effects. The expected availability of advanced instrumentation, especially those that will provide more spectral bands and those that will produce large amounts of data (e.g., synthetic-aperture radar), will add to the overall data volume.

As the science represented in these strategies matures, it is reasonable to expect that the complexity of measurement requirements and data interpretation will also mature and that new sets and kinds of data will be requested, especially for the intercomparison of measurements of common sites or the comparison of widely separated sites. In this regard, the Committee wishes to call particular attention to the area of data interpretation. The present ability and time required to translate space observations into analysis and understanding lags well behind the technology to build measurement devices and to collect data from space. To a large degree this lag is the result of overemphasis on an empirical approach to remote sensing. The effect has produced unmeasurably large delays not only in the interpretation and scientific understanding but also in our ability to guide future measurements and instrument development based on the results of interpretation techniques. For this strategy, a major effort must be made in the development of new interpretation techniques in remote sensing for geology if the primary scientific objectives are to be met in the next decade. Beyond the need to reduce remote-sensing data and to archive them in a common format is the essential need to apply a variety of analysis and image-processing techniques, to select among the data sets, and to combine the most appropriate data in a multispectral approach. An ongoing research effort should be maintained to develop optimum interpretational techniques for specific geologic problems. In oceanography, a similar research program in data-interpretation techniques should be supported for such new data-

acquisition systems as synthetic-aperture radar. *We strongly recommend that the development of data-interpretation techniques be accelerated to ensure that space measurements for earth science will produce the maximum scientific return within reasonable time periods following data acquisition.*

The science objectives specified earlier place no severe demands on U.S. capability to obtain data; i.e., the Committee foresees no apparent technological barriers to the acquisition of data implicit in this first-phase strategy. The new precedent for data demands lies rather in the organization and management of data acquisition and analysis systems, and the Committee is fully aware that these new requirements are due in large measure to the now global extent of the earth sciences. The Space Science Board Committee on Data Management and Computation (CODMAC) recently completed an extensive study of space data issues over the next decade.* Their report addresses data problems over a broad range of space-science disciplines and makes recommendations of general applicability for data management and computations. From this Committee's perspective in earth sciences, we concur with their general findings that data-management problems account for many of the shortcomings in the science returns of space observation programs.

As noted earlier, this strategy is the first of a two-stage effort; we anticipate that the second stage will be completed in approximately one year. Taken together, these two documents will represent an integrated strategy for earth sciences of about 10 years duration. *The Committee recommends, following completion of this second strategy phase, that an interagency study be convened on the requirements of a global data-management system for the next 10 to 15 years.* This study should include at least the following elements: data processing, distribution, storage and retrieval, and analysis needs. We suggest that this strategy for earth science from space and the report of CODMAC be utilized as a science-requirement guideline for the study. In the interim, we urge the relevant agencies to begin to articulate the data issues and define the framework for establishing management and organization systems. We further urge, given the strong relationship between science and applications in the earth sciences, that the study be broad enough to consider the data issues in the transition phase from research and development to operational systems.

IV. THEORETICAL AND LABORATORY STUDIES

Future missions to make measurements of the Earth from space provide the opportunity to obtain a large amount of new information. In order to make a

**Data Management and Computation. Volume 1: Issues and Recommendations; Volume 2: Technology Trends* (National Academy Press, Washington, D.C., 1982).

significant advance in our understanding of the Earth as a planet, there must be, in addition to such new observations, a development of new hypotheses through theoretical studies and laboratory experiments. Quantitative hypotheses for the behavior of earth processes provide a predictive capability that is important to the planning of individual space missions and to the interpretation of space-derived data. The strategy for earth science from space developed in this report is based on existing theory for the ways in which the Earth works as a planet. The successful completion of this strategy will require both a thorough and continuing exchange between further theoretical development and mission planning and, for some research areas, an augmented level of support for the development of new theoretical tools.

The field of solid-earth dynamics has undergone a scientific renaissance over the past two decades through the theory of plate tectonics, which has permitted the synthesis of a wide variety of geologic phenomena. The theory of plate tectonics is largely kinematic, in that the relative angular velocities of the major plates averaged over the last few million years can be specified, but the forces that produce these motions cannot. The theory nonetheless has considerable predictive power to describe the direction and rates of plate motions at most places on the planet. The strategy for solid-earth dynamics presented in this report includes as a primary objective the direct observation of plate velocities to provide a first-order test of this fundamental theory. Such observations will also permit tests of the common assumption of plate rigidity and will lead to the incorporation into the kinematic framework of a number of smaller plates whose motions are currently poorly defined.

Despite the success of plate-tectonic theory, our ability to describe the time-dependent deformation near plate boundaries is quite poor at present. Such deformation is highly diagnostic of the rheological structure of the nearby crust and mantle, and an understanding of the deformation, if any, prior to large earthquakes may lead to an earthquake-prediction capability. The time-dependent deformation near the boundaries of plates can be predicted using assumed models for the mechanical properties of the Earth and extensive numerical calculations. The possible modeling assumptions and calculational techniques are growing in number and sophistication and need to be tested by reliable data from a number of plate-boundary zones of different geometry. These types of calculations should continue to be used as a basis for planning the locations and sequence of measurement sites for the determination of time-dependent deformation in major seismic zones as part of the strategy.

Although the relative plate velocities averaged over time scales of millions of years are reasonably well known, the nature of the mantle flow at depth that must accompany such motions is a major unsolved problem. Mantle convection is held to be responsible for driving plate motions, yet we know

neither the radial extent of the convection system involving the plates nor the regions of upwelling and downwelling within that flow system and their relationship to plate boundaries and to intraplate volcanic and tectonic activity. The governing equations for mantle convection are known, but their solution in complete form is not tractable even with the largest and fastest computer systems. Laboratory-scale models have proved useful in exploring a number of important aspects of convection but cannot provide an adequate model of the mantle in all significant respects. It has been only recently that theoretical solutions to simplified versions of the mantle convection problem have indicated a relationship between the pattern of mantle convection flow and anomalies in the surface gravity field. The gravity-field measurements recommended in this strategy will require a closely coupled and vigorous program in the theoretical and laboratory modeling of mantle convection if the long-term goal of establishing a dynamical theory for plate tectonics is to be attained.

The state of theoretical development is, for the most part, less advanced in the area of continental geology than in solid-earth dynamics because of the complexity of most geologic processes. This statement is also true of geologic remote sensing. Remote sensing from space for geology has been accomplished primarily using sensor systems designed for nongeologic applications. The extensive set of Landsat images of the Earth's surface, for instance, were obtained with sensors designed and flown primarily for problems in agriculture. The striking radar images of land areas obtained by Seasat were made by a synthetic-aperture radar system designed for oceanographic purposes. Partly as a result of this heritage, much of the geologic remote sensing to date has been based on a strictly empirical approach. Such an approach, while occasionally successful in developing diagnostic tools in limited situations, does not lead to interpretational techniques of general applicability and is not an efficient use of resources. *To accomplish the objectives for continental geology, it will be essential to develop techniques for the interpretation of remote-sensing data from space that are founded on a thorough understanding of the underlying physical and chemical processes.* Such a development effort will involve a coordinated program of theoretical studies, laboratory experiments, and field tests. The theoretical tools for the interpretation of geologic remote-sensing data should form part of the basis for the design of the future instrumentation and missions needed to achieve the scientific objectives for continental geology.

Physical oceanography has had a long and fruitful collaboration among theory, laboratory modeling, and observation. The springboards for theoretical studies are Newton's laws of motion and the laws of thermodynamics, which are cast into a system of equations known as the Navier-Stokes equations, essentially the same starting point for the study of all fluvial motion whether it be the oceans, planetary atmospheres, or planetary mantles. In

simplified forms, the equations have been used to describe a variety of oceanographic phenomena from surface waves, to tides, to the large-scale ocean circulation, and a host of other time-dependent phenomena. In their full complexity, the governing equations have no analytic solution. Even when cast in finite-difference form, the most powerful computers are not adequate to solve the equations for the full range of physical phenomena, even if accurate time-dependent boundary forces and fluxes were available. Instead, further approximations are necessary; these include some combinations of parameterizing small-scale processes, smoothing bottom topography, reducing the vertical structure to a finite set of layers, filtering out short time-scale processes, or ignoring convective processes entirely. Continuing interplay between theoretical studies and the observations called for in this strategy will be necessary to understand fully the dynamics of the ocean.

Thus for the fields of earth science included in this strategy, the states of development of the underlying theory are quite varied. For some of the scientific objectives, the theory is sufficiently well developed that the measurements recommended in this strategy will immediately lead to the tests of important hypotheses. For others, the development of theoretical tools must progress together with the development of new techniques of measurement. For all of these areas, theoretical and laboratory experiments provide results vital to the planning and execution of the space measurements called for in this strategy and laboratory. *Vigorous support of theoretical and laboratory investigations should be an essential component of the future program for earth science from space.*

7

Science Policy Considerations

In the early stages of its task, the Committee came to the conclusion that a new science strategy for earth exploration from space must be global in nature. There are a number of factors that have compelled adoption of this global premise. First, all the fundamental questions identified that could be addressed from orbit were characteristically global; that is, we could expect to make major advances in understanding earth processes or dynamics only by considering them in their largest effect and dimensions. Second, it is clear, based on our present state of knowledge, that the major phenomena or processes that comprise the total environment of the Earth are profoundly interlinked and interdependent and that to understand these complex relationships a unified concept of investigation must be adopted. Third, investigation of other planets in the solar system has of necessity begun with a global approach, and our knowledge of these bodies has progressed to the point where answers to fundamental questions are being derived from comparative studies. To understand the role of the Earth as a planet in the solar system we must similarly adopt a global framework for its study. Last, the technology required to begin global investigation of the Earth is available. Current instrumentation, techniques, and capabilities can address substantially most of the major objectives in this strategy. The Committee is confident that a vigorous and properly paced development program could provide the advanced instrumentation concepts to complete the present strategy for the 1980's successfully and to anticipate the flight instrumentation and scientific requirements for the continued investigation of the Earth in the 1990's.

All of these factors have influenced the shape and content of the strategy and its science objectives. In addition, the strategy may be characterized as a

baseline effort; that is, its implementation is the minimum level of effort to maintain a vigorous science program and to achieve major advances. It is also intended to establish and maintain U.S. leadership and position by identifying the critical areas of science, from a strategic perspective, that need to be addressed and that will provide a large potential and base for subsequent applications. The strategy is also flexible, to allow periodically for economic perturbations or national priorities of higher rank. It achieves this degree of flexibility by focusing only on the science to be achieved. The long-range mission planning and the science content of specific missions are left to the appropriate agency. The science objectives in the major areas, however, are linked; omission of a set of objectives from a major area will consequently have a serious impact on other areas. To some extent, this effect is due to the construction of the strategy. In a larger sense, it is a reflection of the inter-related nature of earth processes.

This strategy and its recommendations have certain related implications for current and future U.S. policy, which the Committee is obliged to comment upon:

(a) The overriding implication of adopting this strategy and its successful implementation is that the United States will embark on a vigorous, systematic program of Earth exploration from space. At present, the lack of a national policy for space exploration is a major obstacle to achieving the present strategy for earth science.

(b) The Committee is fully aware that the United States will not be alone in undertaking such a global initiative. We are informed of the interests and planning efforts currently under way in individual western European nations, in the European Space Agency, in Japan, in the Soviet Union, and in China, all of which are capable of carrying out independent national programs without U.S. participation or assistance. We have noted particularly that the cumulative interests of these parties touch on every aspect of the strategy developed in this report, and we conclude that the pursuit of capabilities in and information from space will be keen and vigorous and should be appreciated and encouraged. In the Committee's judgment, implementation of this science strategy will provide the United States with a leading position in science return and the useful ends to which this knowledge is directed.

Further, for the foreseeable future nations involved in pursuing earth science from space, regardless of whether they have satellite capabilities, will be dependent on each other to establish and carry out programs that require coordinated space and ground-based techniques and measurements. The United States will be no exception to this interdependency. Therefore, a

U.S. position of leadership in earth science from space should be a mandatory basis for this nation's negotiation for cooperative programs.

(c) For some time there has been an ongoing, unresolved question on whether remote sensing from space violates the sovereign rights of nations being sensed. Those nations who feel their rights have or will be infringed upon have attempted to resolve the issue by striving for international agreements that place limits on the resolution accuracy and that require prior consent and full disclosure of results and interpretation of remote-sensing data. The present U.S. civil space policy, which postulates an open program, insists that remote sensing of the Earth's surface does not breach sovereign rights and that an open-space policy is essential for scientific investigation of the Earth from space and the utilization of the knowledge acquired. As an expression of this policy, all remote-sensing data from U.S. civil satellites are available to any requestor within a short time of their collection.

If the United States adopts a coherent policy that directs programs to be undertaken for systematic global-scale investigations of the Earth, then, in the opinion of the Committee, it is vital that the present open-space policy be maintained; further, the strategy in this report, and subsequent strategies, is predicated on such a policy.

(d) The Committee expects that global earth-science investigation from space will be followed, in some cases fairly rapidly, by global exploration for natural resources (e.g., a global inventory of minerals) and by application of scientific knowledge (e.g., natural-hazard predictions and warning systems). It is not within the purview of the Committee to address strategically these subsequent programs and policy issues. However, we are convinced, on the basis of the testimony and information acquired during development of this strategy, that applications, in the general case, undertaken with inadequate scientific understanding or primarily based on empirical relationships cannot be sustained. The Committee is confident that the scientific return and new information to be derived from implementing the strategy contained in this report will provide an adequate foundation for applications in these major areas.

(e) The strategy in this report also assumes that a U.S. global effort for implementation will be coherent, vigorously carried out, and provided with sufficient and sustained fiscal resources. It is outside the competency of the Committee to advise on the organizational or institutional base required for such an enterprise. We note that, up to the present, responsibility for earth-science programs at the federal level has been scattered among several independent agencies. To a large extent, this division of responsibility is a reflection of long-standing policy that did not anticipate that eventually a global or unified framework would be necessary. Our strategy is driven by a

global premise. At present, there is no single organization or bridging structure at the federal level that could assume responsibility for organization and management of an integrated global program. It is the Committee's judgment, given the high level of importance assigned to the science strategy and the policy implications of its subsequent applications, that an optimal organization for global program responsibility is vital and deserves primary consideration.

8

A Look toward Completion of the Strategy for Earth Science from Space

This report has detailed the first part of a 10-year strategy for earth science from space, covering the areas of solid-earth dynamics, continental geology, and ocean dynamics. At the completion of this strategy, we will have measured the present rates of motion among the Earth's major tectonic plates, the time-dependent deformation near several major plate boundaries, and the variations in planetary rotation rate and polar motion. We will have measured the Earth's gravitational field with sufficient accuracy and resolution to address important questions in mantle convection, ocean dynamics, and large-scale crustal structure. Surface elevation and wind stress will have been measured over the global oceans so that the general three-dimensional oceanic circulation may be reasonably well understood. And substantial progress will have been made toward mapping globally the distribution of rock units and the surficial structure and physiography of the continents.

The second part of the 10-year strategy, a report now in progress, will present the scientific objectives for the investigation from space of atmospheric circulation, global climate, atmosphere-ocean interaction, the Earth's water and ice budget, and major global chemical cycles. The full strategy for the integrated scientific study of the Earth from space for the next decade will be complete once that report is finished.



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