DOCUMENT RESUME

ED 340 596 SE 052 462

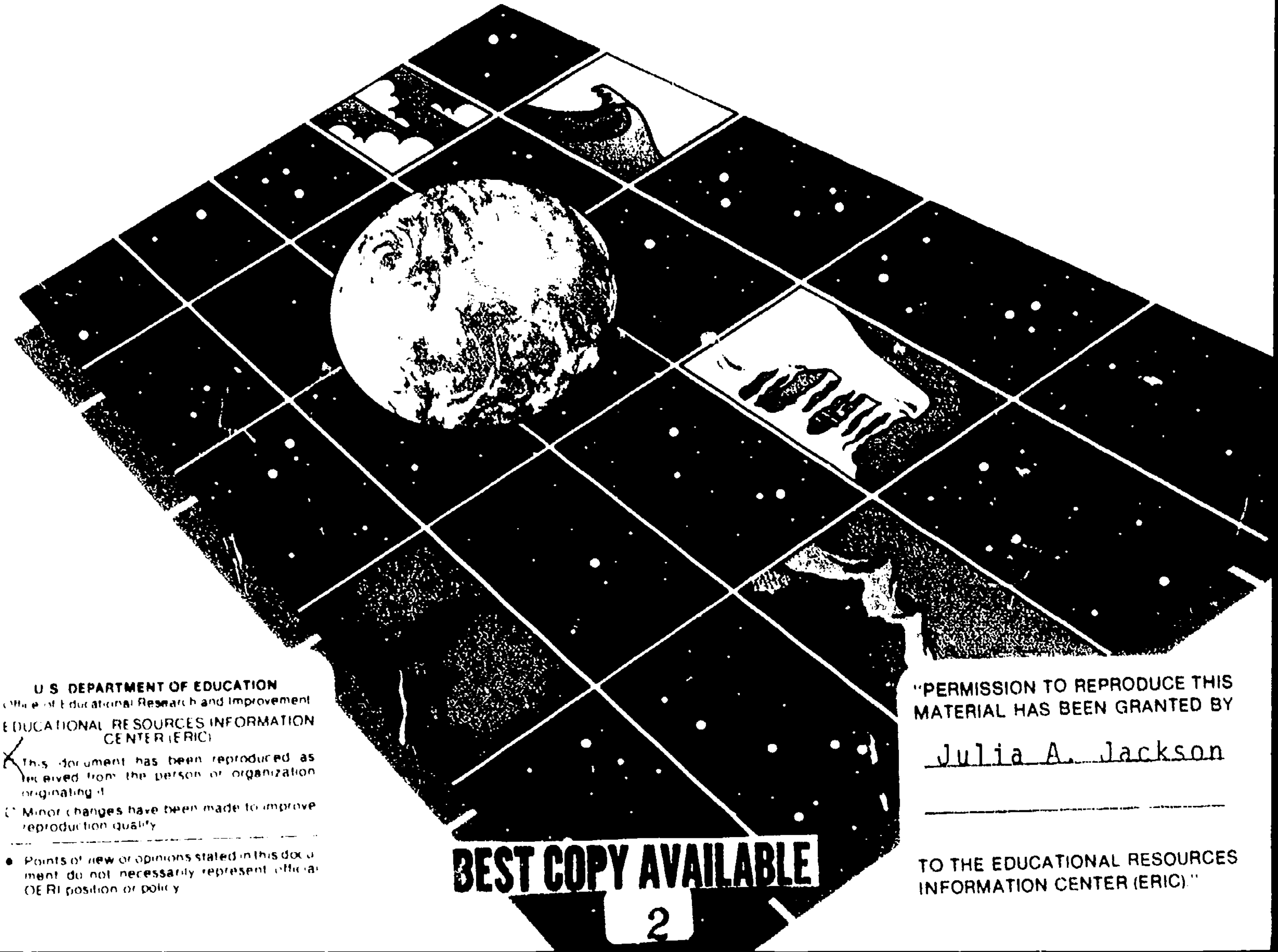
TITLE	Earth Science Education for the 21st Century: A Planning Guide.
INSTITUTION	American Geological Inst., Alexandria, VA.
REPORT NO	ISBN-0-922152-11-X
PUB DATE	Feb 91
NOTE	42p.
AVAILABLE FROM	American Geological Institute Publications Center, P.O. Box 2010, Annapolis Junction, MD 20701 ($10.00 plus shipping and handling).
PUB TYPE	Guides - Non-Classroom Use (055)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*College Preparation; *Curriculum Development; *Earth Science; Educational Change; Elementary Secondary Education; Evolution; Geology; Inservice Teacher Education; *Material Development; Preservice Teacher Education; School Business Relationship; Science Curriculum; Science Education; *Scientific Concepts; Scientific Literacy

ABSTRACT

In response to the growing national concern about precollege science education, this guide was developed to assist school administrators, curriculum planners, teachers, and scientists in incorporating earth science in K-12 science curricula. The guide is divided into four main sections that provide a framework for planning and implementing earth science education programs. The sections are as follows: (1) goals to guide the development of K-12 earth science curricula (in the areas of stewardship, appreciation, scientific thought, and knowledge); (2) concepts that are basic to understanding the earth and its interacting systems (with discussions of the earth in space, earth systems, geologic time, change, evolution, cycles, scales, and resources); (3) recommendations for teaching earth science subject matter in grades K-12 (discussed in terms of curriculum objectives, how students learn, teaching strategies, and assessment); and (4) recommendations for implementing new earth science curricula in the schools (discussed in the context of four essential tasks, namely, developing materials, developing support, preservice and inservice teacher education, and partnerships). The goals, concepts, and recommendations were developed by scientists, science educators, school administrators, and teachers who attended one or more of six regional conferences conducted by the American Geological Institute. (KR)

Earth Science Education for the 21st Century:

A PLANNING GUIDE



The American Geological Institute

The American Geological Institute (AGI), founded in 1948, is a nonprofit incorporated federation of 20 scientific and professional societies. AGI provides information services to earth scientists, advocates for the interests of the earth science community, plays a major role in strengthening earth science education, and strives to increase public awareness of the vital role earth science plays in mankind's use of resources and interaction with the environment.

Two AGI projects of the 1960s and 1970s have had a significant effect on earth science teaching methods and materials. The Duluth Conference produced the *Geology and Earth Sciences Sourcebook for Elementary and Secondary Schools*. The Earth Science Curriculum Project (ESCP) produced the secondary school textbook *Investigating the Earth* and related materials, including laboratory equipment and audio-visuals.

The Institute's National Center for Earth Science Education develops teaching resource materials, provides recognition for outstanding teacher and student achievement, and responds to [illegible] earth science education.

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Earth Science Education
for the 21st Century:

A PLANNING GUIDE

National Center for Earth Science Education
American Geological Institute
Alexandria, Virginia

recycled paper

Printed on Mohawk 50-10, an acid-free paper containing 60 percent recycled fibers. Dark flecks result from the 10 percent printed post-consumer waste paper from which the ink has not been removed. Chemicals required to remove ink may be more hazardous than those used in the manufacture of paper.

Design and cover illustration by Julie De Atley
Typeset in ITC Eras by Alexandria Typographic Services, Inc
Printed by St. Mary's Press, McGregor and Werner, Inc.

ISBN 0-922152-11-X

Contents

The scientifically literate person . . . understands key concepts and principles of science . . . and uses scientific knowledge and scientific ways of thinking for individual and social purposes.

American Association for the Advancement of Science
Science for All Americans

Introduction

Scientific literacy, so essential in our modern world of interwoven scientific and political actions, can only be achieved by making science an integral and interesting part of the kindergarten through grade 12 curriculum. America's lack of scientific literacy is clear evidence that we have turned off rather than switched-on our children's innate curiosity.

With the 1983 publication of *A Nation at Risk: The Imperative for Educational Reform*[1] and *Educating Americans for the 21st Century*,[2] scientists, educators, government officials, and others showed their concern about the lack of scientific literacy in America. At the same time, concerned citizens began looking at science, mathematics, and technology education in the nation's schools and were appalled at what they saw. Since 1983, hundreds of articles and reports have expressed alarm at the lack of scientific literacy in America and about the quality and quantity of science, mathematics, and technology being taught in the nation's elementary and secondary schools.

One of the most recent and compelling reports, *Science for All Americans*,[3] provides a comprehensive set of recommendations on how to move the nation toward scientific literacy. The report opens as follows:

> The terms and circumstances of human existence can be expected to change radically during the next human lifespan. Science, mathematics, and technology will be at the center of that change—causing it, shaping it, responding to it. Therefore, they will be essential to the education of today's children for tomorrow's world.

Concerns about scientific literacy are not new. In the late 1950s, following the launch of the Soviet satellite Sputnik, the U.S. Congress, the National Science Foundation (NSF), and the scientific and education communities voiced their concern about the poor quality of science and mathematics education in the nation's schools. The American Geological Institute (AGI) and several other professional organizations and groups of scientists responded by conducting major, precollege curriculum improvement projects. These projects, funded for the most part by NSF, produced a large volume of classroom materials oriented toward student inquiry, conducted teacher institutes, and involved scientists, mathematicians, and teachers. Great improvement in precollege science education occurred as a result of these projects. Unfortunately, the efforts of the 1960s and 1970s were not sustained.

Ever-increasing success in our space program, outstanding achievements in scientific research, and tremendous progress in technology seemed to make the nation forget that success and achievement in science and technology depend heavily on a scientifically literate society.

Fortunately for the nation, the message of *Science for All Americans* and myriad other reports has once again generated interest and concern in the Congress; federal, state, and regional funding agencies; corporations; and foundations. As a result, considerably more effort and money is now being spent on precollege science education programs.

In response to the growing national concern about precollege science education, AGI has developed this guide to assist school administrators, curriculum planners, teachers, and scientists in incorporating earth science in K-12 science curricula.

Earth Science Education for the 21st Century: A Planning Guide was prepared primarily for individuals with little or no background in earth science. It should, however, be of interest to earth scientists and others who are working to improve the quality of science education at local and national levels. The guide is divided into four main sections that provide a framework for planning and implementing earth science education programs. The sections are

- Goals to guide the development of K-12 earth science curricula.
- Concepts that are basic to understanding the Earth and its interacting systems.
- Recommendations for teaching earth science subject matter in grades K-12.
- Recommendations for implementing new earth science curricula in the schools.

The goals, concepts, and recommendations were developed by scientists, science educators, school administrators, and teachers who attended one or more of six regional conferences conducted by AGI. See the Acknowledgments for a complete listing of the organizations, universities, and individuals who assisted in preparing this guide.

Materials developed at each conference were reviewed, organized, and edited by an advisory board chaired by Robert L. Heller, and by a steering committee chaired by Fred N. Finley. A report listing the prioritized outcomes of these conferences, entitled "Open-File Report No. 90-1," has been compiled by AGI and is available at a nominal cost.

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1. The National Commission on Excellence in Education. *A Nation at Risk: The Imperative for Educational Reform* (1983).
2. The National Science Board Commission on Precollege Education in Mathematics, Science and Technology. *Educating Americans for the 21st Century* (1983).
3. American Association for the Advancement of Science. *Science for All Americans* (1989).

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Earth science is the study of the planet Earth's composition, processes, environments, and history, focusing on the solid earth and its interactions with air, water, ice, and life.

AGI National Center for Earth Science Education

Goals for Earth Science Education

Our children must understand ideas from earth science and the ideas earth science shares with other scientific disciplines. Without that understanding, we cannot hope to increase scientific literacy or to safeguard the Earth. Nothing less than the survival of our children and our planet is at stake today.

With scientific literacy as our general goal and earth science literacy as our particular goal, we proffer four interrelated goals that are essential to help guide the earth science education of our children. These goals are presented under the headings Stewardship, Appreciation, Scientific Thought, and Knowledge. Each goal refers to what students need to know to prepare them for becoming responsible participants in the social and political dynamics of the world.

Stewardship

Students need to become stewards of the Earth.

Stewardship means making informed decisions about using the Earth's resources and maintaining a high-quality environment. Making students aware of earth science issues, communicating knowledge about the issues, and learning about the Earth must be employed to solve existing problems and plan the future. Dealing with degradation of the Earth's water, soil, and air, for example, requires knowledge and appreciation of the Earth. By raising students' awareness and increasing their abilities to respond to environmental and resource issues in an informed way, we can attain effective stewardship.

Nothing less than the survival of our children and our planet is at stake today.

Appreciation

Students need to develop a deep aesthetic appreciation of the history, beauty, simplicity, and complexity of the Earth.

The day-to-day lives of students will be enriched if they know more about the areas where they live and travel. Developing an aesthetic appreciation of the Earth is essential to good stewardship.

Scientific Thought

Students need to understand ways in which earth scientists investigate the Earth.

Students should understand the nature of scientific thought within earth science. They should know that the quest to understand the Earth is based on observation; logic; ethics; theory; imagination; technological innovations; and the social, political, and economic context of the times. Scientists study the Earth in the field, in laboratories, in libraries, from submarines, and from space. Over the years, their ideas and methods have changed many times and will continue to change as scientific investigation continues. Their inquiries have enabled us to understand better the Earth and the impact of our actions, to predict future events, and to anticipate and minimize environmental problems. The success of inquiries by earth scientists has enabled responsible citizens to become an increasingly significant force within our environment.

Knowledge

Students need to understand essential earth science concepts.

The following eight concepts, developed or enhanced by earth scientists, are considered profound and historically important:

- The Earth is a unique member of the Solar System and may be replicated in other galaxies in the Universe.
- The Earth is a complex planet with five interacting systems
- The Earth is at least 4.5 billion years old.
- Changes in the Earth's systems occur over periods of microseconds to millions of years.
- The Earth's systems have evolved through time.
- Repeated interactions and transitions occur in the Earth's systems
- Scales in the Earth's systems vary from subatomic to astronomical.
- The Earth's systems contain a variety of renewable and non-renewable resources that sustain life

While learning these essential concepts, students should come to understand the Earth's past, present, and probable future. Students should be able to apply this understanding to accomplish the following

- Describe the objects and events that concern earth scientists.
- Provide reasoned, scientific explanations of those objects and events.
- Make justified predictions about future events.
- Make informed decisions about personal, day-to-day actions related to earth science.
- Make social, political, and economic judgments and decisions based on information from earth science.
- Express positive attitudes about science and the natural world.

Essential Concepts in Earth Science

Earth science has revolutionized the way we think about ourselves and our planet. Earth science also serves as an excellent vehicle for understanding and utilizing the theories and methods of other sciences—chemistry, physics, and biology. Chemistry is essential to understanding the ways the Earth was formed. Ideas from physics have been used to study the Earth's interior. Biology is vital for learning about the evolution of our atmosphere and the diversity of life that inhabits the planet.

Stephen Jay Gould, a prominent earth scientist, has labeled earth science an historical science because of its unique perspective on processes that operate for great periods of time. By careful observations, earth scientists can interpret how the Earth and other planets have evolved. Those observations are based on diverse scientific methods—qualitative and quantitative, field based and laboratory based. Data are collected while hiking in the field using maps, compasses, portable computers, seismographs, magnetometers, and gravity meters; from deep drilling to collect samples below the surface of the Earth and below the floor of the ocean; from the oceans using research vessels and submarines; from aircraft equipped with aerial cameras and other remote-sensing devices; and from orbiting satellites using a variety of remote-sensing instruments and other sophisticated equipment. The data are analyzed and represented using simple drawings, maps, charts, and tables, physical models; complex mathematical models; and computer-generated graphics. The full range of our technological abilities, simple and complex, old and new, are used by earth scientists in investigating the Earth. The following sections provide an overview of what students should know about earth science.

Earth science ... serves as an excellent vehicle for ... utilizing the theories and methods of ... chemistry, physics, and biology.

Earth in Space

The Earth is a unique member of the Solar System and may be replicated in other galaxies in the Universe.

The Earth, with its complex systems, and its Moon—along with the other planets (and their moons), asteroids, comets, and dust—travel in a well defined orbit around the Sun. These bodies make up the Solar System. The Earth's relative position and motion within the Solar System greatly influence the interaction of Earth's systems. This Solar System, however, is only a small part of the Universe in which it resides. The Sun is one of perhaps 300 billion stars that constitute the Milky Way galaxy in which the Solar System is located. The Milky

Way is only one of the more than one billion galactic clusters in the known Universe, each of which contains about 100 galaxies.

Stunning successes in space exploration came during the second half of the 20th century. Neil Armstrong's walk on the Moon; spacecraft flybys of Venus, Mercury, Jupiter, Saturn, Neptune, Uranus, and their moons; orbiters around the Moon, Mars, and Venus; and the landers on Mars and Venus provided an expanded perspective of the Solar System. These voyages, especially those that returned pictures to Earth, illuminated the fragility of our environment and, through comparative planetology, have told us much about our own origin and evolution. The Earth is unique in the Solar System, but the other planets and satellites represent stages that Earth has passed, could pass, or will pass through. Thus, these "snapshots" are useful for further unraveling Earth's history. Earth's Moon is a partial window into the first 1.5 billion years of Earth's history. Mars has earthlike channel patterns and volcanoes. Venus has volcanoes and may have undergone tectonic activity. Titan's atmosphere may be analogous to that of early Earth. Further afield, the study of star formation and evolution helps us understand the chemistry of Earth's rocks, air, water, and life. Other stars, like our Sun, may have earthlike planets. The challenge is to continue to explore and learn about the Earth in space.

Earth Systems

The Earth is a complex planet with five interacting systems.

The Earth is unique among the planets of the Solar System. It has five interacting systems, which consist of the solid earth (lithosphere), air (atmosphere), water (hydrosphere), ice (cryosphere), and life (biosphere). All these systems are dynamic, though their rates of change vary dramatically.

Solid Earth—Lithosphere

The lithosphere is the solid earth, the portion of the Earth that includes the surface and the resources that sustain and develop life and civilization. The Earth's surface consists of continents and ocean basins, which are composed of numerous plates that are driven by forces deep within the Earth. The plates, which are in constant, slow motion, separate and collide, causing mountains and deep ocean trenches to form and volcanoes and earthquakes to occur. At the same time, the continents are being eroded, and the sediments and organic contents are transported to the oceans by wind, water, ice, and gravity.

Internal forces also modify the Earth's surface. The concept of plate tectonics, originally based simply on the fit of continental margins, was later supported by geophysical studies of Earth's properties. Studies of the Earth's magnetism provided some of the best evidence for plate tectonics and showed how magnetic properties could be used to measure plate movement. By studying the thermal properties of the Earth and measuring how seismic waves, generated by earthquakes, are transmitted through the Earth, geophysicists have also uncovered evidence that the Earth's interior is a dynamic, moving environment that has caused mountains to rise, basins to sink, and entire landmasses to move, continually rearranging the surface pattern of continents and the configuration of oceans.

Surface and internal processes interacting with the solid earth and other Earth systems produce and distribute resources.

Air—Atmosphere

The atmosphere is the gaseous envelope surrounding the Earth. It is continuously in motion, circulating in complex but regular patterns and driven by direct and stored solar energy. The strong interactions between the atmosphere and the hydrosphere determine weather and climate and profoundly influence our daily lives.

Atmospheric scientists study the Earth's gaseous sphere in an attempt to understand the atmosphere's origin and evolution. They also monitor and predict daily and longer-term weather and climatic changes, solar activity, stratospheric wind shifts, and changes in the atmosphere. In the mid-20th century, the first computerized forecasting began, and the first weather satellites were launched. About the same time, measurements of carbon dioxide and chemical indicators of atmospheric temperature variations in Antarctic ice cores revealed significant global changes during the past 160,000 years. Advances in computer technology allowed scientists to create models of atmospheric circulation called global circulation models.

More recent research has focused on smaller-scale phenomena. Much of what determines the details of the weather depends on phenomena such as sea breezes, thunderstorms, tornadoes, wind shear, and squall lines. These phenomena are now better understood because of new computational techniques and new observational systems, such as Doppler radar, acoustic sounders, microwave profilers, and Doppler laser probes.

Recent research has also focused on understanding global changes in Earth's climate caused by increasing amounts of carbon dioxide and other greenhouse gases such as methane. Depletion in the thickness of the ozone layer in the upper atmosphere has been linked to release of such gases as chlorofluorocarbons into the atmosphere. Understanding the effect of these and other possibly toxic gases is also important. Because global change involves the oceans, land surfaces, and ice, atmospheric scientists work with other earth scientists to understand the interlinked processes that change the Earth.

...the Earth's interior is a dynamic, moving environment that has caused mountains to rise, basins to sink, and entire landmasses to move ....

Water—Hydrosphere

The hydrosphere consists of water on and beneath the Earth's surface. It is the dominant feature of the Earth's dynamic surface and interacts with all other Earth systems. It is a major agent in changing the shape of the surface. It is essential to supporting life and is a major determinant of the Earth's climate and weather.

Almost 73 percent of the Earth's surface is covered by the continuous body of salt water that surrounds the continents and fills the Earth's great surface depressions. This area is the realm of oceanographers and other marine scientists, who study the physical, chemical, biological, and geological aspects of the world's oceans and ocean floors.

As knowledge of the oceans has increased and technology has advanced, oceanography changed from an observational science to an experimental science. This change resulted in several large multidisciplinary, multinational programs to investigate specific problems. Today, oceanographers study the ocean floor (its formation and structure), seawater (its circulation and chemistry), and the organisms that inhabit the seas. They also investigate human impact on the ocean and its resources and the ocean's influence on global climatic change. Ships and submersibles specifically designed for scientific research, and remote-sensing techniques, such as satellites, side-scan sonar, and remotely operated vehicles, are important tools of oceanographers.

Earth scientists also study fresh water. Surface water and ground water provide essentially all of the world's water-supply needs. Ground water is the largest readily available supply of fresh water and is especially important in those regions where precipitation and surface water—such as rivers and lakes—are rare. As the world's population increases clean fresh water may become the most important commodity for the survival of the human race! Ground-water specialists focus on the quality and quantity of ground water, on the movement of underground water, and on depletion rates. Questions of ground-water quantity and quality—related to natural and man-made pollution—are increasingly important.

Ice—Cryosphere

The Earth's cryosphere is frozen water in the form of snow, permanently frozen ground (permafrost), floating ice, and glaciers. The presence or absence of glacier ice is a function of global climate. Fluctuations in the volume of glacial ice bring about changes in sea level.

As the world's population increases, clean fresh water may become the most important commodity for the survival of the human race!

Scientists who study various components of the cryosphere are called glaciologists. They study seasonal changes in glacier area and volume in the Arctic and Antarctic by analyzing images from aircraft and satellite sensors and by making field observations from ships and submarines. Glacial geologists also study deposits and landforms left by past and present glaciers.

Life—Biosphere

The biosphere, which has existed for at least 3.6 billion years, is that part of the Earth where living organisms are found. It includes parts of the lithosphere, hydrosphere, and atmosphere. The biosphere profoundly influences the composition of the atmosphere and interacts with the other systems of the Earth.

From primitive single-celled to sophisticated multicelled organisms, life has evolved to fill virtually all of the ecological niches on Earth. The geologic record is replete with the fossilized remains of past organisms, such as trilobites and dinosaurs, which reached an evolutionary dead end. Human activities, such as deforestation, are contributing to an acceleration of the pace of naturally occurring extinctions of flora and fauna. This reduction in biodiversity of certain ecological niches, such as tropical rain forests, may have unsuspected consequences.

Interaction of Earth's Systems

The Earth's systems influence each other in important ways. The complex interaction of these systems is exemplified by how changes in the Earth's orbit, periods of intense volcanic activity, and climate affect glacier variation and fluctuations in sea level. In this case, the interactions are between the Earth-Sun system, the lithosphere, the atmosphere, the cryosphere, and the hydrosphere.

The Milankovitch theory, which concerns natural (astronomical) changes in the Earth's orbital elements, may explain changes from cooler to warmer climates and vice versa. Also, volcanic activity may cause short-term perturbations in climate. For example, when volcanic dust in the atmosphere blocks incoming solar radiation, global cooling may occur. A pronounced cooling interval can lead to a rapid expansion in the global volume of glacier ice, especially in the Northern Hemisphere. The volume of glacier ice on Earth today, if completely melted, would raise sea level by about 100 meters. Conversely, during the peak of an ice age; the volume of glacier ice on our planet about doubled, resulting in a substantial drop in sea level, perhaps as much as 125 meters. If the planet has begun a gradual natural cooling toward another glacial epoch, as some scientists believe, human activity (especially through generating excess carbon dioxide, methane, and other greenhouse gases) may mask or even override this natural process. Conversely, if climatic warming increases, as many scientists predict, melting of glacier ice may accelerate, and sea levels will rise. A significant rise in sea level would cause severe damage to most of the world's coastal and estuarine areas, home to more than half of the Earth's population. Glacial epochs, unlike greenhouse warming, which is likely to become significant over the next several decades, develop over tens of thousands of years.

Geologic Time

The Earth is at least 4.5 billion years old.

Geologic time is the time frame within which planets form, continents move, climates change ... organisms evolve ....

Few concepts in science are more difficult or important to appreciate and understand than geologic time, which is vastly longer than time as we usually perceive it. Geologic time is the time frame within which planets form, continents move, climates change, seas flood, continents recede, organisms evolve, and mountains develop.

Sedimentary rocks found in sea cliffs on the coast of Scotland in the late 1700s revolutionized scholars' perception of time and demonstrated the great disparity between historic time and geologic time. Sedimentary rocks, formed by the natural cementation or compaction of chemical precipitates, clay, sand, or gravel, occur in layered sequences. Most layers are deposited essentially horizontally, and only after compaction and cementation can they be tilted, as an integral mass, to any significant degree. Also, in any undisturbed sequence of sedimentary layers, the bottom layer must have been deposited first, and is thus the oldest. In Scotland, exposures studied by early geologists show that the nearly horizontal sequence of sedimentary rocks that lay beneath the local landscape rested on the eroded edges of what had to be a vastly older sequence of sedimentary rocks whose original horizontal layering is now nearly vertical. It is obvious that an earlier succession of sediments must have been deposited, cemented, tilted, and eroded. The Earth's history held a previously unexpected richness

Change

Changes in the Earth's systems occur over periods of microseconds to millions of years.

Changes in the Earth's component spheres are caused by natural processes and, in recent times, human activities. Some changes are obvious, such as large earthquakes caused by movement along faults in the Earth's crust, burial of a town by volcanic ash or lava or both, or floods. Other changes are more subtle, such as the slow creep of rocks on either side of a fault, slow movement of a glacier, or the drift of sand-sized particles along ocean shores.

Changes during parts of the Earth's geologic past took place in environments very different from those of today. Some of those environments required extremely long periods of time (millions of years) to develop. The record of those changes is preserved, to a lesser or greater degree, in terrestrial and marine sediments, in sedimentary and other types of rocks, in glacier ice, and in tree rings. Changes that have been deciphered from the geologic record include evidence of the Earth being struck by large asteroids, evidence of life forms that no longer exist or subsequently evolved into new forms, movements in the relative positions of the continents, past periods of extreme volcanic activity, and the repeated waxing and waning of great ice sheets in North America and Eurasia.

James Hutton, one of the principal founders of geology as a science, once stated a classic precept in geology: the present is a key to the past. Active processes that cause changes today can be used to decipher evidence of the past, found in the rock record. It is also true that the past is a partial key to the future. What we know about past changes allows us to predict what changes may occur, predictions that are especially important as we strive to understand and deal with the impact of humans on the Earth.

The processes of change in geologic time are often so slow that they may not be perceived within a lifetime. At other times, they are swift and destructive. There is a dramatic contrast between the nearly imperceptible uplift and erosion of mountains and the immediate impact of hurricanes, tornadoes, earthquakes, volcanic eruptions, and floods. Our perceptions of rates of change are crucial because they affect the way we choose to deal with many issues facing society. Important areas of earth science research now focus on predicting events that happen at both the slowest rates--such as climatic changes--and at the most rapid rates—such as earthquakes and volcanoes. We must assess present and future events on time scales ranging from seconds to millenia

Evolution

The Earth's systems have evolved through time.

Life, the Earth, and the Universe have evolved over the vast expanse of geologic time into what we know today. The concept of evolution started a revolution in science. One exciting task in the early 1800s was the attempt to unravel Earth's history and to understand its evidence as preserved in the rocks. Fossils were essential in this process. By the mid-1800s, generalized historical periods of Earth's history had been defined based on fossils. The oldest communities of organisms contained mostly life forms unknown among living communities. Successively younger communities gradually approached the composition of modern communities.

Charles Darwin accumulated massive documentation supporting a theory of gradual change of the biosphere, caused by natural selective forces acting through the newly discovered vastness of geologic time. His observations also led him to imply that the human species was a part of this lengthy ongoing process.

The Earth's hydrosphere has also evolved during the course of geologic time. Volcanoes add small amounts of "new" or juvenile water during eruptions. The oceans are the largest reservoir of water on Earth, about 97 percent of the total. Another two percent is water in its frozen state, the cryosphere. Surface water, ground water, and atmospheric vapor (about one percent of the water on Earth), are the water sources that support life. The hydrologic cycle governs the movement of water over, on, or under the Earth.

Planetary evolution has become a major theme in understanding Earth's history. The origin and evolution of our Solar System was one of the first topics to be examined during the early development of western science. The French philosopher Pierre Laplace proposed in 1796 that the Sun was surrounded by a large rotating disk of gas from which the planets and their moons formed. It was his theory that was eventually accepted as the standard against which others could be compared. Our increasing knowledge about interstellar clouds and star formation has given further credence to the theory, though many details remain to be established firmly.

All citizens need to understand the limit and vulnerability of the Earth's resources.

Cycles

Repeated interactions and transitions occur in the Earth's systems.

Cycles of change affect all Earth materials—solids, liquids, and gases—and incorporate all the processes that affect Earth materials. Cycles of great magnitude and importance are given special names and depicted in specially constructed diagrams (e.g., hydrologic cycle, rock cycle, plate tectonic cycle, carbon cycle, trophic cycle). Other cycles are also important to earth scientists Examples include geochemical cycles that describe the movements of elements within the Earth, the annual weather cycle, and tidal cycles.

Scales

Scales in the Earth's systems vary from subatomic to astronomical.

Changes in the Earth's environment are measured on many scales. Some changes are so small and others so great as to be nearly incomprehensible. Scale is important in every science. The scales of size and time involved in Earth processes and phenomena are, however, even more varied than those usually encountered in the other sciences. Volume and distance scales—used in studying Earth processes, Earth materials, and the Earth's place in space—range from those that describe the atomic structure of matter to those that describe the size and location of distant galaxies. The scales used to measure time and rates of change range from those that measure infinitesimal fractions of seconds to those that measure billions of years.

Comprehending the times, distances, and rates of change involved in Earth's processes is difficult, but it provides an exceptional challenge to students to expand their intellectual and conceptual horizons.

Resources

The Earth's systems contain a variety of renewable and non-renewable resources that sustain life.

Renewable and non-renewable resources are those gaseous, liquid, and solid earth materials that support life. All must be managed wisely. Non-renewable resources, such as soils, minerals, and fossil fuels, are not regenerated on a human time scale and are thus vulnerable to both overuse and misuse. Renewable resources, such as air, water, and plants, are recycled through the Earth's environment, but are changed by human activity, changes that are often deleterious, causing the resource to become unusable or unsafe. In extreme cases, seemingly unlimited renewable resources, such as water, can be made limited by pollution and overuse. All citizens need to understand the limit and vulnerability of the Earth's resources.

Teaching Earth Science

The teaching of earth science requires new curriculum objectives, new information on how students learn, new teaching strategies, and new procedures for assessing changes in student knowledge and understanding.

Three problems have hampered past and present curricula. First, earth science curricula have usually just exposed students to a broad range of topics from astronomy, geology, meteorology, and oceanography. Students have seldom been asked to develop an understanding of any one topic that would be complete enough to be meaningful and useful in their daily lives. This approach has resulted in attempts to teach far too much in far too little time.

Second, earth science curricula, developed before and after the reform era of the 1960s, were intended for a limited audience, primarily eighth and ninth grade students. Little, if any, earth science has been taught in elementary schools or senior high schools, and hardly any consideration has been given to developing the potential of women and minorities. As a result, many students have never developed an enthusiasm for earth science. This result is particularly unfortunate at a time when understanding the Earth's systems is so exciting and essential to creating a sense of lifelong stewardship for the Earth.

Third, most teaching methods have been based on the implicit assumption that students learn new ideas by listening to lectures, reading selections from a textbook, and completing worksheets and an occasional laboratory exercise. We now know that students may not develop the ability to describe and explain natural phenomena or develop the ability to make informed personal and political decisions in this way. Instead, students must be intellectually involved in activities that by design require them to construct their own understanding of the Earth's systems. They must also face the misconceptions they bring into the classroom, and experience the satisfaction of being able to use their new ideas fruitfully and independently. Fundamental changes in the principles that direct the development of new earth science curricula are essential. In addition to being guided by the goals for earth science education presented earlier, new curricula must reduce the number of topics covered in classes so that students can develop a greater understanding of a smaller number of topics. The curricula must engage all students at all grade levels, especially women, minorities, and those who are handicapped. The curricula must also provide for the extensive experience and time necessary for students to develop their knowledge of the Earth's systems and apply their knowledge with confidence.

... new curricula must reduce the number of topics ... so that students can develop a greater understanding of a smaller number of topics.

Curriculum Objectives

Meeting the goals of earth science education requires planning units of instruction for elementary schools, junior high and middle schools, and senior high schools. In planning these units, specific objectives are necessary. New earth science curricula should enable students to achieve the following:

- Develop empirical descriptions of the Earth's systems, the interactions of those systems, and their evolution. For example, students should be able to describe the major geologic features of the Earth's surface.
- Develop explanations of the Earth's systems, their evolution and interactions, and the basic reasoning that supports the explanations. For example, students should be able to explain the co-evolution of the Earth's atmosphere and life forms.
- Make justified predictions about future events. For example, students should be able to predict basic local weather patterns and justify their prediction in terms of meteorological data and principles.
- Make informed decisions about personal, day-to-day actions related to the Earth's systems. For example, students should be able to decide how to limit their use of materials that are not recyclable.
- Make informed social, political, and economic decisions regarding issues related to Earth's systems. For example, students should be able to decide to support local, regional, and national efforts to improve water quality.
- Appreciate the history, beauty, simplicity, and complexity of Earth's systems. For example, students should be able to enjoy observing the night sky through the "eyes" of science and explain their observations to family and friends.

To meet these objectives, students will need to learn both content and methods from earth science. The content must be in the form of coherent ideas or concepts, not isolated words, phrases, and statements that are simply memorized. The content should be limited to essentials, but should be of sufficient depth to be understandable at any particular level. Various methods of inquiry that earth scientists use to study the Earth and its systems must be selected carefully and should represent the full range of methods, which include the historical and experimental, the technologically simple and complex, the qualitative and quantitative, and laboratory and field methods. These methods should be taught along with the appropriate content and not learned as isolated "skills."

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How Students Learn

Curriculum design depends not only on establishing objectives, but also on understanding what students know and can do. We need to assess students' prior knowledge of earth science phenomena, their academic skills, and what will motivate them to learn.

Children bring to the classroom their own ideas about natural phenomena. Some of these ideas may be correct and more or less complete, but many others will be incorrect. For example, many students come to class believing that mountains were formed over a few years, "long ago, as many as a million years." Students do not easily give up these misconceptions. When they are told new ideas, they either select a few ideas that fit their existing view or misinterpret the new information to make it fit their existing misconceptions. The most substantial changes in students' knowledge seem to occur when students face their misconceptions and are then provided alternative explanations to develop new ideas.

In addition to understanding students' prior earth science knowledge, we must also understand their basic academic skills in reasoning, reading, writing, and mathematics. If certain skills are identified as missing or incomplete, they can be taught in the context of teaching about the Earth's systems. For example, students can be taught to explain some basic ideas in chemistry in an activity about ground-water contamination, to construct and interpret graphs of changes in barometric pressure over time, and to use mathematics to calculate travel times to near and distant planets. Students are more likely to understand the Earth's systems when they have the academic skills to read appropriate text materials and to interpret data in graphs and tables. Furthermore, students' academic skills are likely to improve when these skills are taught in the context of learning specific earth science topics.

Finally, it is important to know what motivates students to be involved in learning. The most basic motivation may lie in the opportunity to gain confidence in their ability to understand the world in which they live. When students learn to explain volcanic eruptions or predict the apparent shape of the Moon a week in advance, their self-concept and sense of competence can be enhanced. With this enhancement comes the desire to learn more. In addition, earth science offers great opportunities to capture students' initial interest. They can become engaged in learning about local and global environmental problems, such as acid rain and the greenhouse effect, through many spectacular and unusual phenomena that arouse their curiosity, such as earthquakes, tornadoes, and the northern lights.

The most substantial changes in students' knowledge seem to occur when students face their misconceptions ....

Teaching Strategies

Substantial advances have been made in understanding the nature of effective instruction. One of the basic premises of a modern instructional strategy is that students need to be provided a few essential ideas at a time and then work with those ideas extensively. Also, instruction is likely to be far more successful when the assigned activities are designed to build upon the students' correct ideas, offer challenges to their misconceptions, and provide new ideas that they can apply successfully to new situations. Under these circumstances, students can learn which of their initial ideas are correct, which ideas they need to abandon, and ultimately, which combination of correct ideas provides them with a more powerful understanding of the phenomena they are studying. This instructional strategy requires more time per topic.

The instruction outlined above requires classroom interactions that are different from what is typical. The primary change is the development of a cooperative atmosphere in which students' ideas are used in developing and conducting the instruction. For instruction to be successful, teachers must view teaching as communication. They need to be cognizant of how their students are thinking about a problem from the beginning of instruction through the end, and then help students refine their thinking.

This type of instruction requires more frequent and more in-depth discussions among students and between the teacher and students. The discussions should be focused on the results and implications of the instructional activities—cooperatively producing well-reasoned answers to questions and solutions to problems.

Even during direct instruction, when the teacher is presenting new ideas to the students (by lecture, reading assignments, films, etc.), classroom interactions need to be cooperative. That is, the teacher needs to hear from the students what is, and is not, being understood. Then the teacher can provide necessary clarifications. These interactions during direct instruction will introduce new ideas and make them understood well enough for a return to a student-centered activity that requires their application.

One additional feature of classroom interaction is important. As students progress to the point where they can begin to apply their new knowledge independently, less direct instruction and coaching should be needed and provided. At this point, the teacher needs to allow the students to gain confidence in their own abilities. The students need to see for themselves that they can apply their new ideas. Their success needs to be confirmed directly by the results of their work in instructional activities and by the teacher.

Assessment

Developing adequate assessment of changes in students' knowledge is critical to earth science education. The first principle of effective assessment is that the methods be authentic, i.e., consistent with the goals and objectives described earlier. Applying this principle means more than saying that tests must be related to the knowledge that the students were taught. Students must be asked to do on tests what they are asked to learn and do in class. For example, if the objective of the instruction is that students learn to debate issues related to domestic oil consumption, then they need to be asked to argue their position as part of the examination process. If the objective is that they learn to interpret weather data, then the examination must present data to be interpreted.

Students must be asked to do on tests what they are asked to learn and do in class.

Today, even when we claim we want students to learn to describe, explain, and predict, they are all too often asked on tests to fill in a blank in a sentence, match a word with a definition, label diagrams, or choose a correct answer from one of four or five alternatives. These types of tests usually can be mastered by students who have learned by rote unconnected facts, definitions and principles. These types of tests provide little insight regarding how well integrated and truly functional a student's knowledge might be.

New methods of assessment that require students to present descriptions, explanations, predictions, decisions, problem solutions, and their reasons or justifications for their work must be developed. Essay writing, solving simulated and, whenever possible, real scientific problems, solving laboratory-based problems, interpreting real data, developing predictions based on patterns of change, and writing descriptions and explanations should be included in all new test instruments. These methods, in conjunction with improvements using more typical techniques, would provide teachers with greater insight into their students' performance.

Implementation of Earth Science in Grades K-12

Implementing new earth science curricula will require substantial changes in the existing educational system. Earth scientists, science educators, teachers, and parents must all contribute to a sustained and coordinated effort.

Earth scientists must contribute their knowledge of the content and methods of their disciplines, their judgments of what people must know to be scientifically literate, and their political influence on educational policy. Science educators and teachers must contribute their knowledge of research in learning, motivation, classroom environments, teaching methods, principles of curriculum design, and the politics of education. Parents must articulate their aspirations for their children.

Four essential tasks must be accomplished if the earth science disciplines are to contribute significantly to the scientific literacy of our citizens:

- Develop new earth science curricula, instructional materials, and other teaching resource materials.
- Plan and implement political and parental support programs for changing educational policies.
- Plan and implement new, appropriate preservice and in-service teacher education programs.
- Form educational partnerships between organizations of geoscientists, business and government agencies, and educational institutions.

Developing Materials

The most critical task is to develop new K-12 earth science curricula, instructional materials, and other teaching resource materials. What is now available is somewhat limited and scientifically and educationally outdated. In addition, recent improvements in educational technology have rarely been applied to earth science education.

The main purpose of this guide is to provide a contemporary foundation for that development. Schools need new materials and resources that are scientifically current and that utilize the most recent educational technologies. Alternative curricula and instructional materials will also be needed for different urban, rural, or suburban localities, and geographic regions. Teachers will need varied curricula and instructional materials so they can select the approach that is best suited to their students and schools.

This development task will take substantial resources and sustained, coordinated efforts that involve scientists, science educators, science teachers, and specialists in educational technology. Necessary materials include the following:

- New and different textbooks
- Activities workbooks
- Sourcebooks of basic earth science content for K-12 teachers
- Manuals for field activities
- Case studies of resource and environmental issues and natural hazards
- Sets of actual earth science problems to be solved by students
- Children's books that "tell the story" of the Earth's systems
- Real-time and archived earth science databases
- Audio-visual materials, from simple maps and models to sophisticated video and compact discs
- Computer simulations

As new curricula become available, public awareness of the importance of earth science must also be developed.

Developing Support

As new curricula become available, public awareness of the importance of earth science must also be developed. This effort to inform the public and at the same time develop a broad base of support will require working with the media and making personal contacts with decision makers. Many groups need to be included: parents and teachers; state education officials, school district administrators, boards of education, and teacher-parent organizations; personnel in federal, state, and private agencies that set policy and determine funding priorities; federal, state, and local politicians, business and community leaders, and the general public.

Once sufficient political support has been developed, those citizens who have become concerned with earth science education need to work to change local educational policies. This effort to change policies is important because many curricular innovations have failed at the local level when the innovations were not consistent with the politics and resources of schools. Proposed innovations will require changes in the current educational philosophy of elementary and secondary schools regarding what knowledge and skills should be taught at various grade levels, how much time should be allocated to instruction in each subject or skill area; and how different curricular areas should be integrated. In addition, administrators will need to promote the innovations, provide support that will assist teachers as they learn to teach new subjects using new methods, and assist them in securing and maintaining the necessary equipment and materials. Finally, additional financial support or substantial reallocations of existing resources will be essential.

Preservice Teacher Education

New earth science curricula should be supported by changes in the preservice education of teachers. At present, too many people teaching earth science in elementary and secondary schools have minimal or no preparation.

Certification standards should be revised for both elementary and secondary school teachers. Elementary school teachers are seldom required to complete even one earth science course. Earth science topics, however, are included in most elementary school curricula. The minimum state requirements for certification for teaching secondary school earth science courses also need to be improved. The depth and breadth of required earth science course work should be increased; loopholes that allow underprepared teachers to teach earth science should be closed.

Changes in certification requirements should be accompanied by changes in college and university programs. New earth science courses, taught by faculty from geoscience departments, are needed for future elementary teachers. The content of the new courses needs to be related to the topics that future teachers will be asked to teach. Today, much of what preservice teachers learn is irrelevant to classroom practice. Also, the content should be presented in sufficient depth so that preservice teachers develop knowledge that is sufficient to critique, modify, and enrich the topics they will teach. The requirement that the topics be taught in some depth means that we may only be able to teach a few important topics well.

... loopholes that allow underprepared teachers to teach earth science should be closed.

New earth science courses will also be needed for prospective secondary school teachers. In these courses, the relationships between earth science and social, political, economic, and environmental issues need to be emphasized. Recent developments in emerging fields of study, like planetary geology, and in obtaining and processing data from remote-sensing devices need to be included in such courses.

There are important commonalities between secondary and elementary teacher education. Teachers usually teach science the way they were taught. Therefore, college and university science courses should be taught in ways that model the instructional techniques that teachers should use with their students. Preservice teaching experiences in the precollege classroom should be guided by master teachers who model the teaching methods used by faculty on the college and university campuses where the preservice teachers are educated. Finally, once new teachers are employed, they need continuing education and support in ways that are consistent with the principles they learned in the colleges and universities.

In-service Teacher Education

In-service training for experienced teachers is essential to enlist their support to implement new curricula and to help them introduce new teachers to earth science education. In addition to programs conducted by colleges and universities, programs that capitalize on informal educational opportunities will be needed. In-service programs should

- Provide teachers with experience in modifying their instructional strategies.
- Help teachers formulate a personal rationale regarding why all students should be literate in the sciences in general and in earth science in particular.
- Help teachers understand why classroom study, field study, and informal learning are all important.
- Provide teachers with the background, training, and experiences to make them aware of the interaction between earth science and society, and to develop an aesthetic appreciation of the Earth
- Provide teachers with the theoretical and practical application of accepted learning theories and a variety of strategies for teaching students from diverse socioeconomic backgrounds.
- Help teachers use new educational technologies and the many information sources available.
- Provide teachers the opportunities to study earth science in depth and to experience the nature of science through exposure to cutting-edge research as interns in a research environment.

... college and university science courses should be taught in ways that model the instructional techniques that teachers should use with their students.

Partnerships

A broad spectrum of partnerships will be needed to implement the recommendations in this report. It is crucial that the schools to be supported and advised are integral and indispensable partners with professional and business organizations and government agencies.

State-wide and national partnerships are important, but local or regional partnerships are essential. Such partnerships are necessary to establish a sense of community identity, an awareness of the natural resource and economic base that makes each community unique, and the identification of community-based environmental issues and concerns

The critical step in this process is bringing together representatives of higher education, school districts, local industry, government agencies, and other individuals to identify and agree on issues important to the community. Once consensus is obtained, plans for changes in school curricula can be formulated, and the partners can identify community resources that can be used to implement these changes in the schools

Many types of implementation are possible. The following are a few examples:

- Creating "visiting scientist" programs in which professionals from the community present guest lectures, assist teachers with laboratory or classroom activities, serve as advisors for students and teachers, and invite students and teachers to visit their organizations. Many earth science government agencies, companies, museums, and professional societies could serve as resources for cooperation. Retired earth scientists are an important group of individuals whose experience, knowledge, and time make them especially valuable.
- Developing new educational materials cooperatively. Teachers, working with local industry, consulting firms, government agencies, and universities, can put together packets of local data and information for classroom use in studying actual earth science problems. These partnerships could be most effective if several school districts cooperate.
- Developing ways that link classrooms (telecommunication networks) to the numerous computerized databases in earth science. The U.S. Department of Commerce and the U.S. Department of the Interior, for example, collect and maintain earth science data on many topics, including weather, mineral resources, water quality, and earthquakes. Teachers and students could monitor events in the world around them via telecommunication links to scientists and to earth science databases. Rural schools, in particular, can gain a connection to the scientific community through this approach.
- Establishing programs between state and federal earth science agencies and local school districts to permit teachers to work closely with research scientists, gaining direct exposure to current research.

Teachers and students could monitor events in the world around them via telecommunication links to scientists and to earth science databases.

Closing Statement

This guide synthesizes ideas and issues discussed by scientists and educators at conferences convened throughout the nation. Participants in these discussions have already begun to use these ideas in developing their own programs. The guide identifies common ground for those interested in improving precollege earth science education, and we hope that it provides a starting point for further discussion, planning, and implementation at all levels.

Acknowledgments

The American Geological Institute Executive Committee wants to acknowledge, with special thanks, the advisory board and the steering committee; all contributors to the six regional conferences; the conference co-conveners, participants, and speakers; and the AGI staff, who helped make this guide possible (see lists that follow). The Executive Committee also wants to extend special thanks to Andrew J. Verdon, Jr., AGI Director of Education, for his role in planning and conducting the conferences and for supervising the production of the guide. Special thanks are also due to Rex Buchanan of the Kansas Geological Survey, who served as editorial consultant for the guide, to William H. Matthews III, Professor Emeritus, Lamar University, for his consultation and written contributions, and to Marvin E. Kauffman, former Executive Director, American Geological Institute, for his support and advice throughout the project.

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Funding for the conferences was provided by the National Science Foundation Directorate for Education and Human Resources, the National Science Foundation Directorate for Geosciences, and by individuals, industries, universities, and other organizations.

AGI gratefully acknowledges the following individual financial contributors: Frank W. Harrison, John D. Haun, Robert L. Heller, Melvin J. Hill, Philip E. LaMoreaux, Grover E. Murray, Jack C. Threet, M.O. Turner, and A.G. Unklesbay.

Industry financial support was provided by Carolina Sunrock Corporation, Butner, North Carolina; LITHCO, Kings Mountain, North Carolina; Martin Marietta Aggregates, Raleigh, North Carolina; Material Sales Company, Salisbury, North Carolina; National Stone Association, Washington, D.C.; Nello L. Teer Company, Durham, North Carolina; North Carolina Aggregates Association, Raleigh, North Carolina; Texaco Denver, Colorado; Union Pacific Resources Company, Englewood, Colorado; and Vulcan Materials Company, Winston-Salem, North Carolina.

The following universities and organizations provided monetary and/or in-kind contributions: Colorado Alliance for Science, Colorado School of Mines, East Carolina University, Education and Industry Committee for North Carolina, Ohio State University, Trinity University, University of Southern California, Los Angeles, and the Wisconsin Academy of Science, Arts and Letters.

Other organizations instrumental in supporting this work include the American Association for the Advancement of Science; member societies of the American Geological Institute; National Aeronautics and Space Administration; National Oceanic and Atmospheric Administration; National Science Teachers Association; state geological surveys of Idaho, Illinois, and Wisconsin; and U.S. Geological Survey.

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