

The National Geomagnetic Initiative

U.S. Geodynamics Committee, National Research Council

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The National Geomagnetic Initiative

U.S. Geodynamics Committee
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

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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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Preface

The U.S. Geodynamics Committee (USGC) began considering challenges and opportunities in geomagnetic research in 1988, thanks in large part to the efforts of John Hermance. A USGC-appointed task group, chaired by Rob Van der Voo, recommended that the USGC convene a workshop to:

- address challenges and future directions in geomagnetic research and applications;
- consider the need for an ongoing mechanism for future discussion, interaction, and coordination; and
- develop a plan of action.

The USGC accepted this recommendation and, in July 1990, convened a planning group to design a workshop for the above-stated purposes, emphasizing those aspects of research and applications related to temporal and spatial variations of the geomagnetic field in the solid Earth and geospace (atmosphere, ionosphere, and magnetosphere) environment. From these discussions, the concept of a **national geomagnetic initiative** emerged.

The National Geomagnetic Initiative Workshop was held in Washington, D.C., on March 16–20, 1992. The workshop addressed scientific challenges in four principal areas:

1. main field and core processes;
2. electromagnetic induction in the solid Earth and oceans;
3. lithospheric magnetic anomalies; and
4. magnetospheric and ionospheric processes.

The workshop also addressed issues common to these areas related to instrumentation, analytical techniques, computational facilities, and data access and management.

As recommended by the task group, the topics of paleomagnetism and archaeomagnetism were not addressed at the workshop. These topics were addressed in an earlier report, *Problems and Current Trends in Rock Magnetism and Paleomagnetism* (Subir K. Banerjee, Robert F. Butler, and Victor A. Schmidt, editors; Washington, D.C.: American Geophysical Union, 1986). The committee has included in the present report some amplifications based on a document, *GP Initiative on the Earth's Magnetic Field* (Kenneth L. Verosub [chairman], George E. Backus, Edward R. Benton, Robert S. Coe, Dennis V. Kent, and Ronald F. Merrill), which was presented to the Geomagnetism and Paleomagnetism Section of the American Geophysical Union in October 1988.

Participation in the workshop (there were about 90 attendees) was sufficiently broad to be representative of the major scientific topics and operational issues addressed at the workshop and the relevant current and planned national and international programs. Several constituencies were represented at the workshop: groups from the National Research Council—in particular, the Space Studies Board, the Committee on Solar-Terrestrial Research, and the Board on Earth Sciences and Resources; national scientific societies through their memberships, especially the American Geophysical Union, the Society of Exploration Geophysicists, and the Geological Society of America; government agencies; and industry. Although several foreign scientists participated in the workshop, the study was undertaken mainly to guide the U.S. scientific community. However, the USGC recognizes that implementation of some of the report recommendations will require the participation of foreign scientists and governments.

This report is based on the findings and recommendations of the workshop as set forth in a draft of the workshop proceedings submitted to the USGC. It is intended as a comprehensive overview of geomagnetism that describes the scope of the science and its interdisciplinary importance.

By describing the totality of geomagnetic activities in research and applications sponsored by a wide range of federal, state, and other organizations, the document identifies a broad spectrum of fundamental scientific and societal concerns and thus constitutes a truly national enterprise.

The report contains three unrefereed appendixes. The first two of these contain draft statements prepared by the working groups of the workshop. The third contains details of the workshop organization.

The statements prepared by the working groups were intended to represent a balanced view of the major scientific problems, challenges, and concomitant needs for various aspects of geomagnetism. The working group reports were prepared under the guidance of working group chairs, who endeavored to take account of suggestions made during the meetings and to reflect a consensus of the discussions. Constraints of time did not permit review of each working group report by all group participants; thus, individual participants may not agree with all statements in the reports, and these group reports do not necessarily reflect the views of the USGC. However, they contain a wealth of information regarding the challenges and opportunities in geomagnetism and provide a basis for further discussion of these issues.

The appendixes in this document are included solely for the interest of the reader. The reports in Appendixes **A** and **B** have not been subjected to review by the National Research Council. Any conclusions or recommendations that are given or implied in them are the opinions of the individual authors or working groups. Responsibility for the main text of the report rests with the USGC.

The USGC expresses thanks to all who contributed to the success of the workshop, especially the members of the Executive Committee of the workshop, John Hermance (chair), William Hinze, Robert Langel, and Christopher Russell, and to the chairs of the working groups and subgroups. The USGC is pleased to acknowledge the U.S. Department of Energy, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration (Headquarters and National

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Geophysical Data Center), National Science Foundation, U.S. Air Force, and U.S. Geological Survey, whose support made this report possible.

The USGC notes with sad regret the untimely death of Edward Benton, who served on the Executive Committee of the workshop and contributed so much of his personal energy toward assuring the success of this enterprise.

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THE NATIONAL GEOMAGNETIC INITIATIVE

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1

Executive Summary

INTRODUCTION

The Earth's magnetic field, through its variability over a spectrum of spatial and temporal scales, contains fundamental information on the solid Earth and geospace environment (the latter comprising the atmosphere, ionosphere, and magnetosphere). Integrated studies of the geomagnetic field have the potential to address a wide range of important processes in the deep mantle and core, asthenosphere, lithosphere, oceans, and the solar-terrestrial environment. These studies have direct applications to important societal problems, including resource assessment and exploration, natural hazard mitigation, safe navigation, and the maintenance and survivability of communications and power systems on the ground and in space.

Studies of the Earth's magnetic field are supported by a variety of federal and state agencies as well as by private industry. Both basic and applied research is presently supported by several federal agencies, including the National Science Foundation (NSF), U.S. Geological Survey (USGS), U.S. Department of Energy (DOE), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and U.S. Department of Defense (DOD) (through the Navy, Air Force, and Defense Mapping Agency). Although each agency has a unique, well-defined mission in geomagnetic studies, many areas of interest overlap. For example, NASA, the Navy, and USGS collaborate closely in the development of main field reference models. NASA, NSF, and the Air Force collaborate in space physics. These interagency linkages need to be strengthened.

Over the past decade, new opportunities for fundamental advances in geomagnetic research have emerged as a result of three factors:

1. well-posed, first-order scientific questions;
2. increased interrelation of research activities dealing with geomagnetic phenomena; and
3. recent developments in technology.

These new opportunities can be exploited through a **national geomagnetic initiative** to define objectives and encourage coordination of efforts among federal and state agencies, academic institutions, and industry to systematically characterize the spatial and temporal behavior of the Earth's magnetic field on local, regional, and global scales in order to understand the physical processes in the solid Earth and geospace environment, and to apply this understanding to a variety of scientific problems and to technical and societal needs.

SCIENTIFIC AND SOCIETAL ISSUES

Geomagnetic studies are driven by a host of first-order scientific problems as well as by significant societal concerns. These studies have a renewed importance because interdisciplinary investigations have defined critical and solvable research problems. Recent technological advances—including increased computational power, improved instrumentation and observational platforms, and inversion schemes—have improved research capabilities.

Examples of fundamental issues in global dynamics that can be addressed by this proposed geomagnetic initiative include the following:

- What are the mechanisms sustaining the Earth's magnetic field?
- How does the geomagnetic field reverse?

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- How are fluids—water phases and/or molten magma—distributed in the deep crust, and what is their role in regional tectonic processes?
- What is the magnitude of true polar wander?
- What petrological and petrophysical processes are associated with large-scale, systematic differences in the magnetization of the lithosphere?
- What are the plate tectonic building blocks?
- How do solar-terrestrial interactions disrupt communication links and power-transmission systems, and can these effects be predicted and mitigated?

Main Field and Core Processes

The mechanism for generating the geomagnetic field remains one of the central unsolved problems in geoscience. Investigation of this problem brings together observationalists, who study the present morphology and history of the field; applied mathematicians, who create numerical models (for example, dynamo models); and theorists, who interpret the observations and numerical models. The geodynamo is one of many interrelated problems addressed by studies of the core and mantle of the Earth. Other problems include core and lower-mantle diffusivities; topography of the core-mantle boundary; fluid motion at the surface of the core; the nature and extent of momentum and energy transfer between the core and mantle; and possible thermal influence of the mantle on core dynamo action.

The conductivity of the lower mantle is a focus of research through laboratory measurements of rocks under high temperature and pressure and through interpretation of changes in the geomagnetic field. At present, conductivity is known only to within several orders of magnitude. To model adequately the conductivity structure of the Earth's deep

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interior, it is necessary to characterize long-term external fields produced by currents in the magnetosphere and to understand how these external fields interact with induced fields in the solid Earth. For very deep Earth studies, such as those of interest to the international Studies of the Earth's Deep Interior (SEDI) program utilizing source fields having periods of a few years and longer, it is also necessary to separate the temporal fluctuations in the Earth's core from those in the magnetosphere.

A better description of the geomagnetic field and its secular variation has applications in many related areas, one of which is navigation, including directional orientation. An understanding of core processes will improve predictive capabilities for global charting. A large number of civilian and military systems still depend on magnetic directional information for either primary or backup systems. The development and updating of standard magnetic field models, such as the International Geomagnetic Reference Field (IGRF), to describe the main field in space and time are invaluable for identifying anomaly fields associated with lithospheric structures, many of which are important in geophysical exploration for mineral and energy resources.

Electromagnetic Induction in the Solid Earth and Oceans

Improved techniques for imaging the electrical structure of the Earth using naturally varying electromagnetic fields have provided important new insights on interior structures and processes. Electrical conductivity is strongly modulated by large-scale dynamic processes in the Earth, particularly when grain-boundary phases, such as fluids (water and/or melt), minerals (especially sulfides), and graphite are involved. Electrical conductivity imaging has important practical applications, particularly at shallow levels in the crust. These include energy, mineral, and water resource exploration; reliability of electric power grids; ground water protection; and waste management.

Electrical structures in the crust and upper mantle are mapped through regional electromagnetic surveys. It is important to map such structures in order to strip off their effects on measurements of the electrical structure of the middle and lower mantle. In this sense, regional surveys are of interest in global studies and for investigating various mechanisms for core-mantle coupling. Ocean currents generate electric fields through interactions with the geomagnetic field. Electric field measurements on the seafloor are useful for monitoring large-scale ocean currents and for studying the long-term variability of the oceans.

Lithospheric Magnetic Anomalies

Few geophysical methods have had a greater impact on the geological sciences than magnetic methods. Magnetic surveys provide key information concerning the geological, tectonic, and thermal state of the Earth's lithosphere. The use of airborne geophysical surveys is a cost-effective way to map the lithosphere.

The discovery of magnetic anomalies in oceanic crust was critical for development of the plate tectonics theory. Insights into the character and depth of magnetic source regions aid investigations of the mechanical and thermal structure of the lithosphere, crustal and oceanic accretion and evolution, true polar wander, the variation of magnetic field intensity with time, and the process of magnetic field reversals. The large dynamic range of magnetization intensity in rocks enables the detection of otherwise subtle variations in lithology, rock properties, and structure. Persistence of magnetization in the lithosphere makes magnetic methods useful for studying its deep levels. The ultimate goal of interpreting magnetic anomalies is an understanding of the three-dimensional distribution of magnetization from which, together with other geophysical data, the geological and tectonic state of the lithosphere can be deduced.

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Magnetic anomaly studies have important societal applications. They can be used to delineate features associated with mineral or hydrocarbon accumulations, such as igneous intrusions, fault zones, salt domes, and anticlines. Because crustal magnetization is sensitive to metamorphism and hydrothermal alteration, magnetic contrasts in the crust reflect variations in thermal and geochemical histories that may be diagnostic for certain energy and mineral deposits. National programs to evaluate earthquake and volcanic hazards, to characterize environmentally contaminated areas, and to permit safe disposal of radioactive waste benefit from magnetic anomaly studies.

Magnetospheric and Ionospheric Processes

The geomagnetic field spans all regions of the Earth, from the core, through the oceans and atmosphere, to the ionosphere and magnetosphere. Spatial and temporal changes in the geomagnetic field provide important information on the physical properties of these regions and their connectivity. These changes also provide warnings of natural hazards in space, such as geomagnetic substorms and storms.

The ionosphere and magnetosphere are a closely coupled system that channels energy and momentum from the solar wind to the atmosphere. A number of coupled current systems flow in the conducting plasmas that fill these regions. These currents are responsible for most of the temporal changes in the geomagnetic field that occur on time scales of seconds to days, including magnetic pulsations. Studies of the ionosphere and magnetosphere seek to obtain a quantitative understanding of the flow of energy and momentum through the solar wind, magnetosphere, and ionosphere systems; understand the physics of magnetic reconnection at the magnetopause, the response of the magnetosphere to changes in solar wind pressure, and the processes responsible for viscouslike interactions;

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and understand the physical mechanisms responsible for generating pulsations and controlling their cross-field transport in the magnetosphere. These studies also address the temporal and spatial morphology of magnetic field transients, particularly the effects of induced fields within the Earth on transients observed on or near the surface. These transients can produce large potential drops and associated current surges that can cause serious damage to large-scale power distribution systems and communications networks.

Operational Aspects and Data Availability

Observational programs have led to important advances in geomagnetic research and to the application of these research results to other geophysical disciplines. Comprehensive magnetic surveys by ship were begun more than 200 years ago. Permanent magnetic observatories were established around the world more than 150 years ago. Magnetic surveys by aircraft were begun about 50 years ago. Initial surveys by satellites were undertaken about 20 years ago. Measurements made directly on the ocean floor are now becoming available. These data represent a rich national resource for both present and future generations of scientists.

Advances in geomagnetic research require observational programs and the timely availability of data derived from:

- land and ocean floor measurements;
- marine and aircraft measurements;
- satellite measurements; and
- prehistorical reconstructions, historical data, and laboratory measurements.

The basic issues regarding availability of geophysical data have been addressed in several National Research Council reports, including those of the Committee on Data Management and Computing (CODMAC)

(1982, 1986, 1988), *Geophysical Data: Policy Issues* (1988), and *Solving the Global Change Puzzle* (1991). The present report emphasizes the importance of effective availability of geomagnetic data and associated data products through national data centers, World Data Centers, and distributed data centers.

OVERVIEW OF RECOMMENDATIONS

The following discussion summarizes the essential recommendations presented in the body of this report. Because it is a summary, however, it is not intended as a substitute for the specificity of the recommendations given in more detail elsewhere. The order of the recommendations does not indicate a priority ranking.

1. A **national geomagnetic initiative** should be undertaken to define objectives and encourage coordination among federal and state agencies, academic institutions, and industry to systematically characterize the spatial and temporal behavior of the Earth's magnetic field on local, regional, and global scales in order to improve the understanding of the physical processes in the Earth and the geospace environment, and to apply this understanding to a variety of scientific problems and to technical and societal needs.
2. This initiative should include a plan with both short-range and long-range objectives to characterize the magnetic field. For studies at the Earth's surface, the objectives should include the following:
 - better distribution of standard geomagnetic observatories with modern digital equipment;
 - improved mapping of the crustal magnetic field at high spatial resolution; and

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- better characterization of the electrical conductivity of the Earth utilizing both magnetic variation and magnetotelluric arrays.

For space studies, the objectives should include continuous monitoring of the following:

- the Earth's main field;
- the state of the magnetosphere; and
- solar wind.

For laboratory studies, the objectives should include the following:

- improved measurements of magnetic properties and electrical conductivities of rocks and the geological processes that control them; and
- reconstruction of prehistorical variations of the Earth's magnetic field using archaeomagnetic and paleomagnetic measurements.

The objectives should also address the issues involving the preservation and release of existing and future data, including:

- the continuation of observational programs and the preservation of resultant data;
- the arrangement, where possible, for the release of relevant proprietary and classified geomagnetic data to the scientific community; and
- the maintenance of national centers to serve as repositories of geomagnetic data, with emphasis on the management of and access to existing and future data.

3. Responsibility for implementation of the national geomagnetic initiative rests with the scientific community, which should develop a

mechanism to carry the initiative forward. This mechanism should involve the relevant federal and state organizations, academic institutions, industry, and national scientific societies, especially the American Geophysical Union, the Society of Exploration Geophysicists, and the Geological Society of America. It should also take account of pertinent international programs and activities. These diverse elements of the scientific community concerned with geomagnetism—and international bodies concerned with relevant international scientific programs—have a clear opportunity to make their own activities more effective through the kind of cooperation and coordination envisioned for this national geomagnetic initiative.

4. As part of this initiative, special attention should be given to maintaining and improving communication and coordination among the diverse activities in geomagnetism in federal and state agencies, the academic community, and industry—with a view toward encouraging improved efficiencies and fulfillment of goals in research and applications. This effort should include a provision for ongoing discussions of the needs and activities of the geomagnetic community, especially the programs of government agencies. It should also include a provision for establishing interdisciplinary task groups involving the scientific and engineering communities that will organize, design, and implement specific research programs.

2

Scientific Framework

THE GLOBAL PERSPECTIVE

The Earth's magnetic field, through its variations on a wide variety of scales in space and time, carries fundamental information on a variety of dynamic systems in the Earth's interior and the geospace environment. The magnetic field originates from chaotic fluid motions in the core and is significantly distorted by its interaction with the solar wind. The Earth's lithosphere, asthenosphere, deep mantle and core, oceans, and solar-terrestrial environment—either as primary sources or as induced secondary sources—contribute magnetic "signals" that must be separated and decoded to obtain an "image" of the underlying physical processes. Recent technological advances present unique opportunities for studies of the geomagnetic field to contribute to the understanding of a variety of dynamic processes in the solid Earth and geospace environment.

Historically, geomagnetic studies have been at the leading edge of geophysical research. The first application was in the field of navigation, then in the monitoring of the Earth's changing geomagnetic environment through global magnetic observatories, next in geophysical exploration and regional surveys from aircraft and ships, and finally in the refined charting of dynamic processes in the Earth's magnetosphere, lithosphere, and core by modern space vehicles. Of particular note, the first quantitative evidence for plate tectonics was derived from precision magnetic charts of the ocean basins.

The future promises even greater contributions from the national and international geomagnetic community. The following are examples of the

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fundamental questions in global dynamics that could be addressed by the proposed initiative:

- What are the mechanisms sustaining the Earth's magnetic field?
- Is the secular variation a fundamental part of the dynamo mechanism?
- How does the geomagnetic field reverse?
- What is the distribution of electrical conductivity in the mantle?
- What role does the magnetic field play in coupling the core and the mantle, contributing to changes in the length of the day over time scales of decades?
- How are fluids—water phases and/or molten magma—distributed in the deep crust, and what is their role in regional tectonic processes?
- How are physical discontinuities within the Earth sustained—petrologically, thermally, and dynamically—on regional and global scales?
- What is the magnitude of true polar wander?
- What are the plate tectonic “building blocks” of the lithosphere and how were they assembled?
- What petrological and petrophysical processes are associated with large-scale, systematic differences in the magnetization of the lithosphere?
- What are the fundamental processes through which plasma and radiation from the sun interact with the geospace environment?
- How are magnetospheric and ionospheric processes electrodynamically coupled?
- Do solar-terrestrial interactions modify short-term weather and long-term global climate change?
- How do solar-terrestrial interactions disrupt communication links and power-transmission systems, and can these effects be predicted and mitigated?

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New opportunities in geomagnetic research are driven by the confluence of these well-posed, first-order scientific questions with recent developments in technology. Among the technological advances are the use of satellites for navigation, communications, and magnetic field monitoring; the application of new computer technology—work stations, supercomputers, and optical disk storage media for large data bases—to geophysical modeling and interpretation; and the implementation of low-noise, high-resolution instrumentation.

The scientific issues that can now be addressed through implementing this technology include the following:

- the recovery and interpretation of low-amplitude, long- and short-wavelength magnetic anomalies from airborne, marine, and satellite surveys;
- the nature of the coupling of ionospheric and magnetospheric processes;
- an understanding of dynamic processes in the core as they affect global magnetic field modeling and long-term prediction of secular variations; and
- regional and global electromagnetic induction phenomena, including those processes associated with the dynamics of the oceans themselves.

An initiative to capitalize on the new opportunities and to address questions related to geomagnetism can be readily and cost-effectively mobilized within the traditional research establishment (federal and state agencies, academia, industry, and scientific societies). Many aspects of this initiative are under way or have already been planned. Interagency coordination would minimize duplication, establish priorities at the highest levels, and assure that the required facilities were in place when needed. Such a broad coalition would not only improve the quality and competitiveness of the basic research enterprise in this country (with its concomi

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tant improvement in the quality of higher education), but it would provide direct benefits to the public at large, including a better understanding of solar-terrestrial influences on the biosphere (that is, the impact of phenomena related to geomagnetism on biological systems), a refined assessment of natural resources and natural hazards of the continental and oceanic crust, improved and safer navigation, and more reliable satellite-based communications.

THE DYNAMICS OF THE GLOBAL GEOMAGNETIC ENVIRONMENT

Contemporary views of the Earth's magnetic field emphasize its variable nature on a wide range of scales in space and time. Although it is sometimes convenient to think of the "main field" of the Earth as having a static, dipole-like quality, this approximation is valid only at time scales significantly less than 10^4 years. Perhaps a third of the core field is nondipolar, and much of that fluctuates significantly over periods of a few years to a few centuries; this is called *secular variation*.

The main magnetic field is created by complex fluid motions in the Earth's core that sustain a hydromagnetic, self-excited dynamo (the *geodynamo*), which arises from processes connected with the chemical and thermal evolution in the core. The geomagnetic field exhibits remarkably rapid variation relative to other deep-seated geophysical phenomena. For example, the speed of westward drift of the geomagnetic field is 10^6 centimeters (cm) per year, whereas the speed of continental drift is typically on the order of a few centimeters per year. The strength of the geomagnetic dipole component is currently decreasing at a rate that, if continued, would completely eliminate it in 1,000 years. In fact, the secular variation of the geomagnetic field observed by archaeomagnetism and paleomagnetism demonstrates significant changes over the time scale of 10^3 and 10^4 years. On the same time scale, but less frequently, the field experiences a complete reorganization known as a *polarity transition*.

or *geomagnetic reversal*. All of these changes, which are rapid in a geological sense, reflect the dynamic features of the main geodynamo mechanism.

At periods of less than a few years to a decade, contributions from internal field sources originating in the core overlap the spectrum of transient external field sources in the magnetosphere and ionosphere. These external magnetic field sources fluctuate over characteristic times ranging from a few seconds to a few years or longer and have characteristic dimensions at the Earth's surface of 10^2 to 10^4 kilometers (km). These fields are due to energetic magnetic disturbances (sometimes exceeding thousands of nanoteslas) from natural electric current systems in the ionosphere and magnetosphere. They are triggered and/or driven by the interaction of the Earth's magnetic field with plasmas and radiation emitted by the sun. A network of recording magnetometers on the Earth's surface can be used in conjunction with orbiting spacecraft to monitor the temporal and spatial morphologies of these magnetic fields to provide important constraints on diagnosing fundamental physical processes in the solar-terrestrial environment.

Because these external fields are transient in space and time, they serve as natural low-frequency “radar” signals that diffuse into the Earth's interior. Some of this energy is scattered by various geological features at depth and arrives back at the Earth's surface. Analysis of these transient magnetic field variations (and their associated electric fields) at the Earth's surface offers a powerful means for “imaging” the conductivity structure of the Earth's interior and for understanding global and regional processes in the lithosphere, asthenosphere, and deep mantle.

Surveys of the “static” magnetic field components from ships, aircraft, and low-orbit satellites are used to understand the geological, tectonic, and thermal state of the Earth's crust. Magnetic surveys on land are used to characterize terrane boundaries, orogenic belts, and sedimentary basins, and thus the genesis and evolution of continents. Magnetic surveys in the marine environment place constraints on conceptual models

of seafloor spreading processes, transform faulting, and the evolution of hot spots. It is increasingly apparent, however, that “static” magnetization is not static in the conventional sense. Rather, this magnetization varies in space and time as the primary magnetic signatures are overprinted by fundamental thermal and petrological processes or are modified by tectonic processes that translate, rotate, or deform the crust.

The *Magnetic Anomaly Map of North America*, published by the Geological Society of America in 1987, was a milestone in the understanding of the static magnetic field of the continent. Yet, this digital data base has critical limitations caused by inadequacy of data in some locations, disparate survey specifications, and uneven treatment of regional fields. A more accurate, second-generation digital data base of the low-altitude magnetic field of the continent could be developed by employing a combination of satellite and high-altitude aircraft surveys to “stitch together” the numerous low-altitude surveys that were used to construct the map.

One of many significant contributions of Magsat, a dedicated magnetic field satellite flown by NASA in 1979–1980, was the measurement of long-wavelength magnetic anomalies which suggest that the petromagnetic character of the lithosphere has been modified through geological time; this finding has profound implications for the evolution of the oceanic and continental crust. However, at the level of precision needed for such refined studies (5 nanoteslas or less), static-field survey data can be significantly contaminated by external fields from transient ionospheric sources. In the future, more accurate surveys—using an Earth-based, global monitoring network—must compensate for these external fields on a more systematic and comprehensive basis than is presently done.

An upgraded global monitoring network is not only essential for correcting magnetic survey data; it would also be used to define the conductivity structure of the Earth's lithosphere and upper mantle and to study fundamental plasma processes in the magnetosphere. Ground-based

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data are critical for discriminating between temporal and spatial effects in satellite observations of processes in the magnetosphere.

There is a strong dependency between space-based and ground-based observational facilities. These facilities, which require major funding commitments and involve long lead times for implementation, have long-term value to many federal agencies and to the scientific community at large.

RECOMMENDATIONS

- **A national geomagnetic initiative** should be undertaken to define objectives and encourage coordination among federal and state agencies, academic institutions, and industry to systematically characterize the spatial and temporal behavior of the Earth's magnetic field on local, regional, and global scales and to apply this understanding to a variety of scientific problems and to technical and societal needs. This characterization should be undertaken using satellites, aircraft, ships, and surface measurements (for example, observatories and regional arrays), to provide a better understanding of dynamic processes in the Earth's interior and its geospace environment, from the inner core to the outer boundaries of the magnetosphere.

3

Scientific Issues and Research Opportunities

ISSUE 1: DYNAMICS OF THE EARTH'S CORE AND FLUCTUATIONS IN THE MAIN FIELD

Core Dynamics and the Dynamo

Self-excited dynamo action—the process by which magnetic fields are continually regenerated within electrically conducting fluids despite ohmic dissipation of magnetic energy—occurs inside most of the planets of the Solar System, within the Sun, and in countless other bodies beyond the Solar System. The details of this process remain obscure.

One of the great challenges in geoscience is to unravel the workings of the Earth's dynamo. The geodynamo can be probed at relatively close range and, in principle, continually in time. Important questions to be addressed include the following:

- What are the energy sources for core fluid motions? Where are they concentrated in the core, and how do they vary with time?
- What is the pattern of fluid flow in the core? What is the nature of core turbulence?
- Is the outer part of the core stratified? Is it stable or unstable from a convective point of view?
- What are the mechanisms by which the geomagnetic field varies with time? How does the field reverse?
- Can geomagnetic secular variations be forecast?

- Is the toroidal magnetic field in the core comparable to, or an order of magnitude or more greater than, the poloidal field?

Core-Mantle Coupling

It is well known that the rotation of the Earth is not a perfect time keeper. Changes in the observed length of day are associated with torques exerted on the mantle by a number of sources on a variety of time scales. Torques are applied externally by the atmosphere, the oceans, and the gravitational fields of the moon and sun. They are applied internally to the base of the mantle by the fluid outer core of the Earth. A number of processes might be responsible for the shorter-term variations, but the changes in length of day at a time scale of decades appear to be too large to be due to anything other than the transfer of angular momentum from the core to the mantle. The physical mechanism of core-mantle coupling remains obscure. Dynamo action in the core requires the transport of heat from the core into the mantle, that is, thermal core-mantle coupling.

The lower mantle may be a relatively good conductor of electricity, in which case dynamo electric currents can leak from the core into the mantle or can be induced in situ without leakage. The resulting electromagnetic body force exerts a torque on the mantle that may explain decadal fluctuations in the length of day and could conceivably contribute to excitation and damping of the Chandler wobble. Flow of core fluid past seismically detected core-mantle boundary topography may also exert a pressure torque on the mantle. A number of first-order scientific issues are associated with processes of core-mantle coupling, including the following:

- Which coupling mechanism (electromagnetic, topographic, or other) is dominant?
- Precisely what is the shape of the core-mantle boundary?

- Is the core flow that produces topographic coupling steady or geostrophic; laminar or turbulent; or magnetostrophic, barotropic, or baroclinic?
- What fraction of the observed terrestrial heat flux is due to heat flow across the core-mantle boundary?
- Do motions in the core contribute significantly to the Chandler wobble?
- At what rate is magnetic energy being dissipated in the mantle?
- What is the magnitude and distribution of electrical conductivity in the lowermost mantle?

Determination of bounds on the depth-integrated conductivity of the lower mantle would serve a twofold purpose. First, as mentioned above, it would constrain the electromechanical coupling between the core and mantle. Second, the attenuation of secular variations with distance from their sources in the core is strongly dependent on electromagnetic induction in a mantle having a large, though finite, conductivity. For a given conductivity, short-period magnetic fluctuations are attenuated more than long-period fluctuations; thus, dissipation in the lower mantle serves to "low-pass" signals emanating from the core. At present, only order-of-magnitude estimates of conductivity are available. Determination of the "cut-off period" of the lower mantle is correspondingly imprecise.

In a loose sense, the analysis of secular variations observed at the Earth's surface due to motions in the core allows one to "sound" the conductivity of the lower mantle from the bottom up, or at least to determine an "upper bound" on the depth-integrated conductivity. The analysis of the external/internal coupling relationship can be used to sound the conductivity of the lower mantle from the top down. In actual fact, however, the problem is much more complicated; it is necessary to discriminate between the effects of both external and internal primary sources and their induced counterparts in the solid Earth. This is a

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significant challenge. Meeting this challenge requires long, stable time series from a well-distributed network of observations.

Main Field and Secular Variation

Knowledge of the main magnetic field and its temporal changes is fundamental to many basic questions relating to the origin and dynamics of the Earth, as discussed above. In addition, global and regional models of the main field have many practical applications in the commercial sector and the military. Such applications include removal of trend from anomaly data for natural resource and crustal exploration; air and sea navigation; surveying; orientation of land and space instrumentation; orientation of drilling tools and instruments in boreholes; and understanding the migration patterns of land and marine animals.

For the past few decades, the Earth's main (core) field has been represented at 5-year intervals by spherical-harmonic models based on current observations. Other models have been produced to represent the historical field covering the past 300 years. For the most part, these models have been retrospective and are of limited use for extrapolating more than a few years into the future. This lack of predictability reflects the lack of a physical model describing field change in the geodynamo.

One of the major obstacles to accurate modeling of the main field and its secular variation is inadequacy of data. No vector satellite mission has been flown since Magsat in 1980. Secular variation data come from about 180 magnetic observatories worldwide. These data are particularly inadequate because they may be several years old before they become available and also because there are large spatial gaps in the coverage provided by the present network, most notably in the oceans of the Southern Hemisphere.

Because of the importance of determining the temporal characteristics of the geomagnetic field, there is great interest in the study of past field

changes. In view of the success of recent efforts to collect and model historical data from the past three centuries, more data of this type could be utilized by the modeling community. Archaeomagnetic and paleomagnetic studies would provide longer-period variations, in the range of 10^3 to 10^5 years, as well as records of more extreme field behavior such as geomagnetic excursions and polarity transitions.

The systematic acquisition and ready accessibility of present-day geomagnetic data, historical geomagnetic data, and archaeomagnetic and paleomagnetic data would enable the scientific community to address the following concerns:

- What is the contribution of external and crustal field components to models of the main field?
- Impulselike variations (jerks) in the secular change have been detected. Are these real? Are they global? Exactly how fast and how frequently do they occur?
- What is the relationship between secular change and other geophysical phenomena, for example, Earth rotation and climate?
- Can paleomagnetic and archaeomagnetic data be used reliably to improve the understanding of the behavior of the main field by producing models for earlier epochs?

Recommendations

In order to understand the main field of the Earth, the fluid dynamics of the Earth's outer core, and core-mantle coupling, it is essential to study the geomagnetic field as a function of time—on a scale of years to decades, as provided by surface and satellite measurements, and on a scale of hundreds to millions of years, as measured by archaeomagnetic and paleomagnetic techniques. It is also essential to extrapolate surface measurements to the core-mantle boundary (CMB), which requires

knowledge of the electrical conductivity of the mantle and the effects of crustal magnetization and magnetic fields from external electric current systems. The following recommendations address these issues. Their order does not imply a priority ranking.

- Long-term, stable time series should be generated from a global distribution of modern, upgraded observatories and repeat stations, tied together with a long-term, preferably continuous, magnetic field satellite monitoring program.
- In order to optimize the global coverage, new observatories and repeat stations should be installed at selected sites. Some stations would need to be located at relatively inaccessible sites, such as on ocean islands and the seafloor. Costs can be minimized if sites are collocated with existing facilities. Instrument sensitivity and data characteristics should be coordinated with other scientific users.
- Greater use should be made of archaeomagnetic and paleomagnetic techniques to provide information on the time scales of hundreds to thousands of years. High-quality data should be obtained for paleosecular variation, including paleointensity, magnetic stratigraphy, and reversal transitions.
- For further progress in understanding core-mantle dynamics, studies should be undertaken to provide better estimates of: (1) core and lower-mantle diffusivities (electromagnetic, viscous, and thermal); (2) topography and other characteristics of the CMB based on seismic tomography; (3) fluid motion at the surface of the core; and (4) toroidal and poloidal magnetic fields in the conducting part of the mantle.
- Because main field models (such as the IGRF) are important to so many scientific disciplines and societal applications, the updating and upgrading of such models should have a high priority.

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ISSUE 2: LITHOSPHERIC MAGNETIC ANOMALIES

Scientific and Societal Framework

Few geophysical methods have had a greater impact on the geosciences than magnetic methods. Magnetic surveys from aircraft, ships, and low-orbit satellites provide key information concerning the geological, tectonic, and thermal state of the Earth's lithosphere. New insights into the character and depth of magnetic source regions have aided investigations of the mechanical and thermal structure of the lithosphere, crustal and oceanic accretion and evolution, true polar wander, the variation of field intensity with time, and the process of field reversals. The large dynamic range of magnetization intensity in rocks (up to five orders of magnitude) permits the detection of otherwise subtle variations in lithology, rock properties, and structure. The persistence of magnetization in the lithosphere makes the magnetic method useful for studying its deep levels.

Continental aeromagnetic (and gravity) data are used in the preparation of many geological maps and often provide the only economical means of investigating subsurface geology. Over oceanic areas, magnetic data collected by airborne and shipborne surveys were critical for the discovery of seafloor spreading, which led to the development of the plate tectonics theory. Magnetic surveys continue to be the primary tool for estimating the age and relative movement of tectonic plates. Indeed, the age of most of the oceanic crust is known from magnetic analyses. The power of the magnetic method as a geological mapping tool has increased with time; high-resolution surveying in conjunction with modern processing and graphic routines continues to improve the understanding of the oceanic and continental lithosphere.

The magnetic method has many societal applications. Magnetic anomaly studies can delineate features associated with mineral or hydrocarbon accumulations; such features include igneous intrusions, fault

zones, salt domes, and anticlines. Magnetic anomaly maps have stimulated and focused mineral exploration in many areas of the world, particularly in areas where the basement is concealed by sedimentary cover. Because crustal magnetization is sensitive to metamorphism and hydrothermal alteration, magnetic contrasts in the crust reflect variations in thermal and geochemical history that may be diagnostic for certain energy and mineral deposits. National programs to evaluate earthquake and volcanic hazards, to characterize environmentally contaminated areas, and to permit safe disposal of radioactive waste benefit from magnetic anomaly studies.

Tectonic Relevance of Magnetic Anomalies

Oceanic Anomalies

The magnetic source layer in the ocean basins contains a continuous, high-fidelity record of geomagnetic field history and tectonic motion since the Jurassic. Understanding the processes that control the recording of the Earth's magnetic field by the oceanic crust (the crustal "tape recorder") and its longevity is an outstanding first-order problem. Such understanding is fundamental to extracting information on paleofield intensity, true polar wander, and the thermal and chemical evolution of oceanic lithosphere.

Another important problem is the plate kinematic framework. The response of the lithosphere to major plate reorganizations is recorded in structures delineated mainly by their magnetic signatures. Shipborne, satellite, and deep-tow surveys reveal systematic age-dependent variations in magnetization. Each of these methods is effective at a particular scale of study and provides a unique perspective on the problem. At all scales, these age-related variations in magnetization reflect changes in the source layer (for example, in its thickness or chemical composition), paleofield

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intensity, or processes operative during the evolution of the crust. Detailed studies of along-strike variations in the magnetization of ocean ridge crests are being carried out to address the cause of morphologically and geochemically defined segmentation of the ridge axis in relation to heterogeneity in magma composition and supply. Paleomagnetic studies of contemporaneous sequences of sedimentary rocks exposed on land or cored on the seafloor will help to distinguish geomagnetic field behavior from the effects of thermal and geochemical processes.

Continental Anomalies

High-resolution aeromagnetic surveys, such as the statewide survey recently completed by the Minnesota Geological Survey (Figure 3-1), provide extremely powerful tools for geological studies of continental lithosphere and set the standard for future aeromagnetic surveys. Inversions of airborne and satellite data have been performed to improve the understanding of the deep structure of the continents and to guide the systematic exploration for geothermal resources. However, meaningful interpretations require an understanding of magnetic mineralogy at depth. Analysis of lithospheric magnetic anomalies provides insight into paleogeography, thereby constraining paleoclimatic conditions. The ocean-continent boundary frequently displays a distinct, short-wavelength magnetic anomaly in airborne and shipborne surveys; however, substantial controversy exists concerning its expression in satellite data. This fundamental lithospheric boundary deserves additional study.

Global and Regional Anomalies

The Polar Orbiting Geomagnetic Observatory (POGO) and Magsat missions have mapped the Earth's magnetic field at a resolution sufficient to reveal previously unknown intermediate-to-long-wavelength (400 to 4,000 km) lithospheric magnetic anomalies without complications from

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Figure 3-1
Shaded relief image of high-resolution aeromagnetic data from Minnesota (courtesy of the Minnesota Geological Survey). Most of the data used to produce this image were acquired under the supervision of the Minnesota Geological Survey; additional data were contributed by the U.S. Geological Survey, USX Corporation, and the Geological Survey of Canada.

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secular variation. Many of these anomalies were previously unknown because of biases inherent in patching together individual data sets from aeromagnetic surveys. Imperfect knowledge of the reference field, lack of anomaly resolution in existing satellite data, and inadequate information on the magnetic properties of the lower crust and upper mantle limit the interpretation of satellite-derived regional magnetic anomalies. External field contamination reduces data quality, especially at the equator and poles. Nevertheless, these anomalies have been exploited for information on the spatial/temporal variations in thickness, thermal gradients, and composition of the lithosphere. Higher-resolution satellite data and systematic airborne surveys will provide data that can be used to interpret the geological and tectonic evolution of the lithosphere, especially in concert with global gravity and topography data sets.

U.S. Magnetic Anomaly Map

The *Magnetic Anomaly Map of North America*, published in 1987 by the Geological Society of America, has proven invaluable for interpretations of regional magnetic structures and for addressing regional geological problems. In spite of its general application, the U.S. portion of this map has many shortcomings, mainly due to inconsistencies in the numerous sets of magnetic data used to construct it. These inconsistencies are a product of disparate survey specifications, nonuniform treatment of regional fields, and inadequate coverage in some regions. This map could be improved with a few new surveys designed to stitch together existing data, replace substandard data, and fill in gaps in coverage. It would be useful to extend the aeromagnetic data offshore, at least to the limits of the Exclusive Economic Zone (EEZ) (320 km offshore).

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Analysis and Interpretation of Magnetic Anomalies

The ultimate goal of magnetic anomaly analysis is to understand the three-dimensional distribution of magnetization in order to interpret the geological and tectonic history of the lithosphere. This process can be facilitated with advancing computer technologies, sophisticated algorithms, and graphical displays. Interpretive products must be easily understood by the nonspecialist.

Further development of interpretation and analysis techniques must proceed parallel with improvements in data quality and representation. This requires improvements in data acquisition, regional data compilations, and knowledge of the Earth's main and external fields. New analysis techniques can take advantage of existing computer processing power. These techniques include three-dimensional modeling and inversion algorithms, pattern recognition methods, and simultaneous analysis of multiple data sets.

Rock Magnetism and Petrology

The goal of rock magnetic-petrological studies applied to magnetic surveys is to understand the physical and chemical properties and evolution of rocks responsible for magnetic anomalies. This understanding requires fundamental knowledge of the physical, chemical, and mineralogical factors that control rock magnetism. An outstanding problem is the extrapolation of data from laboratory measurements to the pressure-and-temperature environment of anomaly source regions.

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Exposed and Shallow Sources

The petrological factors that control the magnetization of crystalline rocks are not well understood. These factors include magmatic composition, temperature, oxygen fugacity, and pressure and composition of magmatic and metamorphic fluids. These factors must be understood in order to use magnetic methods to elucidate the histories of igneous and metamorphic regions near the surface.

Magnetic contrasts within sedimentary rocks are important aeromagnetic targets. The interpretation of these contrasts relies heavily on theoretical and experimental rock magnetic, petrological, and geochemical data. Magnetic surveys over thick sedimentary sections have potential for detailed mapping of geological features and zones affected by geochemical alteration.

Intermediate-Depth and Deep Magnetic Sources

The magnetizations responsible for long-wavelength magnetic anomalies in the lithosphere are poorly understood. Even the possible range of Curie temperatures of deep-seated magnetic minerals is a matter of dispute. An especially challenging problem is that magnetizations inferred from satellite measurements are several times larger than those measured in rocks. Better understanding of lithospheric magnetic anomalies will come from experimental and theoretical research on the physical chemistry of mineral assemblages at high temperatures and pressures, as well as experimental studies of temperature and pressure effects on both induced and remanent magnetizations of different rock types.

Oceanic Sources

It is well recognized that magnetic anomalies in oceanic lithosphere provide a record of seafloor spreading, yet the magnetization causing these anomalies remains incompletely understood. Many enigmatic magnetic features, such as anomaly amplitude and skewness, may provide clues to the evolution of oceanic lithosphere. A better understanding of these features requires experimental work on the magnitudes and stabilities of secondary remanent magnetizations acquired under in situ physical and chemical conditions. A critical question concerns the magnetic mineralogy of the deeper magnetic layers and the associated depth to the Curie isotherm: where is the base of the magnetic oceanic lithosphere?

Recommendations

In order to reconstruct the geological and tectonic history of the lithosphere, it is essential to understand the three-dimensional distribution of magnetization at a variety of scales, as addressed by the following recommendations. The order of these recommendations does not imply a priority ranking.

- A second-generation digital magnetic anomaly map should be developed for the United States and its Exclusive Economic Zone (to 320 km offshore). This would involve the reprocessing of existing data and the collection of new data to "stitch together" existing data sets and to replace substandard data. New data should be collected using state-of-the-art instrumentation (that is, vector magnetometers with 0.01 nanotesla precision, gradiometers, and Global Positioning System [GPS] navigation)

and flight-line spacings appropriate for the local geological setting.

- Higher-resolution data should be obtained to better characterize the spatial distribution of magnetization in the lithosphere. There is a particular need for data from a new, low-altitude satellite to map the lithospheric magnetic field of the Earth and to improve main field models. Orbital altitudes should be as low as practical in order to focus on lithospheric problems. There is also a need to develop a marine mid-depth-tow magnetometer package to increase the resolution of seafloor anomalies and to enhance interpretation of high-resolution swath bathymetry surveys.
- High-resolution and high-sensitivity magnetic surveys over specific local areas should be collected to study a number of important geodynamic processes associated with the development of sedimentary basins, midocean ridges, continental margins, volcanoes, faults, and continental rift zones. Surveys should also be collected in remote areas, such as the southern ocean and antarctica, to improve the understanding of first-order plate motion histories.
- Improvements in data quality should proceed hand in hand with development in analysis and interpretation techniques and with new ways to visualize data using interactive graphics.
- Studies should be undertaken to improve the understanding of magnetization processes in oceanic and continental lithosphere, particularly at depth. Of particular relevance are laboratory studies that address important physical and chemical factors that control the acquisition and longevity of rock magnetization. Experiments at high pressure and temperature are needed to understand deep-seated lithospheric magnetization. Paleomagnetic studies are needed to distinguish geomagnetic field behavior from the effects of thermal and geochemical process.

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ISSUE 3: MAGNETOSPHERIC AND IONOSPHERIC PROCESSES—COORDINATED SATELLITE AND GROUND- BASED STUDIES

The geomagnetic field spans all regions of the Earth and surrounding space, from its interior, through the oceans, atmosphere, ionosphere, and magnetosphere (Figure 3-2). The spatial and temporal changes in the field provide important information on the physical properties of these regions and their connectivity. These changes can also provide warnings of natural hazards in space, such as geomagnetic substorms and storms. Although other scientific initiatives currently planned by NASA, NSF, and the Air Force are largely focused on one region or discipline, they substantially complement the geomagnetic initiative proposed here. These focused activities would benefit from the coordinated approach proposed in this report, as demonstrated by the following two examples from two subfields of magnetospheric and ionospheric physics.

Solar Wind Coupling to the Magnetosphere, Ionosphere, and Upper Atmosphere

The solar wind, magnetosphere, ionosphere, and upper atmosphere constitute a closely coupled electrodynamic system that channels energy and momentum from the solar wind to the Earth's atmosphere. A number of coupled current systems flow in the conducting plasmas that fill these regions of space. These systems are responsible for most of the temporal changes in the geomagnetic field that occur on time scales from seconds to days.

The currents that flow in the magnetosphere are produced by a global convection system created by solar wind drag on the Earth's magnetic field. This drag transports dayside magnetic field and plasma to the nightside, creating a long, cometlike geomagnetic tail. Two processes contribute to this interaction: (1) a quasi-viscous interaction with closed

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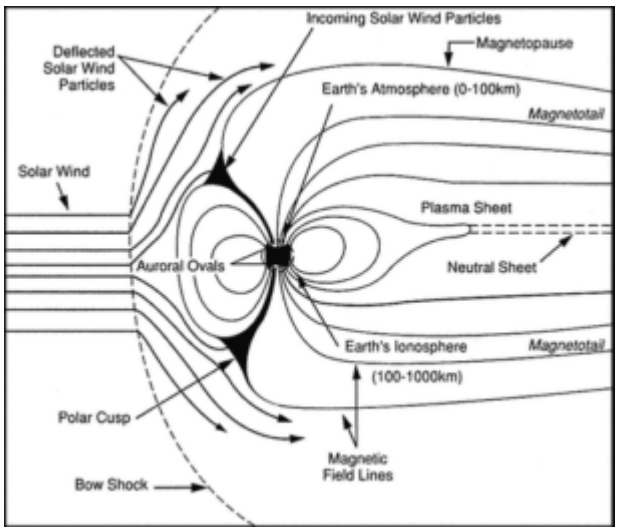


Figure 3-2
The geomagnetic field and geospace environment (modified from a figure provided by NASA).

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field lines along the flanks of the magnetosphere, and (2) magnetic reconnection between southward interplanetary field lines in the solar wind and the dayside geomagnetic field. Large-scale instabilities in the global convection system lasting over periods from a half hour to several hours are known as *magnetospheric substorms*. Larger-scale instabilities lasting several days and longer, and having global effects, are known as *magnetic storms*. The number and energy of charged particles in the Van Allen radiation belts increases during storm activity. The drift of these particles produces a ring of current around the Earth whose magnetic field observed on the ground is responsible for the *main phase* of magnetic storms. The space-time morphology of the ring current, its closure in the magnetosphere, and its relation to field-aligned currents during all levels of disturbed conditions are of fundamental importance in magnetospheric physics and solid-Earth induction studies.

Charge-dependent drifts of particles in the Earth's magnetic field and streaming of electric charges along field lines produce electrical currents. The perturbation fields from these currents fundamentally alter the outer portions of the Earth's field. The electric currents that flow along field lines couple the solar wind and magnetosphere to the ionosphere. Convection of plasmas in the solar wind or magnetosphere is reflected in similar patterns of charge motion in the ionosphere. Collisions between these ions and the neutral constituents of the atmosphere transfer heat and momentum derived from the solar wind to the lower atmosphere.

A quantitative understanding of these phenomena requires coordinated magnetic measurements in the solar wind, the magnetosphere, the magnetotail, the ionosphere, and on the ground. These measurements, together with simultaneous observations of the particles trapped in the convecting field lines, will make it possible to create phenomenological models of the processes responsible for magnetic activity. These models are the input used by theorists in numerical simulations to provide more quantitative explanations for these processes. Eventually this knowledge will be used to understand the consequences of magnetic activity on

communication and navigation systems, and to make corrections to magnetic data used to the study the solid Earth. These models represent a time-and-space averaged behavior and do not describe three-dimensional currents on very short time scales (less than few tens of minutes) or short spatial scales (less than few hundreds of kilometers).

A coordinated study could address several fundamental problems, including the following:

- A quantitative understanding of the flow of energy and momentum through the solar wind, magnetosphere, and ionosphere systems.
- At the magnetopause, an understanding of the physics of magnetic reconnection, the response of the magnetosphere to changes in the solar wind pressure, and the processes responsible for the viscouslike interaction.
- At the magnetosphere-ionosphere interface, an understanding of the complex coupling mechanisms that control the plasma dynamics and the flow of energy from the solar wind to the upper atmosphere.

Magnetic Pulsations and Rapid Temporal Variations

Geomagnetic pulsations are variations in the geomagnetic field on time scales of 0.1 to 600 seconds. The amplitudes of these variations range from a fraction of a nanotesla to tens of nanoteslas. These pulsations are the most visible sign of magnetic activity external to the Earth at low and middle latitudes. They are now recognized as diagnostic for plasma processes remote from the Earth and as means of dissipating solar wind and/or magnetospheric energy at ionospheric altitudes.

Energy derived from the solar wind is coupled to magnetospheric pulsations via several mechanisms. The interaction of the solar wind with

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the geomagnetic field generates turbulence upstream of the nose of the magnetosphere and Kelvin-Helmholtz waves along the flank region. This wave power propagates inward and couples to field-line resonances with periods of the order of minutes. Ions energized in the nightside magnetosphere are injected into the magnetospheric ring current during periods of increased magnetic activity and drift westward through the late evening and dusk toward noon, providing energy for electromagnetic ion cyclotron waves (with approximately 1-second periods) and a variety of long-period waves. Other, less structured waves are focused along magnetic field lines directly into the polar cusp and cleft regions and, on the nightside, into the auroral zone.

Pulsations having periods in the range 10 to 150 seconds (commonly known as Pc 3,4 pulsations) are observed at all dayside latitudes. Because these waves derive from the interaction of the magnetosphere with the solar wind, a widespread, semiglobal magnetometer array carefully synchronized with spacecraft in the magnetosphere and upstream solar wind would allow researchers to discriminate between effects driven by the global interaction and those more localized effects governed by conditions on a given flux tube. Studies of the phase, polarization, and amplitudes of such waves at low latitudes would be particularly useful for "probing" the plasma in the near-Earth (less than several Earth radii) magnetosphere.

Magnetic pulsations are the subject of intensive study, not only to improve the understanding of the sources and propagation of these waves through the magnetosphere and ionosphere, but also because of their applications to other areas of magnetospheric physics and in studies of the solid Earth. Observing these phenomena from ground-based stations provides an economical method of probing dynamic features and basic plasma processes. Applications include remote sensing of plasma densities, determining the onset of magnetospheric substorms, and diagnosing processes at distant magnetospheric boundaries. Pulsations also constitute the source field for electromagnetic induction studies, which can

be used to infer structures related to first-order processes in the lithosphere. Knowledge of the contribution of the magnetic field from these "internal" sources can help researchers in ionospheric and magnetospheric physics understand the effects of induced fields on magnetic field transients observed at and above the Earth's surface. These transients can produce large potential drops and associated current surges that can cause serious damage to large-scale power distribution systems and communications networks.

Satellite studies coordinated with arrays of ground-based magnetometers are needed to make progress on the research problems described above both at high latitudes, where magnetic field lines from the dayside magnetospheric boundary are focused to the cusp and cleft regions and where auroral substorms originate on the nightside; and at middle and lower latitudes, where pulsations and equatorial currents constitute the main components of the external field. A coordinated study could address several fundamental problems, including the need for the following:

- In the magnetosphere, an understanding of the physical mechanisms responsible for generating the pulsations and the mechanisms controlling their cross-field transport.
- At the surface of the Earth, an understanding of the effects of induced fields within the Earth and of transients observed on the surface.

New Programs in Solar-Terrestrial Physics

The coupling of the solar wind to the Earth's magnetosphere, ionosphere, and atmosphere is incompletely understood, as evidenced by the questions listed in the previous two sections. Efforts to address these questions are being made by numerous U.S. agencies and the international research community. Focused programs include the GEM (Global

Environmental Modeling) program at NSF, the ISTP/GGS (International Solar-Terrestrial Physics/Global Geospace Science) program at NASA, the specification models at the Air Force, and the STEP (Solar-Terrestrial Energy Program) of SCOSTEP (Scientific Committee on Solar-Terrestrial Physics).

The GEM program was established by the Magnetospheric Physics Program of the Atmospheric Sciences Division of the National Science Foundation. This program comprises a sequence of overlapping campaigns, each dedicated to specific parts of the global convection system. The final campaign will be dedicated to a synthesis of a global circulation model of the entire magnetosphere.

The ISTP program and its U.S. component, GGS at NASA, have the objective of measuring energy transfers from solar wind using satellite-borne instruments. Simultaneous measurements will be provided by spacecraft in the solar wind, the inner magnetosphere, and the geomagnetic tail. These data will be combined with information from operational spacecraft operated by NOAA and the DOD and from ground stations around the globe.

The specification models currently under development by the U.S. Air Force are an ambitious attempt to capture the current understanding of global convection and its low-altitude effects in a series of numerical models. These models will provide means for specifying and forecasting space weather and its effects on critical space systems.

STEP is an international program sponsored by SCOSTEP. Its primary goal is understanding the flow of mass, momentum, and energy from the solar wind, through the magnetosphere to the ionosphere and atmosphere.

The ultimate energy source for all external magnetic field variations is the solar wind and its embedded interplanetary magnetic field. Consequently, studies of these external fields require a continuous and permanent monitoring capability provided by an upstream satellite. Nearer to the Earth, understanding the dynamic properties of the ring

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current requires research-oriented satellites. Ongoing studies of the ring current make considerable use of data from the limited number of properly equipped satellites in geosynchronous orbit and in low-altitude polar orbits. These studies would benefit from three satellites, widely spaced in local time, in each of these orbits. Filling gaps in the current global network of ground magnetometers, facilitating the dissemination and archiving of the relevant data, and mounting focused campaigns in selected regions would greatly increase the scientific value of all of these studies.

Recommendations

Magnetospheric physics is primarily concerned with study of the interaction of the solar wind with the Earth's magnetic field to create the various current systems described above. The study of magnetic fields and currents in the magnetosphere and ionosphere requires a suite of simultaneously recording instruments on spacecraft and on the ground. In addition, data from ground-based geomagnetic observatories are essential in order to characterize the disturbance magnetic field induced in the solid Earth due to currents in both the ionosphere and magnetosphere. These data are used both for modeling the complete current system and for the creation of magnetic indices that provide a measure of the level of large-scale magnetic disturbances. The following recommendations address needs for spacecraft and ground-based instrumentation. The order of the recommendations does not imply a priority ranking.

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Spacecraft-based instrumentation:

- A permanent platform (such as an L-1 satellite) should be established for monitoring the interplanetary magnetic field (IMF) and solar wind for a variety of scientific and societal applications. It is essential that solar wind data with at least 5-minute temporal resolution be continuously available to users in near real time in order to support research and operational activities.
- Inside the magnetosphere, at geosynchronous orbit, the normal complement of two Geostationary Operational Environmental Satellites (GOES) does not allow for a complete coverage in local time. Another magnetometer at geosynchronous orbit should be added at 6 to 8 hours in local time from both GOES East and GOES West.
- Between geosynchronous and low-Earth orbit, available magnetic field data are inadequate for developing accurate models of the magnetospheric field. When new scientific and operational missions in this region of space are developed, they should include a research-grade magnetometer to support modeling of the magnetospheric field as a function of IMF direction and substorm activity.

Ground-based instrumentation:

- Existing permanent observatories should be upgraded to record the magnetic field digitally at sampling rates of at least one vector per minute for normal operation and up to two vectors per second (0.5 hertz) for special epochs.
- The latitudinal spacing of these permanent observatories should be no greater than 10° at equatorial and middle latitudes in order to obtain adequate spatial resolution of the main field and field variations due to magnetospheric and ionospheric sources. In the

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subauroral and auroral regions and the polar caps, latitudinal spacing of 3° or less is desirable. For specific research purposes, temporary stations are needed with spacing of approximately 100 km in both latitude and longitude. Where possible, arrays should be deployed conjugately in the Northern and Southern Hemispheres and should take advantage of complementary measurements from other ionospheric instruments such as radars, riometers, and optical imagers and spectrometers.

ISSUE 4: ELECTROMAGNETIC INDUCTION IN THE SOLID EARTH AND OCEANS

Imaging Earth Conductivity

The dynamic processes of metamorphism, magmatism, convection, and deformation in the Earth give rise to anomalously high temperatures, volatiles, and magmas. Electrical conductivity is the physical property most sensitive to these manifestations, particularly to the configuration and chemistry of fluids and other conductive grain-boundary phases. Electromagnetic (EM) measurements made at or near the Earth's surface are used to delineate conductivity structure and are therefore appropriate tools for understanding the evolution of the planet.

EM methods also have important applications to several problems of societal concern, including energy, mineral, and water resource exploration; the reliability of electric power grids; and water quality and waste management. The Earth's oceans have a significant influence on climate through long-term storage and transport of heat. Ocean water is a good electrical conductor; it generates easily measurable electric fields as it moves through the geomagnetic field. Therefore, EM measurements in the ocean are an extremely useful tool for probing large-scale ocean dynamics and monitoring long-term variability of the sea.

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Background on Natural EM-Field Methods

Transient magnetic field disturbances from sources in the ionosphere and magnetosphere produce electromotive forces that drive electric currents in the Earth. These currents, in turn, cause secondary magnetic fields over a wide range of scales and amplitudes. Observations of these magnetic and electric fields at the surface can be used to characterize the conductivity structure of the solid Earth. The magnetic variation (MV) method (also called geomagnetic deep sounding, or GDS) measures magnetic fields; the magnetotelluric (MT) method measures the orthogonal components of the horizontal electric field (the so-called telluric field). For a medium of given conductivity, long-period signals decay less rapidly with depth than short-period signals. Therefore, by estimating the response of the Earth over a range of increasing periods, one can progressively sound the electrical conductivity to increasingly greater depths.

Interpretation of EM data is usually broken into three steps. The first extracts a set of one or more frequency-dependent response functions from long time series of magnetic and electric field data observed simultaneously at one or more sites through estimation of frequency domain transfer functions between measured field components. Data reduction is complicated because the Earth is multidimensional, external sources may not be ideal, and noise processes are commonly non-Gaussian. The second step inverts these transfer functions to obtain Earth structure. Besides the nonuniqueness problems shared by all inversions of incomplete and inaccurate data, this inverse problem is both difficult and numerically intensive because it is unstable, nonlinear, and commonly multidimensional. However, progress in recent years has significantly improved the ability to image electrical structure. The third step relates conductivity to physicochemical processes in the Earth. This step requires laboratory measurements of relevant materials at carefully

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controlled conditions and can often be improved by incorporation of independent geophysical and geological information.

Monitoring Large-Scale Fluid Motions in the Oceans

The motion of seawater through the geomagnetic field induces electric currents in the ocean through the usual dynamo process. The resulting electromagnetic fields contain information about a variety of oceanographic processes: surface waves, internal waves, and steady flows. In the case of large-scale ocean currents, for instance, the electric field at the deep seafloor is closely related to mass transport of the water column above the point of measurement. Although the net vertically integrated electric current is small, direct measurements of the electric field have been found to be an excellent means to monitor large-scale barotropic flows. For example, an 8-year time series of transport in the Florida Current has been derived from measurements of electric voltage using a cable that spans the Florida Strait. Other oceanic flows, such as surface and internal waves, produce appreciable magnetic as well as electric fields. These flows can be measured using EM methods, especially on the continental shelves and the floors of shallow seas.

Research Needs for Electromagnetic Induction Studies

Crust

Electromagnetic methods are useful for understanding the distribution and character of fluids in the crust. Four fundamental classes of questions can be addressed by these methods:

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1. What are the present microscale and macroscale configurations of crustal fluids?
2. How are fluids emplaced and distributed in the crust?
3. How are fluids modified by the ambient geological environment?
4. How do fluids affect and modify the geological/tectonic environment?

Fluid-rich sedimentary rocks and oceanic crust are transported in subduction zones to depths that require dewatering and conversions to higher metamorphic grades. Do fluids persist in the deep crust over long geological times? What paths do they take in returning to the surface? Fluids trapped at depth have a significant effect on the rheology of the lower crust and upper mantle. In the shallow crust, high pore pressures have been implicated in large-offset horizontal thrusting, in the low strengths of strike-slip faults such as the San Andreas fault, and in controlling rupture during earthquakes. Because fluids can have a large effect on electrical conductivity, EM methods are appropriate tools for investigating these problems. Many of these problems can be addressed with new, more accurate EM data collected in a more systematic fashion.

MV studies involving large-scale arrays of simultaneously recording magnetometers on the Earth's surface have historically served two functions: (1) to support solar-terrestrial physics campaigns to study the temporal and spatial morphology of current systems in the magnetosphere and ionosphere; and (2) for reconnaissance of electrically conducting features in the Earth's interior, such as sediment-filled basins, anomalies associated with fluids in the deep crust, and thermal anomalies in the upper mantle. The collection and interpretation of MV data from arrays are valuable prior to detailed MT profiling to help ensure optimum profile location with respect to structures of interest and to constrain the three-dimensional context in which MT interpretations are made. MV surveys are also useful in areas with too much topographic relief or cultural noise for conventional MT measurements. These MV arrays can also be used

during MT profiling to understand and correct for the effects of external source complications. As in the case of modern MT systems, modern MV systems require broadband capabilities, remote referencing, and in-field processing.

Upper Mantle

The conductivity observed in the outer 200 km of the mantle through long-period MT and MV studies is controlled by such intrinsic factors as the composition, temperature, and mineralogy of the crystalline matrix, as well as by such extrinsic factors as the composition, quantity, and connectivity of interstitial pore fluids and the presence of intergranular partial melts, graphite, and sulfides. Given this plurality of effects on conductivity, what independent constraints are required to make unique interpretations? Dynamical considerations suggest that temperature and melt gradients should produce order-of-magnitude lateral variations in conductivity. Can such lateral variations in conductivity in the upper mantle be mapped? Theoretical studies suggest that MT methods, when deployed with adequate spatial coverage, may be a more effective tool than presently available seismic methods for studying melt segregation zones.

Observed conductivities in the upper mantle are as much as three orders of magnitude lower than conductivities of candidate rocks and rock-forming minerals measured in the laboratory at the same temperatures. Does this difference reflect the influence of one or more of the intrinsic factors discussed above, such as bulk composition, or is it an effect of extrinsic factors, such as interstitial phases along grain boundaries?

Middle and Lower Mantle

Evidence is strong for a steep rise in conductivity in the seismic transition zone (approximately 400 to 700 km) in the mantle. Existing data are consistent with steplike increases in conductivity at the seismic discontinuities at 400 and 670 km, but such "steps" are not required by the data, and features with scales shorter than 200 km are poorly resolved. The conductivity may approach about 1 siemens per meter below 800 km, but resolution deteriorates rapidly below 1,000 km. There are significant differences in ultra-low-frequency response functions at different magnetic observatories. How much of this signal is due to deep lateral heterogeneity? How much is due to biases associated with shallow conducting features such as the oceans with inadequately represented external source field morphologies? Improving the knowledge of deep-mantle conductivity and understanding the constraints it provides on composition, physical state, and dynamics of the Earth's interior require a multifaceted approach. Both the maximum depth of inference and the resolution of features within that depth range can be improved with the following:

- more accurate data in the presently available bandwidth;
- improved observatory coverage; and
- new data at longer periods.

Better a real data coverage is required to map lateral variations and to characterize the external source properly. In ocean areas without suitable islands, this requires ocean bottom facilities. Abandoned submarine telephone cables offer an attractive possibility for electric field measurements and are also likely to be an important tool for ocean flow studies.

Extending the low-frequency limit requires improved separation of temporal fluctuations from the Earth's core and magnetosphere. In turn, knowledge of the conductivity structure of the deep mantle can contribute to studies of the magnetic fields associated with hydromagnetic processes

in the core dynamo. Finally, additional studies of candidate lower-mantle materials under carefully controlled thermodynamic conditions can be used to interpret lower-mantle conductivities. For instance, interpretation of the conductivity increase between 400 and 700 km requires additional laboratory studies of the electrical properties of β - and γ - $(\text{Mg,Fe})_2\text{SiO}_4$ (spinel structure)

Material Properties

Laboratory studies of electrical conductivity provide the link between models of conductivity and the physical and chemical processes occurring within the Earth. Because conductivity is sensitive to environmental parameters, interpretation of mantle conductivity requires extrapolation of data obtained under the limited conditions accessible in the laboratory. This requires a thorough understanding of the basic mechanisms that control conductivity. Oxygen and sulfur fugacities, pressure, and the chemical environment of surrounding minerals can affect conduction and are particularly important for adequately constraining thermodynamic conditions. Other fundamental questions remaining to be addressed relate to stability and interconnectedness (pore geometry) of conducting fluids (aqueous and partial melts), and grain-boundary phases (such as carbon and sulfides) over geological time. Extrapolation of laboratory studies to in situ conditions requires improved modeling of the bulk electrical response of composites and networks and is critical to understanding crustal and upper-mantle conductivities.

Recommendations

The study of crustal and mantle conductivities and the constraints they provide on composition, physical state, and dynamics of the Earth's interior requires a multifaceted approach. It should include new data,

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improved observatory coverage, and improved laboratory measurements of mantle minerals under controlled thermodynamic conditions, as addressed by the following recommendations. The order of these recommendations does not imply a priority ranking.

- Existing magnetic observatories should be upgraded with higher-quality, faster-acquisition-rate instruments. New observatories should be established at additional sites, including relatively inaccessible locations such as the seafloor. A small task force should be established to estimate the cost and feasibility of installing long-term observatories on the ocean bottom. This group should include scientists and engineers with ocean floor instrumentation experience.
- The instrument base should be expanded and upgraded to satisfy the growing interest in utilizing electromagnetic methods for geophysical and geological investigations. Newly acquired MT instruments should be mobile and easily deployable, fully remote, and referenced for cultural noise cancellation, with complete in-field processing to ensure that quality data are obtained. MV array facilities, consisting of up to several dozen digitally recording, three-component fluxgate magnetometers, should also be acquired for use with MT profiling. Some of these instruments should have the capability for electric field recording to enable collection of low-frequency MT data. The limited number of ocean bottom electrometers should be augmented to support water motion, ocean dynamics, and mantle studies.
- The monitoring of long-term variability of the geoelectric field for both MT and deep ocean studies requires long, grounded dipoles. The use of abandoned submarine cables for this purpose is promising and should be explored by scientists in cooperation with telephone companies.

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- Improved laboratory measurements of mantle minerals under controlled thermodynamic conditions should be undertaken to extrapolate laboratory results to Earth conditions. In particular, the influence of minor elements such as hydrogen, nickel, and aluminum on the point defect populations that control solid-state conduction in olivines and pyroxenes should be determined. New experimental techniques are needed to study nonequilibrium electrical properties of water-saturated crustal rocks at elevated temperatures (50 to 500°C). Systematic experimental and theoretical studies of the electrical response of multiphase aggregates and networks should be undertaken to improve understanding of upper-crustal conductivities. Effects of the presence and distribution of other conductivity-enhancing phases such as carbon, magnetite, sulfides, and partial melts should be investigated using advanced experimental techniques that can carefully control thermodynamic variables. Conductivity and complex impedance measurements linked to physical properties such as porosity, permeability, and acoustic velocity in porous, water-saturated crustal rocks should also be collected.

4

Observational Needs and Facilities

Observational programs have led to important advances in geomagnetic research and its application to other geophysical disciplines. More than 200 years ago, comprehensive surveys by ship were begun; more than 150 years ago, permanent magnetic observatories were established around the world; approximately 50 years ago, magnetic surveys by aircraft were begun. In the 1970s, initial surveys by satellites were undertaken; today, measurements made directly on the ocean floor are becoming available.

The study of geomagnetic phenomena continues to grow. It is increasingly apparent that the time has arrived to optimize the use of geomagnetic facilities through shared use and the introduction of advanced technology.

Observational facilities are discussed below in four categories:

1. land and ocean floor measurements;
2. marine and aircraft measurements;
3. satellite measurements; and
4. prehistorical reconstructions, historical data, and laboratory measurements.

LAND AND OCEAN FLOOR MEASUREMENTS

Approximately 180 magnetic observatories send digital data to World Data Centers (Figure 4-1) in support of the geomagnetic studies described in this report. At present, 13 observatories are operated by the United States. Although their actual number is significant, they are unevenly distributed; most are located in the Northern Hemisphere, particularly in Europe. There are no observatories on the ocean floor; consequently, vast areas of the globe—the ocean basins—are not sampled. In addition to standard observatories, there are temporary or semi-permanent variometer stations, which do not record absolute values, as well as repeat stations for recording long-term baseline fluctuations (typically measured at intervals of a year or longer). In the past, arrays of many tens of simultaneously recording variometers have been temporarily deployed to detect electrical conductivity anomalies in the crust and upper mantle or to record activity in the ionosphere and magnetosphere, but at present there are no arrays of high-frequency instruments available to the scientific community in the United States.

The uneven distribution of magnetic observatories, which is the result of historical circumstances, provides incomplete knowledge of the field behavior and biases many global studies, including the model of the IGRF and the derivation of magnetic activity indices such as the auroral electrojet magnetic activity index (AE) and the disturbance storm time equatorial magnetospheric activity index Dst.¹ The IGRF is a spherical harmonic description of the magnetic potential to degree and order 10.

¹ The much-used Kp index (planetary K-index) as traditionally constructed, while purportedly a "global" index, is an indicator of magnetic activity at midlatitudes and does not rely on a regional or global distribution of observatories as do the AE and Dst indices, respectively; thus, the Kp index is not "biased" in the same way that the high-latitude AE index and the low-latitude Dst index are.

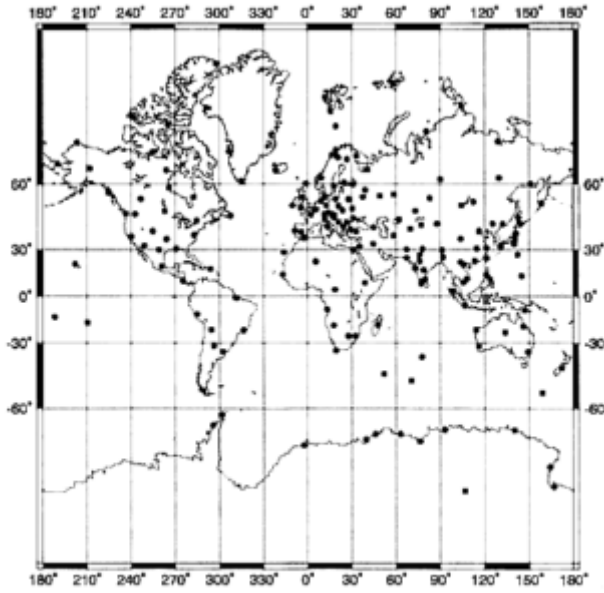


Figure 4-1
Global distribution of magnetic observatories in operation in 1993 (courtesy NOAA-National Geophysical Data Center).

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To fit an observational data set to this degree and order with observatories on the Earth's surface requires a magnetic observatory for each $2,000 \times 2,000$ -km square on the surface—whether land or ocean.

For magnetospheric and solid-Earth studies at equatorial and high latitudes, magnetic variations from magnetospheric and ionospheric sources have smaller spatial and temporal scales, requiring observatories to be more closely spaced—for example, 3° in latitude (about 330 km) and 2 hours in local time. In some cases, significant temporal variations of global interest occur over time scales as small as a few tens of seconds, and certain classes of pulsations have characteristic periods of a few seconds. Ideally, it would be useful to have a global network continuously sampling at data rates of a few hertz or more. However, present needs of most of the scientific community can be met with data continuously acquired at rates of 1 sample per second, with allowances for data rates of 10 samples per second for specific coordinated campaigns.

An excellent beginning for real-time recording from land magnetic observatories has been the INTERMAGNET project, which uses four satellites to relay digital magnetic data from about 25 observatories to four ground Geomagnetic Information Nodes (GINs). Development of the global network envisaged here would require the installation of additional observatories. Some of these new observatories could be established at sites selected for other purposes: at STEP sites, at the Crustal Dynamics (very-long-baseline interferometry [VLBI], Satellite Laser Ranging [SLR], or GPS) geodetic Fiducial Laboratories for an International Natural Science Network (FLINN) geodetic stations of the United States or other countries, or at Incorporated Research Institutions for Seismology (IRIS) or other seismic network stations. Ocean bottom installations can be located on transoceanic communication cables that have recently become available to the scientific community.

In addition to the observatory network, there is a critical need for a portable network facility to measure magnetic variations for induction studies and for studying the ionosphere and magnetosphere. For regional studies of sources in the magnetosphere, sites must be spaced on the order of the height of the ionosphere or greater (from approximately 100 to 1,000 km or more). For solid-Earth studies, sites must be spaced from

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1 to 10 km, depending on the expected depth to target, over areas approximately 100 km to 500 km on a side.

MARINE AND AIRCRAFT MEASUREMENTS

Following the development of the proton precession magnetometer in the late 1950s and the use of magnetic anomalies to study seafloor spreading, a vigorous program was undertaken to measure the total field with ship-towed magnetometers. The number of marine measurements increased by a factor of 10 from the late 1950s to the late 1960s. By the late 1980s, however, measurements dropped to the level of the 1950s in spite of the utility of these data to a number of geophysics disciplines. Vast areas of the ocean basins are still grossly undersampled. These data are essential not only in reconstructing patterns of plate motion but also in developing main field reference models (for example, the IGRF), because they are often acquired in regions where no other data exist. With the advent of the satellite-aided GPS, the accuracy and usefulness of such data are greatly increased.

The U.S. Navy and the Defense Mapping Agency have classified data bases that cover continent-sized areas of the oceans. These data are of excellent quality for science and, if released in usable form, would be of great benefit to marine geophysics. Similarly, industry-acquired magnetic data are proprietary. In some areas of the world, no other magnetic data exist, aside from either military or industry sources. These data would be helpful in constructing regional-scale magnetic maps for research purposes or in updating the IGRF to develop more accurate models in the areas covered by the data. They could be filtered or averaged to maintain their scientific usefulness while protecting the proprietary interests of the source.

The needs of the scientific community will not be met by simple add-on activities (for example, "ships of opportunity") or by gaining access to classified or proprietary data; new surveys are necessary. Project Magnet aircraft operated all over the world and provided important data for the construction of magnetic charts during the 1959-1989 period, but it may be phased out of operation. If this occurs, an enormous hiatus in critical

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activity will need to be filled by other agencies or countries. Historically, Canadian, German, and Soviet (now Russian) groups have conducted long track-line surveys. In the United States, P-3 aircraft are operated occasionally for surveys by the U.S. Navy. At the present time, opportunities exist for using Russian aircraft at a greatly reduced cost.

Continent-scale magnetic anomaly maps now exist for North America (excluding Mexico), the Commonwealth of Independent States, Europe, Australia, China, the Arctic, and much of Africa and South America. Many of these maps, including the U.S. and North American maps, are of variable quality, due largely to the variable quality of the data used to construct them and to difficulties in leveling the data. The existing digital data set for the United States is of limited use for addressing many scientific problems. Additional surveys are required to stitch together existing data, fill in gaps in coverage, and replace substandard data.

SATELLITE MEASUREMENTS

The value of satellite measurements of the Earth's magnetic and plasma fields has been evident since the first measurements by Sputnik 3 in 1958. Subsequent pioneering missions include the Magsat mission that made a major advance in the characterization of the internal magnetic field; the Defense Meteorological Satellite Program (DMSP) that has allowed the auroral plasma environment to be monitored routinely; the GOES/SMS (Synchronous Meteorological Satellite) program that has provided routine energetic particle and magnetic field data at synchronous orbit; and the ISEE-3 (International Sun-Earth Explorer) spacecraft that has provided nearly continuous solar wind monitoring at the L-1 Lagrangian point. These missions were extremely successful in advancing the understanding of the geomagnetic environment from the outer reaches of the magnetosphere to the interior of the Earth. However, much remains to be done. Characterization of the spatial morphology of the Earth's magnetic field at one moment in time is not sufficient to under

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stand the internal dynamo. It is equally important to characterize temporal variations over months, years, and decades.

Measurement of electric currents associated with the auroral plasma environment is a key element in characterizing the state of the magnetosphere, because Joule dissipation provides almost twice as much energy deposition into the upper atmosphere as particle precipitation does. Commerce, the military, and society increasingly rely on a network of sophisticated communication and other service satellites in geosynchronous orbit, but these systems are vulnerable to the flux of particles and fields. In many cases, the impact of solar disturbances on these satellite systems can be mitigated with only a few minutes' or even a few seconds' notice of an impending hazard. This warning is sufficient to allow vulnerable systems to be shut down and backup systems to be brought on line. Thus, monitoring the plasma environment of the magnetosphere at a variety of longitudes is essential. In fact, the ISEE-3 measurements at the L-1 point proved that the state of the magnetosphere could be forecast with as much as an hour's warning. Such forecasts, if made on a continuous basis, would be of great benefit to operations that are affected by geomagnetic activity. Nevertheless, at this time there are no real-time data available from L-1, nor are there any firm plans to provide these data.

PREHISTORICAL RECONSTRUCTIONS, HISTORICAL DATA, AND LABORATORY MEASUREMENTS

Descriptions of the main geomagnetic field must take into account its long-term history. The behavior of the geomagnetic field over the past few hundred years can be determined from a combination of data from long-running observatories and ship-track records. Much would be gained by examining and evaluating the yet-unstudied historical records of maritime nations such as the Netherlands, Spain, and Portugal.

The longer-term behavior of the field, on time scales of 10^3 to 10^5 years, is determined by a combination of records from archaeomagnetism, lavas, and lake and marine sediments. This is an extremely important time scale to aid in an understanding of the fundamental mechanism of the core dynamo.

The behavior of the geomagnetic field on time scales of 10^6 years or more is determined principally from paleomagnetic measurements. Although there is a first-order record of the field for the past 200 million years from oceanic crust, many details of that record remain to be determined from the paleomagnetic study of rocks exposed on land or recovered from the seafloor. Measurements of the field beyond 200 million years must rely on continental records of good quality, which are rare.

The interpretation of archaeomagnetic and paleomagnetic data requires substantial laboratory facilities. Current efforts are distributed through many universities and some government agencies. Studies of rock physics and petrology that can be applied to magnetic surveys require specialized facilities dedicated to the mineralogical, petrological, and geochemical aspects of magnetic petrology. Since no single investigator or institution now supports the necessary range of analytical and experimental facilities needed for such studies, an increased level of collaboration will be required among individual investigators measuring both physical and chemical properties.

In an analogous way, laboratory studies of electrical conductivity provide the means for inferring the nature of physical and chemical processes in the Earth from estimates of the conductivity from field observations. Such laboratory experiments require a thorough understanding of the ways in which the oxygen and sulfur fugacities, pressure, and other aspects of the physical-chemical environment affect conductivity. In addition, one needs to consider the stability and interconnectedness (pore geometry) of conducting fluids (aqueous and partial melts), and grain-boundary phases (such as graphite and sulfides). In order to relate studies on small laboratory scale samples to understanding crustal-and upper-mantle-scale bulk conductivities in the Earth, it is necessary to model the bulk electrical response of composite materials and networks.

RECOMMENDATIONS

A modern, well-distributed system of observational facilities, including land and ocean floor observatories as well as satellite, aircraft, and ship-based facilities, is essential for the collection of geomagnetic data to address the problems outlined in this report. Collection of prehistorical data is also essential for understanding the long-term behavior of the geomagnetic field. The order of the following recommendations does not imply a priority ranking.

- A coordinated effort should be undertaken, perhaps on a phased basis, to complete the ground-based global magnetic observatory network at the density required for this geomagnetic initiative. The installation of approximately 20 island stations and 25 ocean-bottom stations would be a major step forward in developing this network in support of ongoing work to update the IGRF and for magnetospheric and solid-Earth induction studies. The community of solid-Earth and space scientists should work with the relevant government agencies to develop detailed implementation plans for the full network and to address funding and management issues. They should also address issues such as location of sites, data resolution (for example, 12 bit versus 16 bit; 0.05-versus 0.5-nanotesla instrument noise levels), acquisition rates, and accessibility to the data by the scientific community in quasi-real-time. Expanding global real-time networks such as INTERMAGNET should be considered as a means of implementing this global network.
- The needs of the scientific community for high-quality magnetic data can be met with the release of classified and propriety data and with a coordinated program to collect new data. Special efforts should be made to communicate to the DOD and to industry the usefulness and mutual benefits of making classified and proprietary data available to the scientific community. The geomagnetic community should take advantage of "ships of opportunity" and long-range aircraft for surveying selected continental areas and vast areas of the ocean basins, particularly

in the southern oceans, antarctica, and the Arctic. A high-altitude (20 km) survey over the United States should be undertaken for baseline control and for regional charting. Data from a high-altitude survey would provide a consistent data set free from intense local anomalies derived from upper crustal rocks, which is needed for leveling and "stitching together" individual low-altitude magnetic surveys to upgrade the magnetic anomaly map of North America.

- A program of satellite missions and measurements is recommended to provide data for both magnetospheric and solid-Earth studies. These should include a main field mission over at least two solar cycles to provide data on both the Earth's core and the fields induced in the Earth by magnetospheric and ionospheric currents; plasma and magnetic measurements at three equi-spaced longitudes in geosynchronous orbit to provide information on the present state of the magnetosphere; and a high-resolution mission at low altitude, such as the proposed mission of the Applications and Research Involving Space Technologies Observing the Earth's Field from Low Earth Orbiting Satellite—called ARISTOTELES² (see [Appendix B](#) in this report) for lithospheric studies.
- Reconstructions of the long-term variations in the Earth's magnetic field should be made using improved archaeomagnetic and paleomagnetic measurements in order to improve the understanding of some of the fundamental time constants of the geodynamo.

² As of the writing of the final draft of this report in late 1993, ARISTOTELES appears to have been canceled, but GAMES (Gravity and Magnetic Earth Surveyor), a similar satellite, is being considered by NASA.

5

Data Management

With the virtual explosion in volume and diversity of geomagnetic data sets in recent times, the need for a coherent interagency data management policy is reaching critical levels. The combination of near-real-time availability of magnetic observatory data provided by global networks and low-cost mass storage media offers exciting possibilities for the research community. However, these advances also present problems for the management of data sets, including problems with data quality and the proliferation of multiple versions of data sets. It is possible that irreplaceable data bases could be lost because of the lack of a general consensus within the geomagnetic community about how they should be managed. The scientific community must clearly recognize the need for stewardship of data that are fundamental for research.

The basic issues regarding availability of geophysical data have been addressed in several reports of the National Research Council, including those of the Committee on Data Management and Computing (CODMAC) (1982, 1986, 1988), *Geophysical Data: Policy Issues* (1988), and *Solving the Global Change Puzzle* (1991). The present report emphasizes the importance of effective availability of geomagnetic data and associated data products through national data centers, World Data Centers, and distributed data centers.

DATA, METADATA, DATA QUALITY, AND FORMATS

High-quality, well-documented data sets are necessary for the success of geomagnetic research. Procedures must be established to assure the quality of both the observations themselves and the metadata (information describing the data) and to assure that these data are machine-readable.

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The use of data for research provides an effective test of its quality. The experiences of the researchers in the use of data are a valuable component of the quality-control process. Scientific peer review of data is another valuable component of the quality-control process.

In addition to information about data quality, the documentation must describe the data set contents, instrumentation, processing, and data formats. Because geomagnetic data are used by several scientific disciplines that employ different nomenclature, the documentation scheme must contain a data dictionary in which all scientific and technical terms applicable to geomagnetic data are clearly defined.

Given the diversity of sources of data required for geomagnetism, it seems unlikely that a single data format could be used. However, it may be possible to use one of several established data formats. Software systems are already available to do this.

After the data are collected, prepared, and stored in the system, their availability and relevant properties must be made known to interested scientists. Some mechanisms have been established to do so. The interagency Global Change Master Directory provides the scientific community with high-level information about data availability and access. NASA is the lead agency in the development of the Master Directory, which is supported by all of the U.S. agencies involved with geomagnetic data and by many foreign governments. Metadata needed for the Master Directory are being put into the Directory Interchange Format. Use of this standard for geomagnetism will simplify scientific access to data.

DATA CENTERS

There are several relevant issues surrounding the use of national centers for managing geomagnetic data bases. They include the following:

- the complementary roles of centralized versus distributed data centers;

- the problem of converting the volumes of analog data currently being archived at the World Data Centers into digital form;
- the urgent matter of "data rescue," that is, the identification, acquisition, and archiving of geomagnetic data sets in danger of being lost or destroyed; and
- the stewardship of geomagnetic data.

Both centralized and distributed data centers have advantages for managing geomagnetic data. Centralized data centers, funded by federal agencies, offer the stability required to preserve the data for posterity. Distributed data systems provide close contact with experts who are knowledgeable about the data. Combined centralized and distributed systems can provide the advantages of both.

The World Data Centers currently house massive quantities of analog data, such as magnetograms on microfilm and tabular data on paper records. These data need to be converted into digital electronic form. In addition, many data bases are in danger of being lost or destroyed; steps must be taken to ensure that this does not occur. Not all data in each data center are duplicated at other centers. Thus, if records at one center are lost, there might be no means to recover them. Furthermore, the sole copies of many data sets that are the results of completed projects—data never sent to any data center—may be stored, with or without cataloging, on shelves or tape cabinets at research institutions. Scientific personnel are needed to identify and retrieve such data for inclusion in the general geomagnetic data base. A window of opportunity now exists for rescuing these various data sets through cooperative efforts with colleagues in other countries, particularly in the Commonwealth of Independent States.

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DATA AVAILABILITY

Data are being made available to users in a variety of ways. Increasingly, users require that data from many locations be made available in as near to real time as possible. Users want to retrieve these data through on-line systems. The availability of geomagnetic data in real time is an important objective, but it also presents some significant problems. For example, data must be retrieved from the observatories over satellite networks, and can contain many spikes, gaps, time shifts, and other quality problems that have to be corrected before the data can be used for research. The INTERMAGNET program is currently implementing such a near-real-time capability from a worldwide distribution of magnetic observatories, and is dealing with many of the operational difficulties that accompany such a program.

On-line data access is currently available for some applications and is very appealing to users who can simply download data directly into their computers. But large data bases that are continually being updated require large storage spaces and can sometimes be labor-intensive. There is a need to provide existing digital data in a form that is long-lasting, inexpensive, and compact, such as CD-ROMs. For longer-term needs, selection of the storage medium must allow for random access and operation on multiple computer platforms. NOAA, USGS, and other agencies are currently distributing large-volume data bases on CD-ROMs, but many data are not yet available on this medium. In view of the limited lifetime, cost, and vulnerability of magnetic tape, CD-ROMs represent a very cost-effective way to distribute data.

DERIVED PRODUCTS

Developments in technology have revolutionized the collection and analysis of geomagnetic data. It is now feasible to monitor a global distribution of observatories in real-time and generate better products at increased temporal resolution. Both the magnetospheric ring current index, Dst, and the auroral ionospheric electrojet index, AE, can now be

determined more effectively and disseminated more rapidly. A polar cap index is now possible, and a new family of power spectra indices could be developed. The understanding of the physical processes coupling the solar wind and the geomagnetic field has progressed to the point that solar wind data are critical for deriving magnetospheric models and for making accurate forecasts of impending activity.

Mathematical models and charts are among the more important products derived from measurements of the Earth's magnetic field. These tools provide information needed for the protection of life and property, for commercial activities, and for scientific research. Geomagnetic models, which are based on millions of field measurements, are a necessity for safe navigation. They are built into the navigation systems of thousands of civilian and military aircraft, ships, and boats. Models and charts of the main field are routinely used for processing magnetic survey measurements taken in the search for minerals and petroleum. They are used to calculate the paths of cosmic rays, to orient spacecraft, and to find the positions of field-line conjugate points. These products require a continuing abundance of high-quality geomagnetic field measurements.

RECOMMENDATIONS

High-quality, well documented data sets are essential for the success of geomagnetic research. The following recommendations address the stewardship and distribution of geomagnetic data. The order of the recommendations does not imply a priority ranking.

- Procedures should be implemented to assure the quality of both the observations themselves and the metadata describing the nature of the data: contents, instrumentation, processing, and formats. Data and metadata should be recorded in machine-readable form. The best way to learn about the quality of data is for investigators to use it for scientific research. Research that "exercises" data sets should be encouraged, and the experiences

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of the researchers should be captured as part of the quality-control process. Scientific peer review of data should be a key component of the quality-control process. A source book should be developed to encourage more interdisciplinary use of geomagnetic data. This book should describe past, present, and future programs and sources of data, along with a glossary that clearly defines all applicable scientific and technical terms, with clear descriptions as to how to access particular data sets.

- As part of the national geomagnetic initiative, special attention should be given to stewardship of data. The activities of centralized and distributed data centers should be integrated to achieve the fullest utilization and to maintain the highest quality of existing and future geomagnetic data sets. The massive quantities of analog data, such as magnetograms on microfilm and tabular data on paper records, that are currently housed at various facilities around the world should be converted into digital form. Data bases in danger of being lost or destroyed should be preserved and properly duplicated. Data sets from completed projects now stored at institutions that no longer have an interest in using them should be identified and turned over to the appropriate data centers. An appropriate entity or organization should be identified to take responsibility for ensuring that these recommendations are implemented.
- Key geomagnetic data should be made available to users in as close to real time as possible. Many of the data could be available virtually instantaneously through on-line systems. Larger, more comprehensive data sets should be distributed on CD-ROMs with as short a delay time after recording as possible. In developing "real-time" systems, advantage should be taken of INTERMAGNET's extensive experience in dealing with the many operational difficulties that accompany retrieving data from observatories over satellite networks. In order to minimize the redundancy of effort among various investigators who use these data and to minimize the required level of computer literacy, there should be close integration of the efforts of USGS, NOAA,

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and NASA in supplying the relevant data bases from observatories, surveys, and satellites to assure the compatible formatting of data and their distribution on similar media. Software to accomplish such an exchange should be readily available and easy to use.

- New descriptors of geomagnetic activity that measure the amplitude and rate of change of magnetic fluctuations over a range of time scales should be developed. The suite of existing indices (for example, AE indices, Dst, and the polar cap index) should be computed at higher resolution and corrected for quiet diurnal variations from the global network of geomagnetic observatories envisaged in this initiative. There should be close coordination among the principal partners concerned with developing, cross-checking, and using the International Geomagnetic Reference Field, particularly universities, NASA, the U.S. Naval Oceanographic Office, the USGS, the British Geological Survey, IZMIRAN (the Russian Institute of Terrestrial Magnetism), and industry.

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6

Communication and Coordination

From meetings and discussions that led to the National Geomagnetic Initiative Workshop, communication and coordination emerged as an essential element in geomagnetic research. Initially, attention was focused on benefits of communication and coordination among activities and programs of federal agencies. As planning for the workshop progressed, it became clear that the entire geomagnetic community should be involved.

INTERNATIONAL SCIENTIFIC UNIONS AND PROGRAMS

The study of the Earth is intrinsically global. This was recognized by geologists, geodesists, and geophysicists in the nineteenth century. During the past hundred years, the need for global collaboration in geosciences has become axiomatic; many mechanisms have been developed to encourage international cooperation in Earth sciences. Much international cooperation in science takes place under the nongovernmental International Council of Scientific Unions (ICSU).

By the latter part of the nineteenth century, international expeditions and exchange of data were common in the geosciences. This led to development of international mechanisms for ongoing cooperation in geophysical and geological sciences. Seismic and magnetic observatories were being established worldwide. These *de facto* global networks of magnetic and seismic observatories led to international agreements on measurement standards and data exchange. These international activities led to the formation of an international organization that was the predecessor of the modern International Union of Geodesy and Geophysics (IUGG). The objectives of IUGG are the promotion and coordination

of physical, chemical, and mathematical studies of the Earth and geospace environment. IUGG now consists of seven essentially autonomous associations; one of these, the International Association of Geomagnetism and Aeronomy (IAGA), is principally concerned with geomagnetism.

International collaboration in the study of the Earth received a major boost from the International Geophysical Year (IGY), which took place from 1957 to 1959. There were at least two major legacies of the IGY: first, the IGY demonstrated the possibility for international cooperation among all countries in a scientific endeavor of common interest and value. Second, the World Data Center System was established. Geomagnetism was a major program of the IGY.

From IGY to the present, geomagnetism has been a major or significant component of many international programs and organizations. Two bodies with major interests in geomagnetism were established in the 1960s: the ICSU Scientific Committee on Space Research (COSPAR) and the ICSU Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). Both of these bodies sponsor programs involving geomagnetism. The International Magnetospheric Study took place from 1976 to 1979. The Solar-Terrestrial Energy Program (STEP) of SCOSTEP is an important current program.

The International Lithosphere Program (ILP), which was instituted by IUGG and IUGS (International Union of Geological Sciences) in 1980 as the successor to the International Geodynamics Project, seeks to elucidate the nature, dynamics, origin, and evolution of the lithosphere, with special attention to the continents and their margins.

The International Lithosphere Program is being carried out under the guidance of the Inter-Union Commission on the Lithosphere (ICL), which was established under the auspices of ICSU. The ILP includes a broad array of topics that naturally call for collaborative efforts between geologists and geophysicists. Emphasis has been given to "key projects." Geomagnetic problems play a role in several of the ILP key projects.

IUGG also established the SEDI (Studies of the Earth's Deep Interior) program. The SEDI program has a major concern with the Earth's geomagnetic field and dynamo processes. A corresponding

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national program, Cooperative Studies of the Earth's Deep Interior (CSEDI), has been proposed by NSF.

International scientific organizations such as IUGG (particularly IAGA and the SEDI program), SCOSTEP, COSPAR, and ICL have activities closely related to various aspects of the geomagnetic initiative and would provide forums for international presentation of the results.

NATIONAL AND INTERNATIONAL ACTIVITIES

Geomagnetic research and development in the United States draws its constituents from a multidisciplinary base of geophysicists, physicists, and geologists affiliated with the major scientific institutions (academia, state and federal agencies, and private industry) throughout the country. Research programs are presently supported by NSF, USGS, DOE, NOAA, NASA, and DOD (through the Navy, the Air Force, and the Defense Mapping Agency). The missions of these agencies encompass a wide variety of geomagnetic research and development activities. These activities include producing global magnetic charts; monitoring and predicting the effects on satellite electronics and space communications of magnetic disturbances, radiation, and particle fluxes in the magnetosphere; and magnetic navigation. The basic research activities supported by the federal agencies include all four areas of geomagnetic research outlined in this report: main field and core processes, electromagnetic induction in the solid Earth and oceans, lithospheric magnetic anomalies, and magnetospheric and ionospheric processes.

Magnetic information for charts and maps is developed by USGS, NOAA, and the Navy. The Navy and NOAA (and the Coast Guard) are responsible for maintaining and improving navigational safety; the Navy provides magnetic information for this purpose. Magnetic models of the geomagnetic field are developed by the Navy (in conjunction with the British Geological Survey), NASA, and USGS. The models developed by these three organizations are the main inputs to the International Geomagnetic Reference Field, produced every 5 years by the International Association of Geomagnetism and Aeronomy.

Magnetic imaging of the Earth is a new initiative that requires parallel initiatives in data acquisition, dissemination, and synthesis. Clearly, there will be scientific and practical benefits in making this a collaborative effort among a number of the major agencies, including NASA, NSF, USGS, NOAA, the Navy, Air Force, and DOE. All of these agencies now perform geomagnetic research that could benefit from the improved communication and coordination envisioned in this geomagnetic initiative.

Lithospheric magnetic anomalies are studied by NASA, NSF-sponsored academic scientists, the USGS, and industry geologists and geophysicists. Some work in this area is also sponsored by the Navy and NOAA. Magnetic induction studies are supported by NOAA (from the Climate and Global Change Program), USGS, DOE, DOD, and NSF.

The geoscience community has established a fertile environment within which geomagnetic studies can flourish. A number of national and international groups have established clear research priorities focusing on studies of the Earth's lithosphere. This includes exploration and assessment of natural resources (for example, minerals, hydrocarbons, and ground water), characterization of the crust for waste repositories, scientific drilling of the oceanic and continental crust, a new national program in continental dynamics, the MARGINS and RIDGE programs (Margins: A Research Initiative for Interdisciplinary Studies of Processes Attending Lithospheric Extension and Conversion; Ridge Inter-Disciplinary Global Experiments), and international projects in collaboration with Japanese, Italian, and French groups, and with the European Space Agency involving low-altitude, Earth-orbiting geopotential satellites.

Major scientific advances in geomagnetic research require cooperation. Nationally, this cooperation must involve the entire geomagnetic community, especially federal and state agencies having related interests. Internationally, the advantages of cooperation include: (1) greater scientific insight and better direction to programs through the involvement of larger groups of scientists, and (2) reduced costs for each country. Many aspects of the geomagnetic initiative discussed elsewhere in this report are appropriate for national and international cooperation. Many

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U.S. government agencies have an interest in geomagnetic phenomena and data.

Geopotential-field satellite programs are currently being discussed by DOD, NASA, and agencies in several other countries. A possible mode for implementing a satellite mission to study the Earth's magnetic field might be through collaboration between two or more countries. ARISTOTELES¹ now under active consideration by the European Space Agency, is an example. The advantages and disadvantages of such interdependence need to be carefully considered. Other complementary programs are also under discussion or are in place, such as SEDI in the solid-Earth community, the Ocean Drilling Program in the marine geology community, the Global Environmental Modeling program in the solar-terrestrial physics community, and the INTERMAGNET project. The geomagnetic initiative also complements projects that ICSU bodies are discussing for the 1990s, particularly the integrative programs for studying the Earth from its interior to near space (Mission to Planet Earth), as well as studies related to the temporal and spatial changes of the Earth's environment over time scales of years, decades, and perhaps centuries (the Global Change Program). Geomagnetic studies are an essential component of these activities.

Communication and coordination are basic factors in the effectiveness of national and international scientific activities. The concept of the national geomagnetic initiative emphasizes the further importance of communication and coordination among national and international activities related to geomagnetic research.

RECOMMENDATIONS

The diverse elements of the scientific community concerned with geomagnetism—federal and state agencies, academia, industry, national scientific societies, and international bodies concerned with relevant

¹ See footnote 2 in [Chapter 4](#) of this report regarding the status of ARISTOTELES.

international scientific programs—have a clear opportunity to make their own activities more effective through the types of cooperation and coordination envisioned for the national geomagnetic initiative.

- As part of this initiative, special attention should be given to maintaining and improving communication and coordination among the diverse activities in geomagnetism in federal and state agencies, the academic community, and industry—with a view toward encouraging improved efficiencies and fulfillment of goals in research and applications. This effort should include a provision for ongoing discussions of the needs and activities of the disparate elements of geomagnetism, especially the programs of government agencies. It should also include a provision for establishing interdisciplinary task groups involving the scientific and engineering communities that will organize, design, and implement specific research programs.

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Appendix A

Topical Working Group Reports

NOTE

The statements prepared by the working groups—and presented here in Appendixes A and B—were intended to represent a broadly balanced view of the major scientific problems, challenges, and concomitant needs among the various aspects of geomagnetism. The statements prepared under the guidance of the respective working group leaders, who endeavored to take account of suggestions made during the meetings and to reflect a consensus of the discussions. Constraints of time did not permit review of each working group report by all participants associated with that report; thus, individual participants may not agree with all statements in the reports. However, these reports contain a wealth of information regarding the challenges and opportunities in geomagnetism and served as the basis for formulating the draft proceedings of the workshop which, in turn, served as the basis for the report of the U.S. Geodynamics Committee (USGC) presented in this volume. The reports are included here in part for the benefit of those who are interested in geomagnetic research and the proposed national geomagnetic initiative but were unable to participate in the workshop.

The working group reports have not been subjected to review by the National Research Council (NRC). Any conclusions or recommendations made or implied herein are the opinions of the individual authors or working groups. These reports have been edited, but otherwise are reproduced essentially in the form in which they were submitted on the last day of the workshop.

A1.

The Magnetosphere, Ionosphere, and Atmosphere

A complete and accurate knowledge of the geomagnetic field and how it changes with time is critical to many aspects of solar-terrestrial physics and applications affected by conditions in near-Earth space. It is the interaction of the solar wind with the geomagnetic field that creates the Earth's magnetosphere. The magnetosphere, in turn, stores energy from the solar wind and dissipates it sporadically in geomagnetic storms and substorms that accelerate large fluxes of energetic charged particles and drive large electrical currents; these currents, in part, are diverted down into the ionosphere. Upper-atmosphere winds also generate global currents through dynamo action as the conducting ionosphere is moved through the geomagnetic field. In addition to receiving steady electrical currents, the Earth is also bathed in a variety of magnetohydrodynamic waves, or pulsations, produced at much higher altitudes in the magnetosphere. The physical processes leading to these phenomena are being actively investigated by the international space physics community.

Geomagnetic storms and substorms are also important from the standpoint of the frequently deleterious effects they have on a variety of critical civilian and government equipment and functions. Energetic particles trapped in the geomagnetic field produce malfunctions and rapid aging in a variety of commercial, scientific, and military satellite subsystems. The currents induced in power and communication cables by geomagnetic storms and substorms can cause considerable damage in ground systems such as transformers. The monitoring, and when scientific advances permit, the prediction of "space weather" is an

Appendix A1 was largely developed by the following workshop group: James Slavin (*Group Leader*), R. Clauer, M. Engebretson, D. Herzog, R. McPherron, J. Olson, V. Papitashvili, V. Patel, F. Rich, A. Richmond, M. Teague, R. Walker, L. Zanetti.

important goal of agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Defense (DOD).

At altitudes from 80 to 1,000 kilometers (km), the motion of ionospheric ions caused by the electric fields imposed by the magnetosphere drives large-scale winds in the thermosphere. Joule heating associated with these currents is an important energy source, and it can result in dramatic temperature and density increases of the upper atmosphere during magnetic storms, affecting the orbits of near-Earth satellites and dynamically altering the global ionosphere. Relativistic charged-particle precipitation may influence some aspects of the neutral atmosphere, for example, noctilucent clouds, as far down as the middle atmosphere. Understanding the coupling between the solar wind, the magnetosphere, the ionosphere, and the thermosphere is a major objective of the solar-terrestrial physics community supported by NASA, the National Science Foundation (NSF), NOAA, DOD, and other federal agencies.

As is discussed below, measurements of the direction and intensity of the local magnetic field by low-altitude satellites and at ground stations located around the world are essential for scientific progress in many areas of solar-terrestrial physics. In addition to contributing to the geomagnetic field models that are needed to describe the flow of energy and momentum between the magnetosphere and upper atmosphere, these observations provide important measures of the strength and intensity of the horizontal currents flowing overhead in the ionosphere. Careful analysis of ground magnetic variations can tell us a great deal about the nature of solar wind-magnetosphere-ionosphere couplings at high latitudes, and about the nature of the upper-atmosphere winds that drive the ionospheric dynamo at all latitudes. Following a more thorough discussion of these scientific and technological issues, this section concludes with a summary of pertinent requirements regarding ground-based and satellite-based magnetic field measurements with respect to instrumentation, ground station location, data collection, data processing, and data archiving.

Scientific Framework

Magnetosphere

The magnetosphere is defined as the region of space above the Earth's ionosphere in which charged-particle motion is dominated by the geomagnetic field. Collisions are so infrequent in most of this region that its electrical conductivity is nearly infinite. Because of this condition, magnetic fields and very-low-energy particles are frozen together, and when the plasma moves, so too do the magnetic field lines that thread it. Finite energy particles also drift in gradients of the magnetic field. These drifts are energy- and charge-dependent and thus must produce electrical currents. These currents create magnetic fields that add to the geomagnetic field originating within the Earth. Because of these currents, the total field in the magnetosphere departs radically from what is calculated by extrapolating the Earth's internal field to distances greater than several Earth radii.

The outer boundary of the magnetosphere is sharp and well defined at a distance in the sunward direction of about 10 Earth radii. It is produced by a sheet of electrical current that cancels almost all of the Earth's field outside the boundary while doubling it inside. This current layer is termed the *magnetopause*, and it separates the geomagnetic field from the field and plasma of the solar wind. At the magnetopause the solar wind interacts with the Earth's field by two major processes: viscous interaction and magnetic reconnection. The viscous interaction occurs along the flanks of the magnetosphere transferring solar wind momentum to closed field lines inside the magnetopause. These field lines flow tailward and create boundary layers with flows internal to the magnetosphere. Magnetic reconnection, on the other hand, allows the interplanetary magnetic field (IMF) to merge with the geomagnetic field near the subsolar point. These field lines are then transported by the solar wind over the poles and laid back behind the Earth as a long, cometlike tail. In the tail these field lines eventually reconnect and return by internal flows to their origin. These flows produced by the viscous and the dominant reconnection process are termed *magnetospheric convection*.

The stretching of the field lines through convection produces the tail current that flows partly on the magnetopause and partly across the interior of the magnetic tail.

The rate at which the magnetic field in the solar wind reconnects with the geomagnetic field depends on the angle between the solar wind field and the Earth's field. Only when the IMF is southward, that is, antiparallel to the Earth's field, does a strong interaction occur. Because this angle is constantly changing, the level of magnetospheric convection also changes. These fluctuations make it possible to energize and trap particles in the inner portions of the magnetosphere, creating the radiation belts. The rapid drift of protons to the west and electrons to the east creates a torus of westward current around the Earth, known as the *ring current*.

The electric field produced in the magnetosphere by convection is projected onto the ionosphere along magnetic field lines. However, the ionosphere has finite electrical conductivity and, consequently, an electrical current flows parallel to the electric field. This is called the *Pedersen current*. Since magnetospheric convection is a closed cycle, some field lines flow tailward and some sunward. The boundary between these flow regions projected onto the ionosphere is called the *convection reversal*. The electric field is divergent along these flow lines; therefore, so is the ionospheric current. This is possible only if field-aligned currents flow in or out of the reversal regions to satisfy current continuity. These field-aligned currents are known as *Region 1 Birkeland currents*. They link the magnetopause and tail currents to the Earth's ionosphere and are the primary source of energy that drives ionospheric phenomena.

A second source of electric field in the magnetosphere is the rotation of the Earth. The plasma polarizes so that the resulting electric field is everywhere orthogonal to the magnetic field. In the absence of other effects, the combination of electric and magnetic fields would cause charged particles to corotate eastward with the Earth. However, when added to the dawn-dusk magnetospheric electric field, this second field source imposes a fundamental asymmetry on the magnetosphere. A result of this is that electrons drift closer to the Earth on the dusk side and ions closer on the dawn side.

The electric field projected onto the ionosphere causes the plasma at the feet of convecting field lines to drift just as the magnetospheric plasma does. However, the ionosphere is not fully ionized, and drifting charges collide with atmospheric neutrals. The collision rate relative to the gyrofrequency is much higher for positive ions than for electrons, and therefore they drift more slowly than electrons. This produces a current in a direction opposite the drift. This current is orthogonal to both the magnetic and electric fields; it is called a *Hall current*. The geometry of the Hall current system is the same as that of ionospheric convection, but with the opposite sense. It is a two-cell system flowing sunward across the polar cap and antisunward in the dusk and dawn sectors of the auroral oval. The concentrations of current in these sectors are known as the eastward (dusk) and westward (dawn) electrojets. Most of the magnetic disturbance seen on the ground at high latitudes is produced by this Hall current system. Because of their solenoidal geometry, the field-aligned currents do not create large ground disturbances.

Fluctuations in the interplanetary magnetic field carried by the solar wind affect the rate of dayside reconnection, and hence cause corresponding fluctuations in the convection electric field and all of the current systems mentioned above. These changes are highly filtered and delayed because of the large inductance of the field-aligned current systems. Nightside reconnection occurs in the center of the tail current sheet, but its onset is delayed relative to the dayside. When reconnection begins in the nightside, it explosively releases the energy stored in the tail field. This release is accompanied by a new current system that temporarily diverts a fraction of the cross-tail current along field lines that close westward across the midnight ionosphere. This current is known as the *substorm current wedge*. Multiple substorms driven by a long interval of fluctuating southward IMF cause many particles to be energized and trapped in the radiation belts. These longer intervals of enhanced convection and intense ring currents are called *magnetic storms*.

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Ionosphere and Atmosphere

At heights of 80 to 1,000 km, the ionosphere and upper atmosphere respond strongly to the electric fields and currents of magnetospheric origin. The rapidly drifting ions set neutral winds in motion through collisional coupling, and the resistive dissipation of electrical energy, or Joule heating, can be the dominant energy input to the high-latitude upper atmosphere. During magnetic substorms, winds approaching sonic speeds can be generated, and the heating is sufficient to raise the temperature of the upper atmosphere by hundreds of kelvins. The expanded atmosphere results in order-of-magnitude increases in the drag on near-Earth satellites, altering their orbits and affecting their orientations. The global upper-atmosphere circulation during magnetic substorms and storms is altered, resulting in a changed chemical composition and large changes in ionospheric density. The high-speed winds can significantly feed back upon the magnetospheric electrodynamics through ionospheric dynamo action. Hence, the ionosphere cannot be viewed simply as a passive sink for magnetospheric energy. Accurately explaining these various effects requires complex simulation models of upper-atmosphere and ionospheric dynamics that take into account the characteristics of electrodynamic energy input from the magnetosphere.

Even when magnetospheric energy inputs to the upper atmosphere and ionosphere are weak, electric fields and currents are generated in the ionosphere by the dynamo action of the ever-present neutral atmosphere winds. Because the ionosphere is electrically conducting, its motion through the geomagnetic field produces an electromotive force (EMF). This EMF results in electrical current flow and the establishment of space charges and electric fields. Typically, two large cells of current flow in the sunlit ionosphere, a counterclockwise cell in the northern magnetic hemisphere and a clockwise cell in the southern hemisphere, each containing on the order of 10^5 amperes. Current also flows along geomagnetic field lines between the two hemispheres because of the extremely high conductivity along the magnetic field. Most of the horizontal current in the ionosphere flows below 200 km, although

measurable currents can also be found at higher altitudes when the plasma and neutral densities are large, as at solar maximum in the afternoon.

A portion of the upper-atmosphere wind that drives the dynamo results from the diurnal variation in absorption of solar ultraviolet radiation in the thermosphere. Another portion is driven by upward propagation of global atmospheric waves, particularly atmospheric solar tides with 24- and 12-hour periods, but also planetary waves of longer periods and lunar tides of 12.4-hour periods. Geomagnetic data from the global network of stations thus record effects of these winds, which are dependent on the state of the middle atmosphere and can provide information about spatial and temporal variations in middle-atmospheric conditions.

The highly anisotropic nature of ionospheric conductivity can result in strong Hall polarization electric fields, especially at the magnetic equator where the horizontal geometry of magnetic field lines inhibits the discharge of these fields. The electric field drives a strong current along the magnetic equator on the dayside of the Earth, the equatorial electrojet, that produces an enhancement in magnetic perturbations on the ground and at satellite altitudes. The latitudinal variation of the currents is closely tied to the mean eastward electric field and to the vertical variation of winds in the thermosphere, so that analysis of latitudinal profiles gives important information about the dynamical state of the ionosphere and upper atmosphere at low latitudes.

The external sources such as ionospheric current systems also induce electrical currents to flow in the conducting lithosphere. Studies by magnetotelluric and global geomagnetic methods have investigated the Earth's electrical conductivity to depths of about 1,000 km. The resulting fields add to the magnetic field measured at the Earth's surface and at low-Earth orbit. It has recently become possible to refine the calculations of magnetospheric and ionospheric current processes by accounting for these induced contributions once the external ionospheric and magnetospheric magnetic fields are known. Implementation of these corrections will allow for more accurate measurements of the currents flowing overhead in the ionosphere.

Geomagnetic Pulsations and Transients

Sinusoidal variations in the Earth's magnetic field with time scales on the order of seconds to several minutes have been observed for over a century. More recently, it has been recognized that these pulsations, or hydromagnetic waves, may be used as diagnostics for magnetospheric plasma processes at high altitudes and as means of dissipating solar wind and magnetospheric energy at ionospheric altitudes. Geomagnetic pulsations with periods of minutes include field resonances and transients in the global current system. Short-period pulsations, on the other hand, are thought to be electromagnetic ion cyclotron waves. These waves are recognized as having a significant role in transporting energy between various constituents of magnetospheric plasmas.

Beginning in the solar wind, energy is coupled to magnetospheric pulsations through several mechanisms. Wave power is generated by turbulence outside the magnetopause near noon and by Kelvin-Helmholtz waves caused by velocity shear along the flanks of the magnetosphere. This wave power propagates inward and couples to toroidal (azimuthally polarized) field-line resonances. Ions energized in the nightside magnetosphere are injected into the ring current during periods of increased magnetic activity and drift westward through the late evening and dusk toward noon, providing energy for poloidal (radially polarized) field-line resonances, storm-time compressional waves, and electromagnetic ion cyclotron waves. Other, less structured waves are focused along magnetic field lines directly into the polar cusp and cleft regions.

The study of pulsations has been pursued for several reasons in addition to seeking an understanding of their underlying mechanisms. First, it allows detailed comparisons between plasma physics theory and observation in ways not possible in laboratory experiments. Examples include drift and ballooning-mode instabilities, bounce resonances, shear-driven instabilities (such as Kelvin-Helmholtz instabilities), nonlinear wave-wave coupling, and ion cyclotron wave instabilities. Pulsation studies also allow for a better understanding of mechanisms of wave mode coupling (for example, from either traveling or globally resonant compressional waves to transverse waves and back again), of

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feedback effects due to local, diurnal, and seasonal variations in ionospheric parameters, and of the importance of spatial boundaries as sources and/or transmitters of plasma waves.

Second, such studies can provide diagnostics of dynamic and static features within the Earth's plasma environment. Many dayside high-latitude magnetic pulsations appear to be related to plasma interactions occurring in the magnetospheric cusp/cleft regions, which link the high-latitude ionosphere to the outer boundary of the Earth's magnetosphere, or to interactions occurring directly at these remote boundaries. Because satellite orbits allow only brief crossings through this complex and critical region, ground-based magnetometers provide the only means of obtaining synoptic coverage of cusp/cleft processes.

Third, geomagnetic pulsations are used for electromagnetic sounding of the solid Earth. By sensing the induction effects of external pulsations, one can infer considerable detail about properties of the underlying crust and mantle.

In the following sections we discuss the present-day knowledge and important unresolved questions associated with magnetic pulsation activity, beginning with the lowest frequencies.

Long-Period and Impulsive Events

Long-period (3-to 15-minute) waves observed at latitudes connected magnetically to the outer boundary of the magnetosphere are designated as being in the Pc 5 period range. These waves, with amplitudes of tens of nanoteslas, include both solitary and continuous-wave trains, with an occurrence distribution spread throughout dayside local times from dawn to near dusk. As a result of intensive study of ground-based observations, many of the magnetic pulsations in this category have been found to be associated with traveling ionospheric plasma vortices produced by moving filamentary field-aligned currents that appear to originate near the inner edge of the low-latitude boundary layer. The generation of solitary vortices appears to be related to transients generated by changes in the interplanetary magnetic field or solar wind pressure. The more continuous events, on the other hand, appear to be caused by velocity shear

instabilities at the magnetospheric boundary (most likely the Kelvin-Helmholtz instability). In this interpretation, these pulsations appear to be the ground signature of driven magnetospheric reorientations traveling tailward along the magnetopause at magnetosheath speeds. How frequently these occur and under what circumstances remain open questions.

Irregular Variations

Variations of large-scale field-aligned and ionospheric currents can also cause large, less structured variations in magnetic fields near the Earth's surface. Those with longer periods, known as Pi 2 pulsations, often resemble an impulsive ringing and are associated with auroral electron precipitation. Near local midnight, Pi 2s are associated with auroral substorm onsets and can reach amplitudes of tens of nanoteslas. At times these signatures can be observed worldwide. How they propagate to equatorial latitudes and to all local times is not yet understood. Higher-frequency irregular pulsations (Pi 1), extending to and even past local noon, appear to be much more highly localized, and are apparently produced by transient currents in the ionosphere due to variations in ionization and conductivity. These latter pulsations are clearly associated with the aftermath of substorm activity.

Pc 3-4 Pulsations

Pulsations in this period range (20 to 50 seconds) are a ubiquitous feature of the dayside magnetosphere, occur over a wide range of latitudes, and typically have amplitudes of from 1 to 10 nanoteslas. Their dependence on IMF orientation and magnitude suggests a driving mechanism related to "upstream waves" and/or processes at the subsolar bow shock, which exhibits oscillatory behavior when its shock geometry becomes quasi-parallel. The mechanism that relates upstream phenomena to dayside field-line resonances in this same frequency band has been studied for many years but still is not understood. However, there is

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growing evidence that processes in the cusp/cleft may play a central role in the transmission process.

Multipoint studies have shown that Pc 3 pulsations are most intense in the dayside cleft regions, and recent observations of relations between magnetic, optical, and very low frequency (VLF) modulations at Pc 3 frequencies, with clear IMF control of all three types of signals, suggest that at least along field lines connecting to cusp/cleft latitudes there are some fundamental unexplored interactions between various kinds of waves and plasma populations. Simultaneous and carefully synchronized information from magnetometer arrays at a variety of longitudes and latitudes will be especially valuable in determining whether cleft and/or cusp sources are involved in the transmission of these pulsations to the ground at lower latitudes, and can help to provide further tests of the proposed wave-entry mechanisms from an upstream wave source.

Pc 1-2 Emissions

Pulsations in this frequency range (0.1 to 10 hertz) are the result of instability in the hot, anisotropic ion distributions that are regularly set up within the magnetosphere and within the boundary layers, magnetosheath, cleft, and cusp. As these ions become unstable to the growth of electromagnetic ion cyclotron waves, their energy and anisotropy decrease as waves are emitted along magnetic field lines. These waves (with amplitudes usually less than 1 nanotesla) serve two functions in magnetospheric research. First, they can function as diagnostics of remote processes and particle populations if their source regions and particle populations can be independently documented. Second, they are indicative of processes responsible for precipitating medium-energy ions out of trapped orbits.

Of particular interest are high-latitude Pc 1-2 bursts, frequently observed in association with traveling vortex events, which appear to originate on cusp or cleft field lines. It is possible that the field compressions often associated with these burst events increase the magnetic field strength and/or alter the particle distributions sufficiently to make ion cyclotron waves grow. It has also been proposed that Pc 1-2 observations

can be used as indicators of local field lines that map to magnetospheric boundaries. Recent reports indicate that, for example, unstructured 0.15-to 0.4-hertz noise is seldom observed more than a few degrees from the cusp.

Scientific Issues to Be Addressed

- **Solar Wind-Magnetosphere-Ionosphere Coupling.** Many aspects of dayside solar wind-magnetosphere-ionosphere coupling are still poorly understood. The physical processes to be elucidated include various forms of reconnection, particle diffusion, and wave penetration of the magnetopause. Two dimensional magnetometer arrays at high magnetic latitude (approximately 60° to 80°) could provide data to map the space-time development of ionospheric currents produced by reconnection and other energy/momentum transfer processes in the dayside and nightside magnetosphere.
- **Substorm Electrodynamics.** The detailed coupling of the magnetotail to the nightside ionosphere is not adequately modeled. Even the relative importance of the two regions and the peculiar quasi-periodic development of the aurora and westward electrojet during substorm expansion phase remain to be explained. An all-digital, real-time auroral network magnetometer array is needed to define the auroral electrojet indices at all levels of activity and to track the details of electrojet development. Observations from a smaller number of stations should be monitored in real time to detect Pi 2 pulsations, which signal the onset of substorm activity.
- **Global Magnetosphere Models.** Improved representations of the sources of external magnetic field are important for further progress of the geomagnetic community. Because the solar wind is changing with time, these models must be parameterized to include solar wind dynamic pressure and substorm phase as well as dipole tilt. Magnetic data from past, present, and future spacecraft collected in a unified data base and annotated with time, location, solar wind conditions, and internal state of the magnetosphere would provide the basis for such a model.

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- **Global Ionospheric Dynamo.** More realistic modeling of the global ionospheric dynamo, using realistic simulations of thermospheric dynamics, would allow full advantage to be taken of the wealth of information contained in geomagnetic data relating to quiet-day variations. Not only would these global data place strong constraints on the uncertain model inputs, but they would guide the evaluation of day-to-day, seasonal, and long-term variations in the wind systems that propagate upward from the middle atmosphere. In addition to improving our understanding of thermospheric and middle-atmospheric dynamics, such studies may also shed light on long-term changes in the global atmosphere.
- **Ionospheric Electric Fields.** An improved model of ionospheric electric fields, taking into account their dependence on magnetospheric and thermospheric conditions, is a critical need for a variety of upper-atmospheric studies and applications. Simulation models of thermospheric and ionospheric dynamics have shown that winds, temperatures, and electron densities depend very sensitively on the electrodynamic conditions. It is also becoming apparent that there is significant feedback on the magnetospheric electrodynamics from winds generated at high latitudes. Further modeling of coupled magnetosphere-ionosphere dynamics is essential to help clarify the nature of these interactions.
- **Magnetic Pulsations as Magnetospheric Diagnostics.** There is great promise that magnetic pulsations can be used as diagnostics to provide real-time monitoring of plasma densities throughout large regions of geospace, to identify magnetic field lines connecting to the magnetospheric boundary, and to warn of substorm onset. Measurements from dense magnetometer arrays deployed at auroral latitudes will be essential if further progress is to be made in pulsation research.

Applications of Geospace Studies

The interaction of the solar wind with the Earth's magnetic field produces a variety of phenomena collectively known as *geomagnetic activity*. Magnetospheric substorms, magnetic storms, and pulsations are the three main classes of geomagnetic activity. Each of these produces

measurable and often significant effects on human activities. Occasionally these effects are so severe that expensive systems are significantly degraded or even destroyed. Repair or replacement can cause long delays in service and enormous expense.

To properly assess the causes of malfunctions and anomalous operations and to prepare systems so they will not fail in extreme circumstances, NOAA and the U.S. Air Force (USAF) cooperate in the acquisition of environmental data. At the NOAA/Space Forecast Center (in Boulder, Colorado) these data are used by space weather forecasters to alert civilian and military customers of current and expected magnetic activity. At the Air Force Space Forecast Center (near Colorado Springs), these and other data are fed to a variety of models to specify the current state of space weather at locations lacking direct measurements and to forecast space weather at given locations.

Examples of systems affected by space weather are extremely varied. Shortwave radio communications are interrupted. Navigation systems for ships and aircraft experience degraded accuracy. Electrical utilities encounter large transients that may damage transformers or trip overload protection. Long-distance pipelines undergo accelerated corrosion. Airline personnel and passengers on transpolar flights are subjected to increased levels of penetrating radiation. Small computers experience memory failures due to the same particles. Low-altitude spacecraft are subjected to increased drag caused by ionospheric heating. Other spacecraft that use the magnetic field for orientation suffer degraded attitude control because of large changes in field orientation. Spacecraft at higher altitudes often experience "single event upsets" from solar cosmic rays and energetic particles trapped in the Van Allen radiation belts. Solar cell arrays experience serious degradation due to energetic particle bombardment. Satellites at geosynchronous orbit are bathed in 10-to 100-kiloelectronvolt electrons raising the potential of the spacecraft surface relative to its interior to the point that sparks jump between electrical components causing anomalous signals.

Such problems require practical applications of the knowledge acquired about the space environment. As technology continues to reduce the size of electronic components and as society becomes increasingly

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dependent on electronic systems that operate in inclement space weather, it becomes critical to maintain adequate monitoring of this weather so that protective measures can be taken. For these reasons as well as for scientific reasons discussed elsewhere in this appendix, solar wind, and synchronous and polar orbiting environmental platforms measuring magnetic field variations have important applications.

Operational Considerations

Need for Comprehensive Magnetic Field Measurements

Magnetospheric physics is primarily concerned with the study of processes through which the solar wind interacts with the Earth's magnetic field to create and change the various current systems described previously. The present understanding of these currents has been obtained through innumerable studies utilizing data taken at ground stations and by spacecraft orbiting the Earth. Today little progress can be made unless magnetic field data are simultaneously available from the solar wind, geosynchronous orbit, the magnetotail, low-Earth orbit, and ground stations distributed around the globe.

Magnetic indices derived from the ground data are used to characterize the level and type of activity so that certain time intervals can be chosen for detailed study and long-term changes in the magnetosphere and ionosphere can be detected. These indices are also used to select measurements for the construction of average models of the external field. A primary use of these average models is to extrapolate the observations taken at various ground observatories and by remote-sensing spacecraft (such as those that image the aurora) into the magnetosphere for comparison with higher-altitude satellite observations. Another major use of magnetic data is to accurately model the currents that produce the ground magnetic variations. The ability to quantitatively remove these external contributions to the field measured at the Earth's surface would greatly enhance the ease and accuracy with which a variety of geomagnetic mapping tasks could be carried out.

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Observational Concerns

For the purpose of measuring and understanding the magnetic fields and currents in the magnetosphere and ionosphere, a suite of magnetometers on spacecraft and on the ground is required. This requirement can be satisfied only by maintaining the existing platforms, augmenting them with modern instrument packages, and adding some new platforms.

Spacecraft Observations

The source of all energy to the magnetosphere and much of the energy to the ionosphere is the solar wind, with its imbedded interplanetary magnetic field. In order to support research and operational activities, it is essential that solar wind data (with at least 5-minute temporal resolution) be continuously available to users in near real time. Presently Interplanetary Monitoring Platform (IMP)-8 provides such data, but the data are collected by NASA only about one-third of the time and are not available to the users until months after they are taken. The Wind satellite will soon be launched by NASA to provide IMF and solar wind data, in support of the International Solar-Terrestrial Physics (ISTP) Program, but only a limited amount of data will be available in real time. A permanent platform for monitoring the IMF and solar wind that could be deployed following the ISTP Program is clearly needed.

Inside the magnetosphere the geomagnetic field is now monitored at geosynchronous orbit by magnetometers on the Geostationary Operational Environmental Satellites (GOES). Unfortunately the normal complement of two GOES satellites does not allow for a complete coverage in local time. Another magnetometer at geosynchronous orbit is needed 6 to 8 hours in local time from both GOES East and GOES West.

Between geosynchronous orbit and the solar wind, there is no requirement for continuous magnetic field measurements, but significant scientific and operational benefits would result if more satellites in this sector of space carried a magnetometer suitable for scientific measurements of the magnetospheric magnetic field.

Existing satellite data sets provide a foundation for the development of models of the magnetospheric field, but the effectiveness of addressing critical scientific problems depends on the acquisition of new measurements. Between geosynchronous and low-Earth orbit, available scientific magnetic field data are inadequate for developing accurate models of the magnetospheric field. The Combined Release and Radiation Effects Satellite (CRRES) mission was providing suitable data when its mission was terminated prematurely by a subsystem failure. When new scientific and operational missions in this region of space are developed, they should include a research-grade magnetometer to support modeling of the magnetospheric field as a function of IMF direction, substorm activity, and other effects. Low-Earth orbit measurements of the electrical currents flowing between the magnetosphere and the ionosphere are also essential to the modeling of both regions. Since the characteristic time scale of the individual substorm phases is approximately 20 minutes, a measurement of the disturbance field is needed at intervals of 20 minutes or less. Present plans call for two magnetometers on Defense Meteorological Satellite Program (DMSP) satellites. To obtain the required time resolution, a magnetometer on at least one more spacecraft is required. The NOAA/TIROS (Television Infrared Observation Satellite) are excellent platform candidates to fulfill this need.

In low-Earth orbit there is also a critical need for a dedicated geomagnetic field-mapping payload to update the models of the internal magnetic field of the Earth. The Earth's magnetic field is changing rapidly enough that a new model is required every 5 to 10 years. Ground-based magnetic observatory data are important for this updating, but for the best possible model over the whole Earth, satellite data are an absolute requirement. Magsat (1979-1980) was the last satellite that completely met this need. Magnetometers on board the Dynamics Explorer (DE)-2 (1981-1983) and the Polar Orbiting Geomagnetic Satellites (1990-1993), for example, provided data that were useful. However, their utility was limited by the lack of a high-accuracy attitude transfer system and an absolute scalar magnetometer. Magnetometers on board future satellites of the DMSP series will provide useful data sets, but again, with limited accuracy. There are possibilities for future NASA

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missions with fully capable instrument packages, but none of these has progressed beyond feasibility and design studies.

Ground Stations

In order to characterize the disturbance magnetic field induced in the solid Earth due to currents in both the ionosphere and magnetosphere, data from ground-based geomagnetic observatories are essential. These data are used both for modeling the complete current system and for the creation of magnetic indices that give a measure of the level of large-scale magnetic disturbances. In addition to the standard ground-based observatories, temporary observatories are also necessary for characterizing the disturbance with the finer detail required for research purposes. In order to meet future research and operational requirements, all existing stations need to be maintained. If a particular country is having difficulty in supporting its existing stations, the international community should take steps to preserve these vital resources.

Many of the existing observatories also need to be upgraded. All observatories must be able to record the magnetic field digitally at a sampling rate of at least 1 vector per minute, and the data must be put into a data base accessible in real time through a computer network such as the one being developed for the International Real-Time Geomagnetic Observatory Network (INTERMAGNET). At least half of the high-latitude stations should have the capability to record data at higher sample rates for studies of magnetic pulsations and other rapidly varying phenomena. Many types of pulsations, for example, Pc 3-4, Pc 5, and Pi 2, can be adequately resolved with 1-second resolution measurements. The study of Pc 1-2 class pulsations, however, requires sample rates of at least 2 vectors per second.

Station Spacing

For adequate spatial resolution (by data from permanent magnetic observatories) of the main field and field variations due to magnetospheric and ionospheric sources, the latitudinal spacing of the stations should be

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no greater than 10° at equatorial and middle latitudes. In the auroral region and the polar cap, a latitudinal spacing of 3° or less is desirable. Where possible, the spacing between stations in local time should be no more than 2 hours. At present, large gaps exist in coverage, such as in the Pacific Ocean and in Siberia. For specific research purposes, temporary stations are needed with a spacing of approximately 100 km in both latitude and longitude. Such stations would be in place for periods of 1 to 5 years. In the past, such temporary stations have been custom-built by various scientific groups and later dismantled. With the development of modern fluxgate magnetometers and the advent of low-cost data retrieval, storage, and communications hardware, appropriate agencies should procure reusable geomagnetic observatory stations. The availability of several dozen would support many important studies at reasonable cost.

Data Retrieval

It is desirable to have as much data as possible returned in near real time and deposited in a central processing facility or cataloged into a distributed system. For example, the Alaska meridian chain data from 10 sites are telemetered, via the GOES satellite, to the NOAA/Space Environment Lab where they are available with a delay of less than 15 minutes. While disk and tape storage should be used at field sites as backups to the normal data flow, users should be able to access data sets in near real time. In cases where users need to monitor activity from a large number of stations but do not need every data point, near real time values of the power spectral density of the data could be calculated either at the station or at the central facility.

Data Archival

Quality control, storage, and distribution of data from magnetic observatories are vital to many research projects. In the past, many magnetograms have been available only in analog form—a form that is cumbersome to use and expensive for a single researcher to digitize. It

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would enhance many studies and make other studies possible, if all magnetograms were made available in digital form. In the past, digital data distribution meant use of reel-to-reel data tapes. It is now desirable to store and distribute massive amounts of data on compact disks. It would also be very helpful to users if the World Data Center would organize such distribution disks with magnetometer data from all stations for a given week or month instead of the present practice of distributing long data sets from a single station on individual tapes or disks.

General Recommendations

Data Management Requirements

A quantitative understanding of the magnetosphere and the thermosphere requires the acquisition of a comprehensive suite of spacecraft and ground-based observations that must be analyzed in association with complex models. It is essential that the outstanding research questions identified earlier be addressed in the context of an efficient and flexible data management environment capable of presenting a wide variety of data to a physically diverse science community in readily usable fashion. The data sources are very diverse. Most modern spacecraft missions are international in nature, with data being processed and analyzed at multiple locations. Ground observations, particularly those relating to the magnetic field, are by their nature multipoint, crossing many agency and national boundaries. Not all collaborative programs involving multiagency and multinational participation give appropriate emphasis to the importance of data exchange and data management planning. The purpose of this section is to identify the data management requirements necessary to support the development of answers to the outstanding research questions posed earlier.

A key requirement for the scientific community is to have timely and effective access to the complete suite of readily usable data necessary for the study of a particular scientific problem. For the proposed initiative, "timely" has a variety of meanings. Certain problems may be approached

only if real-time geomagnetic data are available. The U.S. Geological Survey (USGS) INTERMAGNET program is endeavoring to establish a real-time data base containing 1-minute ground-based magnetometer observations from around the world. The NOAA Space Environment Laboratory Data Acquisition and Display System (SELDADS) program provides real-time spacecraft and ground data that support a variety of forecasting activities relevant to this initiative. This initiative should endeavor to maximize use of these systems and should advocate the expansion of the data-base contents through the inclusion of such data sets as the DMSP magnetometer.

Three essential aspects of "readily usable" are generally not well addressed by modern data systems. First: "Where are the data?" Particularly for geomagnetism, there is a requirement for a comprehensive catalog that is on-line accessible through a diverse set of computer hardware. Second: "Can I use the data easily?" The answer relates to documentation and format and the use of Standard Data Formats within the geomagnetic community. It is not necessary to constrain the community to the use of a single standard, since conversion between one standard and another is relatively simple. The National Office of Standards and Technology (NOST) at NASA/Office of Space Science and Applications (OSSA), for example, supports such activities. Third: "Can existing data be used?" A large body of data exists in the geomagnetic arena. Some components of this are in danger of extinction, or at least of underutilization as a result of a lack of proper maintenance and support. Ground-based magnetometers fall into this category because the number of sites is decreasing and certain data sets are available only in analog form. The U.S. geomagnetism community would benefit greatly from digitization of selected existing data sets.

In summary, the data management requirements to support the present initiative are as follows:

- extensive collaboration with existing and planned data systems;
- real-time and on-line interactive data bases;
- data systems that catalog, display, and deliver data in on-line fashion;

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- extensive use of Standard Data Formats; and
- a data rescue program.

Magnetic Indices

Magnetic variations on the Earth's surface are produced by a variety of electrical currents in the magnetosphere and ionosphere. The patterns of disturbance are characterized by magnetic indices that crudely represent the important physical properties of these current systems. The Dst (disturbance storm time) index is proportional to the total energy in the drifting radiation belt particles that make up the torus called the ring current. The AE (auroral electrojet) indices are roughly proportional to the density of horizontal overhead currents that flow near midnight in the auroral oval. The Polar Cap Index measures the current density in the overhead currents flowing across the polar cap. These indices provide essential tools that allow researchers to identify quiet and disturbed intervals and to select different phases of magnetospheric substorms and magnetic storms for detailed study. Improvement of these indices through the addition of ground stations for improved spatial coverage, increased time resolution, better removal of uninteresting currents, real-time generation, and rapid dissemination to users are matters of great importance to the geomagnetic community. Accordingly, the relevant agencies should work together to meet the following goals:

- upgrade the current network of geomagnetic observatories used for the AE index, replacing analog stations with digital and adding real-time satellite links;
- expand the AE network with additional stations at crucial points in eastern Canada, eastern Siberia, and possibly the Southern Hemisphere auroral oval; stations located at higher and lower latitudes to record electrojet activity for expanded or contracted auroral ovals should also be established when resources permit;
- calculate the Dst index with 1-minute resolution and make it available in real time via network access;

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- obtain real-time digital data from appropriately located polar cap stations and compute a real-time Polar Cap Index; and
- continuous monitoring of Pi 2 pulsations from three ground stations spaced evenly in longitude around the globe should be undertaken and an index representing Pi 2 pulsations should be created and distributed.

Ground-Based Arrays

A variety of temporary (1-to 5-year) arrays of magnetometers is needed to make progress in the research problems described above. At high latitudes, dense (approximately 100-to 200-km separation) two-dimensional arrays are required to investigate the detailed properties of magnetic pulsations and the electrodynamic of high-latitude current systems. Where possible, arrays should be deployed conjugately in the Northern and Southern hemispheres and should take advantage of complementary measurements from other ionospheric instruments such as radars, riometers, and optical imagers and spectrometers. Because of the synergism between such arrays and the even denser arrays needed for electromagnetic induction studies, these efforts should also be coordinated whenever possible. Sampling rates should range from approximately 5 seconds to 0.5 seconds to investigate Pc 5 to Pc 1-2 scale variations. At middle or low latitudes, magnetometers are required at about 30° longitudinal increments to investigate variations due to solar wind dynamic pressure changes, substorm current systems, the ring current, and the ionospheric equatorial electrojet. These scientific objectives can be reached if the following actions are taken:

- deploy dense (100-to 200-km separation) two-dimensional arrays of temporary observatories at high latitudes and one-dimensional arrays at lower latitudes;
- deploy conjugate magnetometer arrays at appropriate locations;
- deploy a small number of new permanent stations in poorly covered regions of the globe; and

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- coordinate the siting of arrays for magnetospheric studies and electromagnetic induction studies whenever possible.

Satellites

Satellites provide the only platform that allows the observation of the flow of energy from the solar wind to the magnetosphere and the ionosphere. Near-real-time data from satellites are needed to warn of major geomagnetic disturbances that affect commercial systems and to support scientific investigations such as rocket and balloon campaigns. In short, satellite measurements provide the only way to "image" the magnetic field across the vast volume of the magnetosphere. To accomplish these goals the following requirements are established:

- The interplanetary magnetic field and the solar wind in the vicinity of the Earth must be measured continuously. These data must be made available to users on a near-real-time basis.
- Measurements of the magnetospheric magnetic field at three or more equi-spaced geosynchronous spacecraft must be made available to users in near real time.
- At least three of the available operational and research satellites in polar low-Earth orbit (for example, TIROS, DMSP) must be instrumented with magnetometers to "image" the large-scale three-dimensional ionospheric current system.
- Measurements of the main field of the Earth with a high-accuracy vector/scalar magnetometer system (for example, Magsat) capable of updating the International Geomagnetic Reference Field (IGRF) model must be obtained at least once per decade.

Modeling

A major need exists for improved quantitative models of the magnetic fields generated by currents external to the Earth. Near-Earth external field models must be time dependent and include the effects of both ionospheric currents and magnetospheric dynamics. In the case of the magnetospheric models, the effects of Birkeland currents must be included and representations of the magnetopause currents and of the near-Earth magnetosphere must be improved. The models must include the changes that occur in magnetospheric configuration in response to changes in the solar wind plasma and interplanetary magnetic field. A goal should be to model the perturbations in the geomagnetic field at low and middle latitudes to within a total error budget of 10 nanoteslas. Conversely, studies of the magnetospheric magnetic field require improved models of the internal magnetic field for analyzing the ground signatures of magnetospheric activity and pulsations. These scientific and operational objectives can be met only if the measurement requirements identified above are met and strong interagency support is provided for theoretical and empirical modeling of ionospheric and magnetospheric electrical currents and magnetic fields.

A2.

Understanding the Nature and Evolution of the Lithosphere From Magnetic Anomalies

Scientific Framework

Few geophysical methods have had a greater impact on the geological sciences than the magnetic method. The Swedish mining compass was used successfully as early as the 1600s to search for iron ores, and dip needles were used until the middle part of this century. Although limited geological applications of ground-based magnetic surveying were realized prior to World War II, the postwar development of the aeromagnetic method and the development of the marine-towed magnetometer have had the greatest impact on Earth science. Aeromagnetic data over continental areas, often in conjunction with gravity data, have helped in the preparation of many geological maps and have often provided the only economic means of investigating geology at depth. Over oceanic areas, seafloor spreading anomalies revealed by airborne and shipborne surveys were critical for the development of the plate tectonic paradigm. Recent surveys continue to be the primary tool for estimating the age and relative movement of plates. The power of the magnetic method as a geological mapping tool has increased with time; high-resolution surveying in conjunction with modern processing and graphic routines continues to improve our knowledge of the oceanic and continental lithosphere.

Appendix A2 was largely developed by the following workshop group: Richard Blakely (*Group Leader*), J. Arkani-Hamed, J. Behrendt, S. Cande, V. Chandler, D. Chapin, W. Dewhurst, R. Frost, V. J. S. Grauch, S. Haggerty, R. Hansen, T. Hildenbrand, W. Hinze, P. Hood, J. MacQueen, R. Pawlowski, J. Phillips, C. Raymond, R. Reynolds, G. Smith, P. Taylor, P. Toft, P. Vogt, P. Wasilewski.

Magnetic surveys carried out on the ground and from ships, aircraft, and low-orbit satellites provide key information concerning the geological, tectonic, and thermal state of the Earth's lithosphere through measurements of magnetization, anomaly fabric, and depth to magnetic sources. While traditional research continues to refine our understanding of plate kinematic frameworks and provide regional subsurface structural and lithologic information, new research directions have emerged. Sources of anomalies are being evaluated at very broad ($\gg 100$ -kilometer [km]) and very fine (< 10 -meter [m]) scales as a direct consequence of the availability of satellite data, properly configured airborne, land, and ship surveys, and the large volume of data accumulated from certain areas during recent decades. New insights into the character and depth of magnetic source regions have aided investigations of the mechanical and thermal structure of the lithosphere, crustal and oceanic accretion and evolution, true polar wander, the variation of field intensity with time, and the process of field reversals.

Magnetic anomaly data—combined with gravity, electrical conductivity, heat flow, and seismic reflection and refraction data—provide interpretations that are superior to those based on only one type of data. The large dynamic range of magnetization intensity in rocks (varying as much as 5 orders of magnitude) enables the detection of otherwise subtle variations in lithology, rock properties, and structure. The persistence of magnetization to great depth in the lithosphere makes the magnetic method useful for studying its deeper levels. Perhaps the most unique attribute of the magnetic method is that it can provide the added dimension of time to geophysical analyses. For example, the age of most of the oceanic crust is known from magnetic analyses.

Societal Applications

In addition to elucidating large-scale geological structures, magnetic anomaly studies can also delineate features associated with mineral or hydrocarbon accumulations; such features include igneous intrusions, fault zones, salt domes, and anticlines. Examples of prospective hydrocarbon-

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producing basins discovered by their magnetic expression include the Navarin Basin in Alaska and the North Sea basins. Magnetic anomaly maps in areas where the basement is concealed by sedimentary cover have stimulated and focused mineral exploration in many areas of the world. Crustal magnetization is sensitive to metamorphism and hydrothermal alteration; therefore, magnetic contrasts in the crust reflect variations in thermal and geochemical history that may be diagnostic for certain energy and mineral environments.

National programs to evaluate natural hazards, to characterize environmentally contaminated areas, and to permit safe disposal of radioactive waste all benefit from magnetic anomaly studies. For example, the active New Madrid Seismic Zone lies within an Eocambrian graben of the Mississippi Embayment. The graben is completely concealed by younger sedimentary rocks and is identified primarily on the basis of magnetic anomalies. Similar magnetic anomaly analysis delineates concealed structures of the San Andreas fault zone, which represent major hazards to urban areas. Evaluation of candidate sites for critical hazards (for example, dams, nuclear reactors) is aided by the subsurface information revealed by magnetic anomaly maps. Changes in magnetic anomalies over historical time scales may indicate magmatic and/or tectonic activity. Permanent monitoring of the magnetic field at volcanoes and fault zones could potentially reveal systematic behavior prior to catastrophic events and contribute to prediction efforts. Magnetic anomalies due to cultural sources, such as metal pipes and drums, can help to locate and characterize areas of contamination.

Despite the obvious scientific and societal benefits of magnetic anomaly studies, the question of who will perform this work in the future remains unclear. The decrease in the ranks of entry-level researchers threatens to produce a critical shortage of trained personnel to perform basic and applied geomagnetic research. This trend appears to be correlated with the decrease in securely funded academic, federal, and industry-related positions. The strongest indicator of the impending shortage of geomagnetists is the decrease in number of graduate students specializing in the field. In order for society to continue to reap the many

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and varied benefits that geomagnetism has to offer, this trend must be reversed.

Specific Issues and Research Foci

Magnetic Anomaly Studies

Studies of Oceanic Lithosphere

The magnetic source layer in ocean basins constitutes a continuous, high-fidelity record of geomagnetic field history and tectonic motion since the Jurassic. Greater understanding of the recording mechanism and its longevity is fundamental to extracting information on paleofield intensity, true polar wander, and the thermal and chemical evolution of the oceanic lithosphere. Knowledge of paleofield intensity will enable investigation of the relationship between the stability of the core field, generation of large mantle plumes, and climatic variations.

Much work in the ocean basins currently focuses on defining the second-order plate kinematic framework and the character of the magnetic source layer. The response of the lithosphere to major plate reorganizations is recorded in structures, such as propagating rifts, microplates, and migrating transform faults, defined mainly by their magnetic signatures. Intraplate deformation, defined by nonclosure of plate circuits, has been investigated by detailed aeromagnetic surveying with track spacings on the order of 20 km.

Shipborne, satellite, and deep-tow studies are being used to define the systematic differences of magnetization with age in the oceanic crust and thus define characteristics of the recording process. Such differences may reflect variables of the source layer (for example, thickness or chemical composition), paleofield intensity, or processes operative during the evolution of the crust. At the finest scale, anomalies that are barely resolvable at the sea surface occur between major anomalies in seafloor spreading profiles (the so-called tiny wiggles); these tiny wiggles are finally being exploited for information concerning the shortest resolvable

time scales of core-generated geomagnetic field behavior. Magnetization-versus-age studies are complemented by detailed studies of along-strike variations in the magnetization of the ridge crest. Their aim is to resolve the cause of morphologically and geochemically defined segmentation of the ridge axis in relation to heterogeneity in magma composition and supply.

Studies of Continental Lithosphere

Magnetic surveying of continental regions during the past 40 years has yielded tremendous scientific and economic benefits. Magnetic studies illuminate the nature and location of terrane boundaries, orogenic belts, continental rift zones, and sedimentary basins. High-resolution aeromagnetic surveys, such as the statewide survey recently completed by the Minnesota Geological Survey, provide extremely powerful tools for geological studies of continental lithosphere. Deep drilling, crustal transect, and tectonic framework investigations draw heavily on magnetic data to extend geological mapping into the subsurface and to place detailed but sparsely distributed geological and other geophysical information into a regional context. Inversions of airborne and satellite data have been performed to estimate the depth and configuration of the Curie-temperature isotherm. This difficult inverse problem has the potential to advance understanding of the geothermal and tectonic setting of regions and to guide the systematic exploration of geothermal resources, but meaningful results will require an understanding of magnetic mineralogy at depth.

In addition to constraining the modern-day tectonic framework of an area, analysis of lithospheric magnetic anomalies can lead to improved understanding of the historical record of tectonic activity. This historical perspective can provide insights into paleogeography and evolving terranes, thereby illuminating paleoclimatic conditions.

The continental margin is a particularly fruitful area of investigation. The ocean-continent boundary frequently displays a distinct magnetic anomaly in airborne and shipborne surveys. Substantial controversy

exists, however, concerning its expression in satellite data. This fundamental lithospheric boundary deserves additional study.

Global and Regional Studies

Satellite magnetic anomaly data and large-scale airborne surveys are being utilized to investigate the regional magnetization of the Earth's lithosphere. These studies show spatial/temporal variations in the thickness, thermal gradients, and composition of the lithosphere. The Polar Orbiting Geomagnetic Observatory (POGO) and Magsat missions have mapped the Earth's magnetic field at a resolution sufficient to reveal previously unknown intermediate-to long-wavelength (400-to-4,000-km) lithospheric magnetic anomalies without complications from secular variation. Many of these anomalies were previously unknown because regional anomalies defined by aeromagnetic data suffer from biases inherent in patching together individual surveys. The most serious problem is our imprecise knowledge of the reference field.

Lack of anomaly resolution in existing satellite data and lack of information on the magnetic properties of the lower crust and upper mantle limit the interpretation of these satellite-derived regional magnetic anomalies. Unresolved external field contamination also degrades the data quality. Regional magnetic anomalies also can be studied with properly compiled airborne and shipborne data. Upper-crustal sources may produce anomalies in these low-altitude data that coalesce into regional anomalies when observed at satellite heights. Comparison of satellite and near-surface data is essential for proper interpretation of regional anomalies. Likewise, knowledge of the satellite anomalies is required to properly calibrate regional compilations of low-level data. Thus, magnetic studies at both satellite and near-surface heights are critical and will enable interpretation of geological and tectonic evolution of the lithosphere, especially in concert with global gravity and topography data sets.

The *Magnetic Anomaly Map of North America* published in 1987 has proven invaluable for first-order regional interpretation of magnetic structure. Perhaps its greatest contribution has been the promotion of

interchange between geophysicists and geologists in addressing regional geological problems. Yet, in spite of its general application, the U.S. part of the map has many shortcomings caused by disparate survey specifications, nonuniform treatment of regional fields, and inadequate coverage in some regions. Studies of long-wavelength magnetic anomalies of the United States based on this map are difficult or impossible mainly due to problems in datum shifts between merged surveys. Now is clearly an appropriate time to evaluate this map quantitatively and determine how it might be improved with existing data or newly acquired surveys. In addition, the aeromagnetic data base should be extended offshore, at least to the limits of the Exclusive Economic Zone (320 kilometers).

Analysis and Interpretation Techniques

The ultimate goal of magnetic anomaly analysis is a better understanding of surface and subsurface geology, rock magnetization, plate kinematics, and paleomagnetic field behavior. Analysis begins with a compilation of magnetic anomaly data, usually in the form of maps or digital data bases. The data are then addressed in several ways that commonly interplay: analysis of the characteristics of the data, modeling of crustal magnetization, and interpretation of the magnetization in terms of geological units and structures. Compilation requires accurate knowledge of a geomagnetic reference field. Analysis and interpretation commonly require knowledge of rock magnetic properties, especially remanence, available geology, and data representation techniques. Many of these techniques for compilation, analysis, and interpretation present opportunities for improvement.

Further development of interpretation and analysis techniques must proceed hand in hand with improvements in data quality. Factors reducing data quality include position uncertainties, external field contamination, and inaccurate geomagnetic reference fields. Increased utilization of the Global Positioning System (GPS) will greatly reduce navigational uncertainties. Survey strategies that employ parameters inappropriate for the relevant geological or geophysical problem also

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introduce errors. In many areas of the United States and the world, surveys that are known to be inadequate provide the only available data. These areas should be resurveyed. Although standard techniques are available to accomplish this task, consideration should be given to applying new technology, such as gradiometry and vector magnetometers, to the problem. Simultaneous acquisition of other airborne geophysical information, such as gravity, gamma ray, and electromagnetic data, has many advantages; future analysis techniques should strive to synthesize multiple data sets.

Analysis and interpretation also suffer from inadequate representation of data during analysis. For example, the standard digital representation of a magnetic anomaly map required by most analysis techniques is an equi-spaced grid. These grids are inadequate for several reasons: (1) information is discarded along densely sampled flight lines and must be interpolated between flight lines; (2) magnetic features are treated as though they are symmetrical; and (3) differences of elevation between points are not taken into account. Intelligent and efficient gridding techniques are needed that can accommodate asymmetric anomalies, unequally spaced intervals, differences in elevation, and a curved Earth. In addition, we should consider new ways to analyze data directly without gridding.

New analysis techniques can take advantage of today's more powerful computers. Highly interactive, easily visualized three-dimensional modeling and inversion algorithms should flourish and become standard practice. Development of techniques that recognize patterns in multiple data sets and associate them with certain geological environments should continue. Previously developed methods that are computer-intensive, such as space-domain filtering and some spectral methods, may now be more useful because of improved computer technology.

It is well recognized that synergistic analysis of multiple data sets provides important constraints on interpretation of subsurface geology. The synthesis of multiple data sets has generally been treated in qualitative ways. New computer technology, such as geographic information systems (GIS), can be utilized to handle multiple data sets. Future

developments should improve on GIS techniques by synthesizing information from all the data sets.

Future developments in analysis techniques should focus on facilitating the modeling of magnetization distributions and the interpretation of these distributions in geological terms. These techniques will evolve toward greater automation. In order to be successful in this direction, a better understanding is needed of how magnetization is distributed in the lithosphere through a broad range of scales and how magnetization (in terms of rock-magnetic properties) is related to geological units and structures. Ultimately, presentation and interpretation of the magnetic anomaly data must have greater relevance to the broad field of geoscience.

Rock Magnetism and Petrology

There is a growing awareness among researchers of the need to link studies of lithospheric magnetic fields, rock magnetism, petrology, and geochemistry. When combined with petromagnetic understanding, magnetic surveys will yield the maximum information on key questions, such as lateral variations in magnetization, the character and location of hydrothermal alteration, the degree of metamorphism, the mineralogical constitution of the deep crust and upper mantle, and the chemical aging of oceanic crust.

The geological interpretation of magnetic anomalies that originate from contrasts in total magnetization depends greatly upon a fundamental understanding of the physical, chemical, and mineralogical factors that control rock magnetism. For example, the magnitudes of induced and remanent magnetization in rocks are largely determined by the abundance, composition, grain size and shape, and microstructure of ferromagnetic minerals; however, diamagnetic and paramagnetic phases may be important in certain settings where ferromagnetic phases are essentially absent. An outstanding problem is the extrapolation of data from laboratory measurements to the pressure-temperature environment of anomaly source regions. As described in the next four subsections, the

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lithologic environments of the sources may be divided as follows: exposed and shallow crystalline rocks, exposed and shallow sedimentary rocks, intermediate-depth and deep magnetic sources, and oceanic sources.

Exposed and Shallow Crystalline Rocks

The petrological factors that control the magnetization of crystalline rocks at shallow depths in the crust are not well understood. In igneous rocks the factors that control the stability and composition of magnetic minerals may include bulk chemistry of the magma, temperatures and oxygen fugacities of formation, and cooling conditions. Factors that influence magnetic properties of metamorphic rocks include bulk chemistry inherited from the original rock, temperature of metamorphism, pressure and composition of attendant fluids, and fabric of the magnetic minerals. Although the general way that these factors affect rock magnetism is recognized, the sources of short-wavelength magnetic anomalies are commonly difficult to decipher. A greater and more detailed understanding of how factors influence rock magnetic properties is needed to help unravel the histories of complex igneous and metamorphic regions near the surface.

Exposed and Shallow Sedimentary Rocks

Magnetic contrasts within sedimentary rocks are important aeromagnetic targets; the interpretation of these contrasts must rely heavily on the application of rock magnetism, petrology, and geochemistry. Magnetic surveys over thick sedimentary sections have potential for detailed mapping of (1) faults that offset layers of different magnetization or that focus the flow of fluids; (2) structurally deformed beds having magnetization greater or less than that of enclosing beds; (3) lithologic contrasts associated with diapiric salt domes; and (4) zones affected by inorganic alteration or microbial production of iron oxide and iron sulfide minerals.

Intermediate-Depth and Deep Magnetic Sources

Long-wavelength magnetic anomalies from the lithosphere can be generally attributed to (1) variations in the thickness of zones of constant magnetization or (2) contrasting magnetizations that reflect different composition and evolution of the rocks. A combination of factors is likely, but the detailed physical and mineralogical basis for changes in deep-crustal and upper-mantle magnetization is not well understood. Indeed, even fundamental magnetic properties, including the Curie temperature, of deep-seated magnetic minerals are a matter of dispute. An especially challenging and perplexing problem is that magnetizations inferred from satellite and regional aeromagnetic anomalies are larger than most magnetizations actually measured in rocks. Better understanding of anomalies from lithospheric sources must come from experimental and theoretical research on equilibrium mineral assemblages and chemistry at high temperature and pressure. In addition, experimental studies of the effects of temperature and pressure on both induced and remanent magnetization of different rock types are needed.

The magnetic petrology of rocks from intermediate and deep-crustal depths and the uppermost mantle can be studied in three ways: (1) investigation of xenoliths from kimberlites and from alkalic volcanic rocks; (2) measurement of rocks from exposed crustal sections; and (3) determination of the likelihood of occurrence of stable magnetic minerals in rocks of particular compositions by theoretical and experimental methods.

Oceanic Sources

It is well recognized that magnetic anomalies from the oceanic crust provide a record of seafloor spreading, yet the magnetization causing these anomalies remains incompletely understood. Many enigmatic magnetic features provide clues to the evolution of ocean crust, including the decrease in amplitude away from spreading ridges, the enhanced magnetization of the Cretaceous Quiet Zone, and discrepancies in ampli

tude and anomalous skewness in intermediate-and short-wavelength anomalies.

Irregularities in the magnetic anomaly patterns can be attributed to many factors, including the geometry, composition, and cooling history of intrusive and extrusive rocks; tectonic evolution and setting; spreading rate; composition and temperature of hydrothermal fluids; geometry and duration of hydrothermal convection cells; and positions of the convection cells with respect to the spreading ridge or the accreting plate. Clearly, a better understanding of these influences is crucial for mapping and interpreting the geology of the oceanic crust. Such an understanding will come partly from rock magnetic and petrological studies of samples from different tectonic and hydrothermal settings and partly from the paleomagnetic study of unaltered rocks of similar age found in outcrop on land or in cores from the seafloor. A critical question concerns the magnetic mineralogy of the deeper magnetic layers and the associated depth to the Curie-temperature isotherm: where is the base of the magnetic oceanic lithosphere? Experimental work is needed on the magnitudes and stabilities of secondary remanent magnetizations (viscous and chemical remanences) acquired under the physical and chemical conditions of magnetic sources.

Programmatic and Operational Considerations

Several operational issues are critical to the improved acquisition and analysis of magnetic surveys. First, future aeromagnetic surveys should implement advancing magnetometer technologies (for example, gradiometers and vector magnetometers) and navigational systems (for example, GPS). Second, research on the configuration and placement of base-station magnetometers is needed to improve the ways by which the detrimental effects of external fields are removed. Third, improved main field models are critical to isolate lithospheric anomalies from the fields of other internal sources. Fourth, magnetic surveys result in large volumes of digital data that must be archived systematically.

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Increased collaboration among individual investigators measuring physical and chemical properties is also essential to the complete interpretation of magnetic anomalies. Laboratory investigations of magnetic and petrological properties of rocks and minerals are supported primarily by NSF. Additional support of laboratory and field studies is crucial to a systematic approach under the recommendations outlined below. While some of this work can be performed by individual investigators, no single investigator or institution now supports the necessary range of analytical and experimental facilities. Centralized support for advanced rock magnetic studies is provided by the Institute for Rock Magnetism (IRM, University of Minnesota). The importance of IRM is demonstrated by the research productivity of this laboratory and by the collaboration and communication that it fosters. What is needed, as an essential complement to the IRM, is a comparable facility dedicated to the mineralogical, petrological, and geochemical aspects of magnetic petrology.

The issues listed above can be more successfully addressed through greater cooperation and increased collaboration among agencies and individual investigators. Indeed, agency cooperation is essential to the scientific objectives of the proposed initiative. As relevant circumstances change, the U.S. Navy should be encouraged to release classified data no longer critical to national security. NOAA and other agencies should promote the use of "ships of opportunity." The USGS observatory program is a key element in understanding the temporal and spatial global magnetic field. Moreover, USGS should take the lead in coordinating statewide and local aeromagnetic surveys and marine magnetic surveys in order to promote a consistent national magnetic data base. NASA and other agencies (NOAA and USGS) should be committed to future low-altitude satellite missions specifically designed to study the magnetic lithosphere. International efforts, such as the ARISTOTELES and Magnetic Field Explorer (MFE) Magnolia missions, are particularly advantageous to the scientific community.

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Conclusions and Recommendations

The following represent the conclusions and recommendations of the Working Group on Lithospheric Magnetic Anomalies. The order of the recommendations does not reflect a priority ranking.

New and Improved Regional and Global Data Sets

An understanding of the lithosphere is required at a variety of scales covering the entire globe. Consequently, the first four recommendations have equal priority. The remaining recommendations in this subsection are crucial to implementing and complementing the first four.

- The launch of a low-altitude satellite to map the lithospheric magnetic field of the Earth, as well as to improve main field models, is needed. Orbital altitudes should be as low as practical in order to focus on lithospheric problems.

The ARISTOTELES mission, currently being considered as a joint venture between NASA and the European Space Agency, or the alternate MFE Magnolia mission between NASA and the Centre National d'Etudes Spatiales (CNES) of France, will provide a valuable data set for lithospheric magnetic studies. Moreover, the extended high-altitude phase of the mission will permit accurate main field and secular variation models to be derived, thus improving the resolution of the lithospheric field. External field contamination of low-altitude data will be severe. Therefore, a high degree of interaction between those working on lithospheric problems and those working on external fields is essential to promote innovative solutions to the problem.

- A second-generation digital magnetic anomaly map should be developed for the United States and its Exclusive Economic Zone (EEZ) (out to 320 kilometers offshore).

To achieve this objective, a systematic survey strategy is required that employs state-of-the-art instrumentation (that is,

vector magnetometers with 0.01 nanotesla precision, gradiometers, and GPS navigation) and flightline spacings appropriate for the local geological setting. As a minimum goal, the quality of this second-generation map should be comparable to those of Canada and Zimbabwe, thereby permitting more sophisticated analysis techniques.

- High-resolution and high-sensitivity magnetic surveys over specific local areas are required to study a number of important Earth processes.

Studies of sedimentary basins, midocean ridges, continental margins, volcanoes, faults, and continental rift zones are greatly improved with high-resolution and high-sensitivity magnetic surveys, especially when constrained by high-resolution bathymetry or topography, gravity and altimetry data, seismic reflection and refraction data, and direct sampling. Key topics of investigation include oceanic evolution, intraplate and interplate deformation, hydrothermal activity, and upper-crustal magnetization. Such surveys should be carried out by ships, deep-towed underwater vehicles, aircraft, and wheeled vehicles on land.

- Studies in remote regions, such as Antarctica and the southern oceans and arctic ice-covered areas, are needed.

Knowledge of global relative plate motions through time, derived from the first-order kinematic framework defined by magnetic anomalies in the ocean basins, forms the foundation of studies aimed at deducing the driving mechanism of plate motions. These studies are hindered by a lack of even first-order plate motion histories in remote areas of the southern oceans. Aeromagnetic surveys over ice-covered seas and reconnaissance ship surveys are helping to remedy this deficiency. However, additional work remains to be done before definitive tests of driving forces and the fixity of hot spots can be conducted. Additionally, such surveys will help to resolve the timing and character of rifting and basin development in the polar regions and structure and evolution of the antarctic lithosphere.

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- Support for stationary magnetometer installations in tectonically and magmatically active areas should continue.

Innovative research on the relationship between catastrophic geological events and changes in the local magnetic field has critical societal implications.

- Increased cooperation between industry, academia, and government agencies is critical to future studies of the magnetic lithosphere.

A highly successful example of such cooperation is the aeromagnetic survey of the East Coast continental margin, funded jointly by USGS and a private contractor, that took place in the mid 1970s. It is imperative that such data be released in a timely fashion, as it was in the example cited. Many foreign magnetic surveys result from joint government/industry funding and cooperation.

- Development and implementation of a marine mid-depth-tow magnetometer package would greatly increase the resolution of seafloor anomalies and enhance interpretation of high-resolution swath bathymetry surveys.
- Magnetic data held by the U.S. Navy should be released to the public if no longer critical to national security.

These data would be a great resource in studies of paleofield intensity and chemical alteration of the oceanic crust. Alternatively, analysis could be carried out without compromising the classified status of the original data. Average values in 1° bins would be useful in some areas for main field models.

- Studies of the effects of ionospheric currents and induced Earth currents are essential to magnetic studies of the lithospheric magnetic field. There is a need for the development of methods to determine time-varying magnetic fields from multiple or distant base magnetometers and seafloor observatories.

Better Ways to Interpret Data

- Improved interpretive and graphic methods of interpretation and presentation of magnetic data are needed to better relate magnetic anomalies to geology.

Recently developed apparent susceptibility and terracing methods represent steps in this direction. New approaches should include ways to better visualize the data in terms of three-dimensional geological features.

- Improvements in data quality must proceed hand in hand with development in analysis and interpretation techniques.

Improvements in data quality can be effected through better survey design, more accurate models of the Earth's main field, and proper compilation of existing data sets.

- Traditional ways of representing the data during analysis need improvement and reexamination.

Interpolating data sampled at irregular spacing onto equi-spaced grids or profiles remains a necessary and standard technique for representing magnetic anomaly data during analysis. This type of data representation is inadequate for modern analysis, which demands high data resolution. Gridding as presently practiced must be reexamined and revamped in order to better honor the original resolution of irregularly sampled data.

- New ways to visualize and model magnetic anomaly data using interactive graphics are required.

Modeling and inversion methods should accommodate the three-dimensionality of magnetic sources. Such development has been hindered in the past by computer limitations. Development in this direction can now progress using modern computer power and advanced programming techniques.

- Techniques to address data characterization and semiautomatic modeling need further development.

The relevant computer-intensive methods, such as pattern recognition and neural network analysis, should follow the lines of artificial intelligence.

- New techniques are needed to facilitate interpretation of gradiometry, vector magnetic data, and multiple data sets.
- Standard data sets are needed for comparing the results of analysis techniques.

The data sets can include both synthetic and real-Earth data. The real-Earth data should come from a variety of geophysical and geological environments that are fairly well defined.

- Analysis techniques need wider distribution, and the users of the techniques need better reference materials and training in their use.

Rock Magnetic and Petrologic Studies

The objective of rock magnetism and petrology applied to magnetic anomalies is to explain the physical and chemical setting, evolution, and magnetic properties of the rocks responsible for the anomalies. This objective may be approached by implementing the following recommendations.

- Collaboration among anomaly modelers, petrologists, and rock magnetists should be promoted.
- Models should be developed that describe the abundance and character of magnetic minerals in metamorphic, igneous, and sedimentary rocks.
- Magnetic and petrological studies of a wide range of rock types that reflect a variety of geological processes should be supported. Such processes include the following:
 - hydrothermal alteration;
 - metamorphic transitions;
 - igneous differentiation and crystallization; and
 - deposition, diagenesis, and alteration of sedimentary rocks.

Such studies should be relevant to and in the context of a full range of lithospheric magnetic anomalies.

- Rock magnetic experiments at high pressure and high temperature should be supported to improve the understanding of deep-seated lithospheric magnetization.
- Centers for the study of the mineralogical, petrological, and geochemical aspects of rock magnetism should be strengthened and new ones established.

A3.

Electromagnetic Induction Studies in the Earth and Oceans

Scientific Rationale

Fluids, magmas, and high geothermal gradients result from dynamic processes such as metamorphism, magmatism, convection, and deformation in the Earth. Electrical conductivity (or its reciprocal, *resistivity*) is the physical property most sensitive to the configuration and chemistry of these fluids, particularly at the low concentrations expected geologically. Temperature and composition strongly influence the mechanical behavior of Earth materials where ionic fluids do not dominate. In such situations electrical conductivity again depends strongly on dynamically important conditions. The possible widespread presence of grain-boundary phases, such as carbon at crustal or mantle depths, has profound implications for the chemical environment, and once again, remote sensing of the electrical conductivity structure is a very relevant tool for understanding the evolution of our planet.

In addition, there are smaller-scale problems of great interest to society—including energy and resource exploration, electric power grid reliability, water quality and waste management—in which electrical conductivity of the target or its surroundings is a diagnostic physical variable. Electromagnetic methods are the only viable way to delineate conductivity structure from the Earth's surface. Thus, basic research in electromagnetic imaging of subsurface structure has potential for many practical benefits.

Appendix A3 was largely developed by the following workshop group: John Booker (*Group Leader*), W. Campbell, A. Chave, C. Cox, A. Duba, G. Egbert, I. Gough, A. W. Green, L. Hirsch, J. G. Kappenman, L. Law, B. Narod, P. Tarits, J. Tyburczy, P. Wannamaker.

Electromagnetic studies are traditionally separated into oceanic and land-based studies. Although much of the science and many of the techniques are very similar for these studies, there are substantial technological differences; oceanic measurements are considerably more difficult and more costly to accomplish. In addition, induction caused by water movement in the ocean has no analog on land. The Earth's oceans are important in the long-term storage and transport of environmental heat and thus affect our climate. As a good electrical conductor, ocean water easily generates measurable electric fields as it moves through the geomagnetic field. Furthermore, at periods longer than a day, the electric fields at any point represent a volume average of the motions. Therefore, electromagnetic measurements in the ocean are an extremely useful tool for probing large-scale dynamics and monitoring long-term, climatically important variability of the sea.

Electromagnetic induction studies of the solid Earth involve either simultaneous measurements of time-varying magnetic and electric fields—in orthogonal horizontal directions for the widely popular magnetotelluric (MT) method or array measurements of the time-varying magnetic field—in three components for the geomagnetic deep sounding or magnetic variation (MV) method. Both methods have been employed on land and on the ocean bottom and have increased our understanding of the Earth's crust and mantle. The MT method in particular has seen rapid advances in recent years. By contrast, studies of low-frequency oceanic motions require only measurements of the vector electric field. This can be done with dipoles a few meters long or with grounded cables hundreds to thousands of kilometers long.

Interpretation of electromagnetic data is usually broken into three steps. The first step involves estimating frequency domain transfer functions between measured field components from long time series. It is complicated by the fact that the Earth is almost always multidimensional, external sources may not be ideal, and noise processes are often non-Gaussian. The second step uses these transfer functions to obtain a representation of Earth structure. Besides the nonuniqueness problems shared by all inversions of incomplete and inaccurate data, this inverse problem is both difficult and numerically intensive because it is unstable,

nonlinear, and often multidimensional. However, progress in all aspects of interpretation has been substantial enough in recent years to constitute a virtual revolution in our ability to image electrical structure.

Laboratory electrical conductivity studies provide the final critical step, linking models of conductivity and the physical and chemical processes occurring within the Earth. Because conductivity is sensitive to environmental parameters, interpretation of conductivity models requires a thorough understanding of the mechanisms that control conductivity under the limited conditions accessible in the laboratory. Oxygen fugacity, pressure, and chemical environment of surrounding minerals can also affect conduction and are particularly important for adequately constraining the thermodynamic environment of the minerals. Critical questions remaining to be addressed relate to longevity and interconnectedness of conducting fluids (pore geometry) and grain-boundary phases—including aqueous fluids, partial melts, and carbon—over geological time.

Research Questions

- Laboratory measurements at simulated in situ conditions of the electrical conductivity of rocks primarily composed of olivine and pyroxene—thought to be primary constituents of the upper mantle—are as much as three orders of magnitude lower than conductivity inferred from inversion of electromagnetic induction data for the outer 200 km of the Earth. What is the reason for this discrepancy between observed conductivity and the measured conductivity of the major mineral phases? The mechanisms known to determine electrical conductivity include the following: composition, quantity, and connectivity of the fluid; partial melts; carbon and sulfides; and composition, temperature, and mineralogy of the crystalline matrix. Given this plurality of ways to explain enhanced conductivity, what independent constraints are required to make the explanation unique?
- The evidence for a steep rise in conductivity beginning by 400 km is strong. Recent work incorporating very long period electric fields

appears to improve resolution substantially and shows that the rise may be steplike. Definitive interpretation of this conductivity increase requires additional laboratory studies of the electrical properties of β - and γ -(Mg,Fe)₂SiO₄ under controlled conditions. The conductivity appears to level out at around 1 siemens per meter below 800 km, but resolution deteriorates rapidly below 1,000 km. How can this depth barrier be broken through? Additional studies of other candidate materials such as high-pressure minerals with varying iron/magnesium contents under controlled thermodynamic conditions are required to interpret conductivities deeper than 800 km.

- Can lateral variations in conductivity be delineated at mid- and lower-mantle depths? It is known that there are significant differences in long-period response functions at different magnetic observatories. But how much of this signal is due to deep lateral heterogeneity and how much is due to biases associated with shallow structure such as the ocean and inadequately represented external source field morphology?
- Can lateral variations in conductivity in the upper mantle be mapped? Dynamical considerations suggest that temperature and melt gradients should produce order-of-magnitude lateral variations in conductivity, and existing data support their existence but are often susceptible to alternative explanations. Can this situation be improved with more accurate new data collected in a more systematic fashion? Can it also be improved with application of better methods of interpreting data containing potentially distorting multidimensional structural information?
- Do fluids persist in the deep crust over long geological times? It is widely accepted that fluid-rich sedimentary rocks and oceanic crust are transported in subduction zones to depths that require dewatering of the rocks and conversions to higher metamorphic grade. But what paths do these fluids take in returning to the surface? Fluids trapped at depth would have enormous importance in the rheology of the lower crust and upper mantle.
- What are the mechanical effects of aqueous fluids in the upper crust? High pore pressures have been implicated in large offset horizontal thrusting, in the low strength of such important strike-slip features as the San Andreas fault, and in controlling rupture during earthquakes and

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aftershocks. Data exist suggesting that these fluids produce resolvable conductivity anomalies, but definitive results remain to be obtained.

- What role do carbon and graphite play in producing deep-crustal and mantle conductors? Graphite of biogenic origin in metasedimentary rocks may extend to great depths in subduction and continental collision environments.
- How is magma segregated from the mantle beneath a spreading midocean ridge? Model studies based on theoretical studies of this segregation process suggest that ocean bottom MT transects across the ridge can discriminate between major alternatives considerably more effectively than feasible seismic studies and will cover a range of spatial scales that seismic methods cannot resolve.
- Can the location of magma bodies in volcanic regions be determined? They can involve both imminent volcanic hazard and major energy resources. Seismic methods have inferred many low-velocity bodies in magmatic environments that have been interpreted as possible melt zones, but electromagnetic methods would appear to be much more sensitive to the important variables. The growing ability to collect very high density electromagnetic data and to deal with complicated three-dimensional geometry is beginning to provide answers.
- How do electric currents induced in the ocean complete their circuit? Even at very low frequencies for which the ocean is less than one skin-depth thick, strong induced currents are prevented from leaking down into the conductive asthenosphere and deeper mantle by the resistive nature of oceanic lithosphere. Where these currents cross a coast into the more resistive continent, more current will flow at shallow depth than is predicted by the continental conductivity structure. However, the observed coast effect is often less than expected, which may be due to short-circuit conductive paths to the mantle. This can occur at coasts with active subduction or at ancient suture zones. Electromagnetic measurements are very sensitive to the location and structural details of these structures as well as those at ridge crests and active hot spots where additional short-circuiting pathways may exist.
- Can motionally induced electric currents be used to sound the oceanic lithosphere? Barotropic tides in the deep ocean drive vertical

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electric currents through the seafloor. If these tides can be accurately specified and their magnetic and electric fields can be measured, one has an electrical sounding technique that is especially appealing because it is preferentially sensitive to the conductivity of the upper lithosphere. The lithosphere is inaccessible to MT because the conductive ocean screens out the necessary shorter-period external source fields.

Applications

Electrical conductivity plays an important role in a wide variety of practical contexts, including the following:

- **Understanding volcanic regimes.** Seismic data have frequently been interpreted to imply magma bodies in the crust, but electromagnetic methods are much more sensitive to the important variables. The growing ability to collect very high density electromagnetic data and to deal with complicated three-dimensional geometry has the potential of giving considerably more information than heretofore available.
- **Assessment of seismic risk.** Active faults can sometimes be distinguished from inactive structures by the higher conductivity associated with fluids in the highly fractured material. In addition, there is a significant probability that an electrical boundary coincides with the brittle-ductile transition in the crust. Conceivably temporal variations of conductivity near active faults may prove useful for earthquake prediction.
- **Geothermal exploration and resource assessment.** Electromagnetic methods have proven effective in this context. Fluid-dominated hydrothermal systems always contain high levels of dissociated salts and are thus very conductive targets. However, they tend to be difficult to develop for environmental reasons. The rarer vapor-dominated systems can be distinguished from the fluid-dominated ones by the lower conductivity of their less saline fluids.
- **Mineral exploration and resource assessment.** Again, electromagnetic methods have proven effective in this context. Many economi

cally important mineral or metal deposits are highly conductive themselves or are associated with highly conducting materials such as carbon.

- **Hydrocarbon exploration.** Many structures that are capable of trapping hydrocarbons are difficult to image seismically, but involve resistive material overlying good electrical conductors. These include crystalline overthrusts, flood basalts, and carbonate reef structures.
- **Secondary and tertiary oil recovery.** Imaging the extent of the zone flooded by steam or chemicals is one of the major practical difficulties associated with these methods for maximizing production. The steam and chemical floods often change the electrical resistivity of the formation so that electromagnetic imaging either from the surface or a borehole is an appropriate tool.
- **Prediction and amelioration of electric power grid transients.** These problems are thought to be due to geomagnetically induced currents in the regional electrical conductivity structure and have been implicated in large-scale blackouts in both the United State and Canada.
- Correction of precision aeromagnetic surveys due to anomalous fields produced by induction in electrical structure.
- **Hazardous waste site characterization.** Dumps with acidic, metalliferous, or other conducting toxic materials make good targets for electromagnetic imaging. Targets such as dense nonaqueous liquids are resistive relative to ground water. When such fluids underlie ground water, they may be imaged by appropriately designed systems.
- **Assessment of saltwater infiltration into an aquifer.** This has become an important hydrologic issue in many coastal and desert urban areas. The conductivity contrast between saltwater and freshwater is ideal for electromagnetic imaging.
- **Measurement of oceanic motions.** Oceanic electromagnetism is having an increasing impact in studies of the water-velocity field based on measurements of motionally induced horizontal electric field in the deep ocean. Electromagnetic measurements offer spatial averaging capabilities that are far superior to more direct measurements and may have substantial impact on determining such climatically important quantities as boundary current transport, especially over the long term. Both the

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theory and the technology are well developed and are certain to play a major role in global change research.

Operational Considerations

MT and MV sensors have generally been deployed for different, but complementary, reasons. An effective deployment might have an MT transect embedded in an MV array to help ensure optimum profile location with respect to a structure of interest and to constrain the three-dimensional context in which the MT interpretation is made. The reasons for this rest in the different nature of the data collected by the two methods.

MV uses an array of simultaneously recording three-component magnetometers and is primarily sensitive to the electric current distribution in the Earth and the source region. Because of the volume-averaging nature of MV data, there will be a sufficiently long period for deployment configurations so that data will be protected against aliasing of small-scale electrical structures within the array. MV data are therefore ideally suited to determining lateral structure. However, the sensitivity of MV data to source current structure requires attention to detecting and eliminating nonplanar source fields or correcting for their effects. Decomposition of MV array cross-spectral density matrices permits isolating uniform sources and synthesizing the response of large arrays from smaller ones. If the source is nonplanar and can be determined from the array (which may require regional or global observatories), response functions closely related to MT may be estimated.

By comparison, MT uses measurements of the orthogonal horizontal electric and magnetic fields and is more closely related to conductivity than current. The electric fields include information about conductivity heterogeneity very local to the measurement site. This effect persists to very long periods and can be aliased if site spacing is too wide. Thus, new deployment strategies such as electric dipoles placed end to end in a continuous profile and new analysis techniques such as spatial filtering of the electric field have been developed to detect and mitigate the distorting

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effect of shallow, three-dimensional structure. MT sensors have been developed that can utilize the background geomagnetic continuum, permitting data to be collected at almost any time. Complete field processing of MT time series in essentially real time now assures that data of adequate quality are being collected. New deployment and processing techniques using remote-reference sensors can mitigate the biases associated with some forms of noise, particularly of cultural origin. Further developments use robust statistical techniques to deal with non-Gaussian aspects of the noise. They produce estimates of transfer functions between the electric and magnetic fields that are more accurate and have more reliable error estimates. Finally, a variety of methods has been devised to stably invert the transfer functions for two-dimensional structure. New computer algorithms are greatly accelerating (by orders of magnitude) the speed with which the necessary computations can be done, and the day seems to be coming when two-dimensional interpretations can be made as the data are collected. Finally, fully three-dimensional inversions are beginning to appear.

Many of the measurement and interpretation developments that are revolutionizing MT can be extended to MV—wideband measurements, remote-reference technique, in-field processing, generalized inverse theory, and so forth. The most important reason that further advances are not being made with MV is that modern equipment in the United States is limited. Another difficulty is that MT fields at a single site are observed to be more highly correlated than MV fields measured between distant sites. Thus, MT measurements result in more precise transfer function measurements. The reason for this needs to be understood and mitigated if possible. It seems likely to be related to stronger effects of nonideal sources on MV than MT. Arrays can characterize the three-dimensional external current distribution that complicates interpretation of the induced response to geological structure. However, the three-dimensional currents in the ground complicate understanding the morphology of external current systems. Thus, MV array experiments complement the needs of the magnetospheric research field. Cooperation between scientists in magnetospheric and solid-Earth induction, particularly with regard to a shared array facility, clearly has much value.

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The success of the MT profiling portion of the EMSLAB (Electromagnetic Studies of the Lithosphere and Mantle Beneath [the Juan de Fuca Plate]) experiment in delineating conductivity structure associated with the subducting Juan de Fuca Plate beneath Oregon, and the geologically interesting implications of MT data along all the transects of the Canadian LITHOPROBE project have substantially raised the credibility of MT work. This has resulted in inclusion of an MT component in many of the consortium proposals to the National Science Foundation. Presently, the U.S. academic community has limited access to state-of-the-art wideband MT systems. This situation significantly curtails the development and the application of the technique by university groups, and it needs to be addressed with greater availability of field systems. Furthermore, the complete lack of digitally recording magnetometers for MV work in the United States also means that MT data cannot be collected at periods above 1,000 seconds, although these data are needed to probe the upper mantle. The recent collapse of industrial contractors capable of providing data of the quality required has made it difficult, although perhaps not impossible, to use an industrial alternative for projects amenable to shorter-period data. There has never been a commercial alternative for MV or long-period MT data collection.

The EMSLAB conclusion that fluids are being actively injected into the deep continental crust by the subducted material could not have been reached with data collected entirely on land. As discussed above, the efficient collection of electromagnetic energy by the ocean and the current path to the asthenosphere near the coast have a profound effect on MT and MV data on land. Full use of this opportunity requires data on the deep ocean side to set the boundary condition for the injected current. The United States has one limited facility for ocean bottom MT and MV measurements. These instruments are increasingly being used for long-term experiments of oceanic rather than geological and geomagnetic interest. Moreover, existing instruments are not suitable for the motionally energetic environment of the continental shelves. There are thus severe operational constraints on conducting both onshore-offshore experiments and other MT and MV experiments of marine geological interest; these constraints can be ameliorated by building more instru

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ments. Since the technical issues are primarily repackaging of proven designs and evolutionary incorporation of improvements in components and data storage technology, engineering would be modest. If amortized over a significant number of instruments, the engineering cost would be low, and a new generation of seafloor equipment would be only marginally more expensive than land-based, long-period MT instruments.

A tremendous opportunity for the geomagnetic community will arise over the next decade as hundreds of analog submarine cables are retired from commercial service. They can, for instance, be used to monitor the geoelectric field averaged over planetary spatial scales for years to decades. This will permit extending the long-period limit for MT from 1 day to 10 to 20 days and monitoring the ultra-low-frequency variability of oceanic motions under a variety of circumstances.

Some of the results of motional induction experiments need to be communicated to the wider geomagnetic community. For example, the spectrum of motionally induced horizontal electric fields rises rapidly at periods longer than a few days and is very likely going to determine the precision with which weak signals from Earth's core can be measured. The signal level from the ocean varies strongly with location; it is at least 10 times larger under western boundary currents than in the more quiescent oceanic interior. This has implications for the siting of seafloor observatories. In addition, very little is known about motionally induced magnetic fields, although they are certainly weak compared to external sources at periods of days to months. Whether this relationship continues to longer periods is unknown, yet it clearly impacts the feasibility of secular variation studies with seafloor observatories, and thus the justification for the observatories themselves.

Finally, funding for electrical property research is minimal. Additional support of laboratory studies is necessary for a systematic approach to the problems outlined in this section. While not entirely a geomagnetic issue, encouragement of the National Science Foundation PACEM (Physics and Chemistry of Earth Materials) initiative is appropriate.

Programmatic Aspects

Land-based electromagnetic induction research is supported by NSF, DOE, and USGS. The major source of funding from NSF is provided by the Continental Dynamics Program of the Earth Sciences Division, but significant support is also provided by the Geophysics and the Instrumentation and Facilities Programs of this division. Funding of specific research is presently being split by NSF and USGS. USGS also funds several induction research projects carried out by its own personnel. In addition, de facto joint funding is shared between NSF and DOE, because imaging advances supported by the Geosciences Program within the Office of Basic Energy Sciences and instrumental development supported by the Geothermal Technology Division are crucial to the MT profiling projects funded by the Continental Dynamics Program. Support has also been provided by the U.S. Environmental Protection Agency (EPA) and by industry.

For the past decade, most ocean bottom electromagnetic studies have been supported by NSF. This was originally regarded as a marine geophysics topic and supported by the Marine Geology and Geophysics Program of the Ocean Sciences Division. Recent evolution in the specific applications has broadened the support within the NSF to include the Physical Oceanography Program (Ocean Sciences Division) and the Geophysics, the Continental Dynamics, and the Instrumentation and Facilities Programs (Earth Sciences Division). NOAA has supported oceanic electromagnetic research within its Pacific Marine Environmental Laboratory for more than a decade and has supported additional academic investigations through its Atlantic Climatic Change Program.

Currently active laboratories measuring electrical properties of rocks and minerals are being supported by NSF, DOE, and USGS. No interagency funding is presently committed, because the efforts are generally those of individual investigators with few or no graduate students.

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Recommendations

- For reconnaissance prior to detailed MT profiling and to constrain the three-dimensional context in which the MT interpretation is made, MV arrays should be used. These arrays should additionally be used to understand and correct the effects of external source complications on the geological interpretations. For these purposes, an academic MV array facility (consisting of about 25 digitally recording three-component fluxgate magnetometers) is needed.
- To be most effective under the widest range of field conditions, MT instruments need to be mobile and readily deployed, fully remote, referenced for cultural noise cancellation, with complete in-field processing to ensure that quality data are being obtained. Historically the major advances in MT have been made at universities. To guarantee state-of-the-art capabilities and to incorporate new operating modes as they are demanded by new field strategies, maintenance of wideband MT systems at academic institutions are essential—the growth of demand suggests the need for additional systems or that existing systems be upgraded.
- To improve our knowledge of mantle conductivity and to understand the constraints it provides on composition, physical state, and dynamics of the Earth's interior require a multifaceted approach. It should include new data, such as ultra-low-frequency, long-baseline MT measurements; improved observatory coverage; better understanding of the effects of source morphology on interpreted conductivity structure; more sophisticated time series processing and inversion methods; and improved laboratory measurements of mantle minerals under controlled thermodynamic conditions.
- To expand observatory coverage to otherwise inaccessible areas requires ocean bottom observatories. A small task force should be established to estimate the cost and feasibility of long-term, observatory-quality geomagnetic observation on the ocean bottom. This group should incorporate strong representation

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from scientists and engineers with ocean floor instrumentation experience.

- To satisfy the growing interest in utilizing electromagnetic methods for marine geophysical and geological investigations, such as delineating the melt segregation zone beneath spreading ridges and carrying out ocean dynamics studies that can, for instance, constrain long-term climate change, it is necessary that the instrument base be expanded.
- To monitor long-term variability of the geoelectric field for both MT and oceanic studies in the deep ocean requires long grounded dipoles. Use of abandoned submarine cables appears to be promising in this context, but it would require close cooperation between scientists and telephone companies.
- To extrapolate laboratory results to Earth conditions, it is important to understand point defect chemistry. The influence of minor elements such as hydrogen, nickel, and aluminum on the point defect populations that control solid-state conduction in olivines and pyroxenes must be determined. More extensive use of experimental techniques complementing conductivity, such as measurement of thermoelectric voltages and complex impedance, is required.
- To study nonequilibrium electrical properties of water-saturated crustal rocks at elevated temperatures (50 to 500°C) in the laboratory, new experimental techniques are needed. To understand upper crustal conductivities, systematic experimental and theoretical studies of the electrical response of multiphase aggregates and networks are required. Effects of the presence and distribution of other conductivity-enhancing phases such as carbon, magnetite, sulfides, and partial melts must be investigated using advanced experimental techniques that can carefully control thermodynamic variables. Conductivity and complex impedance measurements linked to physical properties such as porosity, permeability, and acoustic velocity in porous water-saturated crustal rocks are needed.

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- To calibrate apparatus in which new materials are being measured, it is essential that the conductivities of known materials at high temperatures be determined. San Carlos olivine (Fo-90) may be a suitable material. Its conductivity is well known under controlled conditions, it is readily available, it is not excessively resistive, and it is reversibly oxidized or reduced if its stability field is crossed.

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A4.

Main Field and Core Processes¹

Scientific Framework

A long-term goal of geophysics is a coherent picture of the structure and dynamics of the solid Earth. The geomagnetic field is a central feature in this quest. Observations of the field are a source of data in some studies, while the understanding of the field and its generation results from other studies. For example, paleomagnetism played a historic role by confirming continental drift and ushering in the birth of plate tectonics by providing an explanation of magnetic striping on the seafloor. On the other hand, understanding the origin and nature of the geomagnetic field is a fundamental component of any coherent picture of the Earth's interior.

The evolution and dynamics of our planet affect all of us, yet the processes and forces involved are hidden from view within the deep interior of the Earth. One of the few tools available to probe that interior is the measurement and interpretation of the geomagnetic field. Three sources contribute to the magnetic field near the Earth: currents in the core, magnetization in the upper lithosphere, and currents outside the Earth and their induced components inside the Earth. The core (or main) field is by far the largest; because it must travel through the mantle, this field yields information both on the region of its generation and on the electrical conductivity of the mantle. In extracting this information, the temporal variation of the field is at least as important as its description at a particular epoch. These time variations occur over periods from months to millennia. Variations in the core's magnetic field that have periods less

¹Appendix A4 was largely developed by the following workshop group: David Loper (*Group Leader*), J. Bloxham, S. Braginsky, J. Cain, M. Fuller, C. Harrison, R. Langel, R. Merrill, L. Newitt, N. Peddie, J. Quinn, P. Roberts, K. Verosub.

than about a year are believed to be screened from surface observation by the electrically conducting portions of the Earth's mantle.

Although there is certainly additional information that might be gleaned from historical records, only a limited number of observations were made, and only a small fraction of those observations survive. Furthermore, many of the most interesting variations of the geomagnetic field occur on time scales that are greater than those accessible through the historical record. In order to extend the history of the Earth's magnetic field beyond the limit of direct measurements, one must turn to the methods and techniques of archaeomagnetism and paleomagnetism. Many natural materials, such as sediments, lava flows, and baked clays, preserve a record of the geomagnetic field existing at the time of the formation or transformation of the material. With appropriate laboratory measurements and procedures, the paleomagnetic record of the geomagnetic field can provide fundamental constraints on the longer time-scale behavior of the geodynamo.

The variety of time and length scales of interest in the study of the main field and core processes is illustrated in [Figure A4-1](#). This is a double log plot with the time extending from 1 year to 5×10^9 years (that is, the age of the Earth) on the horizontal axis and length extending from 1 m to 6×10^6 m (that is, the radius of the Earth) on the vertical axis. Here the crustal fields are a source of noise (except for those components contributing to paleomagnetic measurements). The processes of interest are enclosed in rectangles and the data sources are enclosed in ovals. It can be seen from this figure that, except for geomagnetic jerks, the phenomena of interest occur over long times ($\geq 10^3$ years) and on large scales ($\geq 10^5$ m), whereas the data are almost exclusively measured contemporaneously in more recent times or on much smaller scales.

The basic premise that virtually everyone accepts is that the Earth's magnetism is created by a self-sustaining dynamo driven by fluid motions in the Earth's core. As to the energy mechanism for those motions, the majority favors convective driving, most probably of compositional origin; a minority believes that the luni-solar precession is the source. The theory of convective dynamos is a challenging branch of

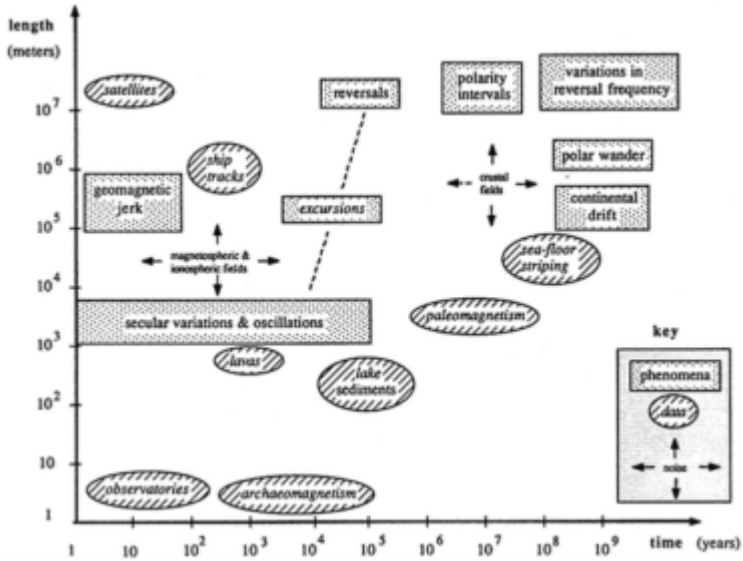


Figure A4-1

Length-time plot showing the relationship between deep-seated geomagnetic phenomena and observations. Note that most phenomena of interest occur over long times and large scales, whereas observations are limited to short times, short scales, or both. Also note that noise due to crustal fields is inherently difficult to extract from the data, because it lies in the middle of the length and time scales of interest (courtesy of D. Loper).

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magnetohydrodynamics (MHD), one in which progress is continually being made, but only slowly. It is known theoretically that such dynamos can operate in both weak-field regimes and strong-field regimes. Although the theory of weak-field dynamos is easy to understand, at least compared with that of strong-field dynamos, most theoreticians believe at the present time that the geodynamo is of strong-field type, in which Coriolis and magnetic (Lorentz) forces are of comparable magnitude. There is at the present time a considerable divergence of opinion about the form a strong geodynamo would take. It centers on the speed of the geostrophic flow within the core and the strength of core-mantle coupling. More concentrated research initiatives are needed to accelerate the removal of uncertainties and a progression towards consensus.

Whatever the outcome of this debate, one thing is clear: the MHD dynamo can take many forms and, without reference to the observational facts and their interpretation, it will be impossible to discover which of the infinity of possible models most closely resembles the Earth's dynamo. The model sought must display the complicated features of the geomagnetic field (from the large irregular reversals to the short-period secular variation) as well as its more regular periodicities and structure. Ultimately the dynamics and thermodynamics of the mantle will have to be incorporated.

The study of the dynamo and its role in the overall Earth system is rooted in geomagnetic phenomena measured at and above the Earth's surface. These data divide naturally into two sets. The first consists of contemporary and historic observations made by satellites, observatories, and surveys; these data are used to construct models of the main geomagnetic field and its secular variation. The second set consists principally of the imprints of past field configurations in a variety of media including baked artifacts, lavas, lake and sea sediments, and magnetized rocks. This information tells us of the past state of the field.

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Present-Day Secular Variations

The secular variation of the Earth's magnetic field, that is, the temporal variations with periods of a few years and longer, provides one of the few probes of time-dependent processes in the Earth's deep interior that can be used in the attempt to unravel the dynamics of this inaccessible part of the Earth. Most other probes of the Earth's interior, such as seismology, are more limited in that they provide only a snapshot of the interior.

In order to study processes in the deep interior, the field at the Earth's surface must be sampled rather densely, so that the observations can be used to construct maps of the magnetic field at the core-mantle boundary, the upper boundary of the region of greatest interest. The data for the past 300 years or so have been sufficient to carry out this program, but not at high resolution. High-quality results have been possible only recently, with the availability of accurate, almost perfectly spatially distributed, satellite observations. Without doubt, one of the most crucial needs for main field geomagnetism is to ensure that data are gathered from evenly distributed permanent magnetic observatories and/or satellites, and that this continues in the future on a regular basis, ideally providing continuous monitoring of the field.

Paleo-Variations

The mere existence of a paleomagnetic record stretching several billion years into the past—implying the existence of fluid motions in the core for at least that long—provides a valuable constraint on the evolution of the Earth. One of the best-documented features of the Earth's magnetic field is that it has often reversed its polarity. However, in the past 10 years, new paleomagnetic studies have provided records of polarity transitions with considerably more detail than was previously available. The new records demonstrate that the behavior of the transitional field is far more complex than was previously believed and that to understand

even a single polarity transition requires a global distribution of high-resolution records.

Progress is being made in this direction, and high-resolution, multiple records are now available for several recent transitions. Some of these records are from the Southern Hemisphere, which until now has been significantly underrepresented in the data base. Many additional records from both hemispheres are needed. Several of the new records have resulted from closely spaced sampling of cores of marine sediment, demonstrating the potential of these cores for studies of polarity transitions. Back-to-back transitions recorded at a given site sometimes show considerable similarity—indicating that the factors which control the details of the transition process may persist over long periods of time. Thus, it is important to study not only a given transition at many sites but also successive transitions at the same site.

An additional source of information about the field derives from the analysis of geomagnetic excursions—short-term, high-amplitude fluctuations in paleomagnetic directions. Although the existence of many reported geomagnetic excursions is still a matter of discussion, some geomagnetic excursions have enough spatial and temporal consistency that they can be accepted as valid geomagnetic phenomena. This acceptance raises the question: should these excursions be regarded as large-scale secular variations or as aborted polarity transitions? Only with more intense study of the phenomenon of geomagnetic excursions can this question be resolved.

Specific Issues

The pertinent scientific issues may be categorized by three questions that are considered in more detail in the following sections:

- How can better spatial and temporal descriptions of the main geomagnetic field be obtained?
- How should those descriptions of the main geomagnetic field be interpreted in terms of mantle properties and core processes?

- How can a theory of core processes be provided?

How Can Better Spatial and Temporal Descriptions of the Main Geomagnetic Field Be Obtained?

The description of the existing main geomagnetic field and its secular variation is based on data that are imperfect and often inadequate for the desired purposes, which require extrapolation to the core-mantle boundary. The data contain errors and have uneven coverage in time and space. Furthermore, the contributions from the crust and core are mingled and thus far are inseparable. The core is believed to dominate up to harmonic degree and order 12; the crust dominates above 16; both sources contribute in the interval 13 to 15.

It is important that better methods be devised to optimize the information content of the data used in the description of the field and secular variation and to place confidence levels on the resulting models.

The time history of the geomagnetic field over the past few hundred years can be determined from a combination of data from long-running observatories and ship-track records. While ship-track records from England have been used successfully to model past secular variation, the reliability of these reconstructions could be significantly increased by "mining" the historic records of other maritime nations, such as the Netherlands, Spain, and Portugal.

The longer history of the field, on time scales of 10^3 to 10^5 years, is determined by a combination of records from archaeomagnetism, lavas, and lake and sea sediments. These data are crucial in the determination of the spectrum of oscillations of the geomagnetic field and possible variations in the strength of the field. This is an important time scale, as there are theoretical reasons to believe that the fundamental oscillation period of the dynamo operates in this range. Lavas are of use in obtaining detailed time-histories of the geomagnetic field at select intervals of time. Of particular interest are those that measure a reversal transition or a geomagnetic excursion.

The long-term behavior of the geomagnetic field, on time scales of 10^6 years or more, is determined principally from paleomagnetic measurements. One area of interest is the average field behavior during a given polarity interval. To first approximation, the long-term average field direction at any given site is that of a geocentric axial dipole field. However, general agreement is lacking as to how long it takes for that mean field direction to manifest itself. Indeed, several studies have suggested that the time-averaged field contains nondipole components that persist throughout a given polarity interval. The existence of such components would place a fundamental limitation on the use of paleomagnetic data to determine plate motions and tectonic movements.

Marine magnetic anomalies provide a first-order record of the polarity transitions for the past 200 million years. However, that record contains certain time intervals where major problems exist and certain unusual features whose precise nature has not yet been determined. Collateral studies of contemporaneous rock sequences exposed on land or obtained by coring at sea are needed to resolve these problems.

Because geomagnetic polarity transitions are the only frequent, globally synchronous geophysical phenomena, high-precision magnetostratigraphy is critically important to the correlation of ocean sediments and to the establishment of a temporal framework for biostratigraphic and isotopic events. An accurate magnetic polarity time scale is imperative for any attempt to place regional events in the context of global change. In addition, an accurate time scale is also a prerequisite to analyses of the statistics of the polarity intervals, which provide information directly relevant to dynamo modeling. Among the topics that have been studied and for which definitive answers do not yet exist are the distribution of the lengths of polarity intervals as well as differences between normal and reversed intervals. Recently there has been considerably controversy about the possibility of periodicities in the frequency of reversals—again without a definite resolution.

While additional work on the time scale for the last 200 million years is still needed, perhaps the most important area for new research will be in determining the magnetic polarity time scale for time intervals prior to the past 200 million years. Because there are no marine magnetic

anomalies and no deep-sea marine sediments of this age, this task will be particularly difficult. However, it is possible that the major questions about the statistics of the polarity intervals cannot be solved without such data.

How Should Those Descriptions of the Main Geomagnetic Field be Interpreted in Terms of Mantle Properties and Core Processes?

The downward extrapolation of contemporary models of the field is complicated by the fact that the mantle has a nonzero electrical conductivity which increases with depth. While the conductivity of the upper portion of the mantle (down to 1,000 km at most) may be estimated from magnetic-induction studies, the conductivity of the lower portion is determined by the character of the geomagnetic secular variation signal that propagates from the core. Variations in this signal shorter than several years appear to be screened by this conductivity, masking from view any rapid variations (1 year) within the core. However, these same data provide valuable information about this conductivity distribution, particularly that in the lowermost portion of the mantle, called the D" layer. Until now, models of the conductivity distribution have assumed axisymmetry. However, there is strong evidence from seismology that the D" layer is nonsymmetric. An important question is whether the geomagnetic data can discern this nonsymmetric conductivity distribution.

Reliable determination of the temporal evolution of the magnetic field at the core-mantle boundary provides a probe of the dynamics of fluid flow in the core (of obvious importance to dynamo theory) through the determination of the pattern of fluid flow immediately beneath the core surface in much the same way that surface plate motions constrain models of circulation in the mantle. Many important questions need to be answered. Is the flow nearly in geostrophic balance, as in the atmosphere, or is the complicating effect of Lorentz forces important? Is the top of the core stably stratified? What is the radial length scale of the flow? In other words, is the flow imaged at the core surface representa

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tive of whole core convection, or is the flow as it is seen indicative of flow only in the near vicinity of the core-mantle boundary and which may be highly influenced by lateral heterogeneity of the mantle? Do abrupt changes in the magnetic field result from magnetic instabilities, such as kink instabilities, or are they just an ingredient of "normal" secular variation?

A related problem concerns core-mantle interactions. These can be split into two classes: those that transfer angular momentum between the core and mantle and which thus affect the length of day, and those that do not involve, at least directly, the transfer of angular momentum, such as thermal interactions, but which are likely to affect the pattern of fluid flow at the core surface. Great progress has been made in the past few years in understanding the transfer of angular momentum: the budget of the Earth's total angular momentum is now well explained on time scales of decades (meteorological studies have led to a similar understanding on seasonal to weekly time scales). But, although the budget is well understood, the mechanism is not, and the great challenge is to understand the relative importance of the various torques (pressure, electromagnetic, gravitational, and viscous) that operate across the core-mantle boundary. This issue is important not only in an understanding of the dynamics of core-mantle coupling; it also has implications for other fields, including dynamo theory and the interpretation of Earth nutation. Thermal and chemical interactions play a central role in determining the convective motions throughout the Earth's interior and are a vital ingredient in the understanding of the thermal and chemical history of the Earth.

There are several questions regarding the nature of a polarity transition:

- Is the Earth's magnetic field predominantly dipolar at the Earth's surface during a transition?
- Are there preferred directional systematics present during a transition?
- What is the temporal relationship between intensity changes and directional changes?

- What similarities and differences are there between successive transitions?
- Is the transitional field predominantly of the dipole (asymmetric) or quadrupole (symmetric) family?
- Are there very rapid changes in direction and/or intensity during a polarity transition?

For many years, it was thought that westward drift was the dominant mode of behavior of the nondipole field. Recent compilations of historical data suggest that individual centers of nondipole activity can move and evolve in a variety of ways.

- What processes govern the behavior of the sources of the nondipole field?
- Are there persistent geographical controls on this behavior?
- What are the characteristic time constants in the secular-variation record?
- Is there a change in secular variation immediately preceding or following a polarity transition?
- What is the relationship between geomagnetic excursions and secular variation?
- Are reversals distinct from normal secular variation or do they represent an end member of a continuous spectrum in secular variation?

Recently, paleomagnetic secular-variation data from lava flows have been used to provide valuable indirect information on the magnitudes of the competing dynamo families (dipolar and quadrupolar). Is the ratio of the strength of dipole to quadrupole family high during the Paleozoic long reverse interval as it appears to be during the Cretaceous long normal interval? What do differences in the mean normal-polarity and reverse-polarity data reflect? What are the changes in time of the mean field-polarity asymmetries? What other paleomagnetic data can be used to provide information on deep-Earth properties and processes?

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The present determinations of the temporal variations in intensity of the field on both short and long time scales are especially significant; key intervals are the past few hundred thousand years and during the superchrons.

How Can a Theory of Core Processes be Provided?

A recent renewal of interest in the precessional driving mechanism was sparked by the discovery that flows with elliptical streamlines—somewhat similar to the flows that are driven by the luni-solar precession—are unstable. Whether this has any significant implications for core dynamics is as yet unclear, but it certainly deserves further investigation.

There is a very great need for further large-scale numerical computation in which MHD dynamos of the same general type as that of the Earth are constructed. Not only would this help resolve the nature of the strong-field balance, but it would also indicate how models can be "tuned" to the geomagnetic data. Ultimately, this tuning will lead to new information about the physical state of the core. Very many numerical experiments need to be performed covering a wide spectrum of input parameters, and the results need to be compared. Moreover, there should be several groups engaged in this research—groups that will benchmark each other's programs, devise increasingly efficient numerical techniques, and generally stimulate each other. So far, no efficient numerical method has been devised that can cope with the dynamics over periods of the order of the free decay time of field (14,000 years) in a system that turns once every day. And of course, because of the celebrated theorem of Cowling, it is necessary to seek fully three-dimensional solutions. It is a little alarming for the standing of the United States in this field that large-scale computational efforts are being made in this country at only one institution. Other nations are making a greater commitment. For example, the United Kingdom has a substantially larger effort in manpower and resources in this area.

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Over the past decade, there has been an increasing awareness of the importance of the upper layers of the core and the lowest (D'') layer of the mantle. A better understanding of these regions and of the nature of core motions is emerging from the geomagnetic data gathered by satellite and, over longer periods, by geomagnetic observatories. Clearly, more insights will emerge from further work in this area, particularly regarding core-mantle coupling and the decadal variation in the length of the day.

The source of secular-variation impulses has baffled theoreticians for more than a decade. It remains an important unsolved problem of geomagnetism.

Applications

Models and charts of the main field and its secular variation have a wide range of practical applications. They provide quick answers to questions about the strength and direction of the geomagnetic field. Navigators, surveyors, and scientists depend on them directly, and nearly everyone makes use of them indirectly. They are the source of the vital magnetic information shown on the millions of nautical and aeronautical charts and topographic maps sold in the United States each year. Models are built into the onboard navigation systems of countless military, commercial, and private aircraft. They provide the declination needed for radio navigation systems and for airport runway designations. Surveyors often need to know the declination, obtained from a model or chart, for surveying land and mines. Models are used by geophysicists to remove the main field trend from aerial survey measurements taken in the search for minerals and petroleum. Information on declination, obtained from models and charts, is used for aiming antennas and drill strings. Models are used for finding the paths of cosmic rays, for the magnetospheric coordinate system, and for calculating field-line geometry and the locations of conjugate points. Magnetic charts are especially useful for visualizing the shape of the Earth's magnetic field.

Accurate knowledge of the present-day magnetic field at the surface is important to a wide range of commercial and military activities,

including natural resource exploration, navigation, and orientation of drill holes in oil exploration and production.

The reversal chronology and secular-variation records provide valuable global and regional dating tools for diverse purposes. They can be used to help establish baselines in global change research or for stratigraphic control in mineral exploration.

Operational Needs

A severe difficulty in modeling the present field is the extremely uneven distribution of observatories over the Earth's surface and the absence of continuous monitoring by satellite. To obtain information about the longer time scales of the secular variation, a major effort in archaeomagnetism and paleomagnetism is required, including the utilization of new techniques of dating and magnetic measurement. The theory of core dynamics requires greater support in manpower and computing facilities.

Improved Global Models of the Geomagnetic Field

The accuracy of any main field model, both in time and space, depends critically upon the quality and distribution of the data upon which it is based. In the absence of global, vector satellite survey data, modelers are dependent on the various types of surface data. Even if periodic satellite surveys were available, determination of accurate temporal change between surveys depends upon the surface data. For study of the Earth's interior, determination of the temporal change is at least as important as determination of the field itself, and the time scales range from less than a year to centuries; therefore, the highest priority in data needs is for temporally continuous and global vector data. The best-quality data would be from Magsat-like satellite surveys.

In the absence of such surveys, the highest priority should be to augment the present distribution of magnetic observatories to obtain as

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nearly as possible an equal area coverage over the entire Earth, with a spacing of no more than 2,000 km. If, in the future, continuous satellite survey data become available, the augmented observatory data network will still play a vital role in modeling. This is because truly accurate models will be those which also model the ionospheric field. Since satellite data are acquired above the ionospheric currents, such fields are a source of inaccuracy for field models based only on satellite data. The combination of satellite data with a good distribution of surface data permits separation of the measured field according to its three constituent fields: the interior of the Earth, the ionosphere, and the magnetosphere.

For incorporation of a definitive model of the ionosphere into our main field models, data from more than a single satellite are required. This is because the morphology of the ionospheric fields varies in local time, whereas the data from a satellite are acquired at only two local times (one ascending, the other descending). A reasonable attempt at such a definitive model could probably be carried out with three satellites in orbit simultaneously and spaced equally in local time.

The network of observatories, even if augmented as described above, can profitably be supplemented by true repeat stations. By that is meant stations that are visited every 2 to 5 years for remeasurement of the field. The measurements at each reoccupation should be taken at the physically identical position, and care should be taken to minimize or eliminate any magnetic disturbance fields and the daily variation.

The observatory data should be supplemented by periodic surveys over oceanic and remote land areas by aircraft or ship. These, in fact, are crucial in any areas where the observatory data do not meet the requirements stated above. Such measurements will never have the accuracy or continuity so valuable in observatory data, but—in the absence of an observatory—will at least prevent the models from being wildly inaccurate.

Because of the importance of determining the temporal characteristics of the geomagnetic field, there is great interest in studying past field changes. This can be done only for the few hundred years during which some sort of magnetic data were acquired. Recent efforts to collect such historical data and use them in deriving spherical harmonic models have

proved very successful and useful. However, large portions of the historical data are not known or available to the modeling community. An effort to gather such data is needed to increase the accuracy of our historical models.

Long-Period Variations: The Need for Archaeomagnetic and Paleomagnetic Syntheses

With modern and historical data, the longest temporal scales accessible are between 60 and 400 years. These are not the only important time scales for study of the geomagnetic field and the underlying dynamo. In fact, it can be argued that longer-period variations are more important and fundamental.

Information about the longer-term secular variation of the geomagnetic field can be obtained from the paleomagnetic study of archaeological materials, lava flows, rapidly deposited sediments, and cave deposits. One clear advantage of using archaeological materials is that they can often be placed in a fairly restricted chronological context. The accuracy and resolution of that context is greatest for samples that are only a few hundred years old. Moreover, samples of that age are an important means of supplementing the historical record of field directions. In addition, paleointensity studies can provide the intensity information that is lacking from the historical observations.

Lava flows represent another source of information about geomagnetic secular variation. The advantage of lava flows is that they are accurate recorders of the geomagnetic field direction at the time of the eruption of the lava. In addition, using relatively well-established and well-understood procedures, it is possible to determine fairly accurately the absolute intensity of the geomagnetic field at the time of the extrusion of a lava flow. However, here too, rock magnetic studies are needed to improve the existing techniques. In addition, the record of volcanic activity in some fields extends over periods of several hundred thousand to a few million years. Paleomagnetic study of these fields can provide

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information about the long-term behavior of the field that is difficult to obtain from any other source.

In contrast to the archaeological materials and lava flows, rapidly deposited sediments have the potential of providing continuous records of geomagnetic field behavior. Recently paleomagnetists have succeeded in obtaining reproducible records of secular variation from lacustrine environments. For at least the past 10,000 years, these records are consistent on a regional scale and contain features that can be correlated on a global scale. At the present time, the resolution that can be obtained for any given area is limited by the understanding of the processes involved in the magnetization of a sediment; considerably more research is needed in this area.

The use of sediments in determining changes in the intensity of the geomagnetic field lags far behind their use to determine the direction of the field; very few paleointensity records are available. This discrepancy is caused primarily by the fact that the methodology for extracting paleointensity data from lake sediments is still evolving; there is clearly a need for more fundamental work in this area. Resolution of the existing questions regarding paleointensity techniques would pave the way for determination of the complete paleomagnetic vector. One or more records of the secular variation of the total geomagnetic field would probably provide important new insights about secular variation itself and about the interaction between the dipole and nondipole components of the field. Furthermore, the intensity of the geomagnetic field and the solar wind are the primary modulators of the flux of galactic cosmic rays that control the production of radiogenic isotopes in the Earth's atmosphere. New data about variations in geomagnetic intensity, combined with existing data on radiocarbon production rates, will lead to a better understanding of major solar processes.

Although initially studies of both directional records and paleointensity records have focused on sediments spanning the last 10,000 years, records extending back in time for the last several hundred thousand years are also very important. Extant and dry lakes in unglaciated areas and long cores of marine sediments will be the primary sources of these records.

No single source of information will provide a complete record of secular variation, and in the final analysis, data from several sources will be needed. It is important to recognize that virtually all aspects of paleomagnetism are involved in this process. For example, the results of laboratory rock-magnetic studies are essential to the interpretation of paleomagnetic samples from the field, because we need to know the conditions under which the recorder of the field is reliable.

As these data are accumulated, they will extend knowledge of the behavior of the Earth's magnetic field from the time scale of a few hundred years (available from observatory data) and historical records to a time scale of tens of thousands of years (initially) and hundreds of thousands of years (eventually).

Priorities

It is generally difficult to set firm priorities. However, on the basis of the discussion above, the following are suggested as the top priorities, grouped in order of importance:

Group 1.

- Augmentation of the observatory network;
- Continuous satellite survey; and
- Archaeomagnetic and paleomagnetic data acquisition.

Group 2.

- Historical data;
- Aeromagnetic and shipborne magnetic surveys;
- Repeat data; and
- Multiple satellite survey.

Programmatic Aspects

Scientific Organizations

The study of the geodynamo is a central component of SEDI (Studies of the Earth's Deep Interior), an international program under the guidance of a IUGG committee of the International Union of Geodesy and Geophysics (IUGG). This committee organizes biennial interdisciplinary symposia allowing intimate interaction between geomagneticians and scientists from other geophysical disciplines having a common interest in the structure and dynamics of the Earth's deep interior. SEDI also encourages the formation of national groups. Two such groups have been formed to focus on geomagnetic studies: in the United Kingdom, a National Environmental Research Council (NERC)-sponsored cooperative study of hydromagnetic oscillations, and in Japan, a project on The Earth's Central Core.

Under the SEDI umbrella, a Cooperative Study of the Earth's Deep Interior is being developed in collaboration with the Earth Sciences Section of NSF. Among other things, this initiative calls for a sustained cooperative effort in the dynamic modeling of the dynamo process. If implemented, this initiative should result in a significant level of support for this activity.

Governmental Agencies

Governmental agencies are involved in two ways: several agencies require the output of modeling efforts, and data acquisition capability crosses agency boundaries.

Modeling requirements exist within DOD, USGS, NOAA, NASA, and NSF. For the latter two, the requirements stem from the use of models by researchers under the grant system.

An important fact is that different data sets are collected under the auspices of different agencies. For example, satellite data are acquired by DOD and NASA; magnetic observatory data are acquired by USGS and

corresponding agencies abroad; and aeromagnetic data are acquired by DOD, USGS, and the natural resource industry. Each of these organizational efforts is directed toward meeting internal requirements, yet each data set is of value for geomagnetic studies and in particular for modeling the main field. To our knowledge, no formal coordination occurs between agencies.

The initiation of minimal joint planning between agencies, with the participation of a scientific advisory group, would provide guidance so that the data acquisition efforts could be planned both to satisfy needs of individual agencies and to better meet the needs of the modeling community.

Conclusions and Recommendations

Recent advances in geomagnetic analysis and theory, the advent of data from recent measurements onboard satellites and historic measurements on wooden ships, and complementary developments in other geophysical disciplines (for example, seismic tomography) have resulted in new insights into the existing picture of the structure and dynamics of the Earth. These insights have also revealed shortcomings both in that picture and in present attempts to improve it. There are several developments in measurement acquisition and research that are particularly crucial for the continued progress of research in this area. They include the following:

- Geomagnetic observatories should be set up to give more uniform coverage over the Earth's surface, especially the oceanic areas. Costs could be minimized by sharing existing facilities (for example, Incorporated Research Institutions for Seismology [IRIS]). On a longer term, there should be a commitment to fly a magnetic satellite at all times.
- Archaeomagnetic and lake-and sea-sediment data should be gathered in order to add significantly to the sparse data available about the geomagnetic field during the past few thousand years.

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High-quality data should be sought that cover paleosecular variation, including paleointensity, magnetic stratigraphy, and reversal transitions. The geomagnetic opportunities afforded by the Ocean Drilling Program (ODP) have not yet been fully realized. Rescue archaeology has the potential to provide useful archaeomagnetic information.

- Better field models should be generated from the data to provide constraints on geodynamo theory.
- When compared with the advances made in the gathering and interpretation of data, the development a model of the geodynamo is seen to be lagging. Future progress would be enhanced if this imbalance were redressed by the commitment of more manpower and advanced computer resources to the modeling of the geomagnetic dynamo.

Appendix B

Operational Working Group Reports

B1. Operational Platforms

Stationary Platforms on the Surface and Seafloor

Introduction

The Earth's magnetic field varies on time scales of years to fractions of seconds; the sources of these variations are both internal and external to the Earth. These temporal variations are not uniform about the Earth's surface but have local and regional differences determined by their sources and by the physical structure of the Earth and the space surrounding it.

These temporal magnetic field variations may be used to study the following:

- resistivity structure of the Earth's crust, mantle, and core-mantle boundary (CMB);
- secular-variation sources at the CMB;
- main field origins;
- morphology of ionospheric and magnetospheric current systems and plasma distributions;
- sources of pulsations (ultra-low frequency [ULF] waves);

Appendix B1 was largely developed by the following workshop group: James Heirtzler (*Group Leader*), J. Arkani-Hamed, J. Behrendt, A. Chave, C. Cox, W. Dewhurst, B. Donovan, M. Engebretson, K. Gebhardt, I. Gough, A.W. Green, W. Hanna, R. Hansen, D. Herzog, T. Hildenbrand, P. Hood, V. Labson, L. Law, J. MacQueen, R. McPherron, P. Mulligan, B. Narod, L. Newitt, R. Pawlowski, J. Quinn, C. Raymond, F. Rich, J. Slavin, P. Tarits, P. Taylor, P. Wannamaker, R. Wold, L. Zanetti.

- atmospheric-ionospheric coupling effects on atmospheric dynamics and weather patterns through monitoring of solar quiet (Sq) variation;
- ocean dynamics (barotropic flow, internal waves, and so on); and
- magnetic activity indices and the nowcasting and forecasting of magnetospheric and ionospheric disturbance.

To use these temporal variations effectively in studies like those listed above requires a hierarchy of local, regional, and global magnetometer arrays (both vector and scalar). Depending on the purpose, array spacings may vary from kilometers to hundreds of kilometers. Because more than half of the Earth is covered by oceans, magnetometer arrays must also be placed on the ocean bottom.

Just as there is a wide range of array separations in the spatial domain, there is also a wide range of frequencies (or periods) in the time domain. The study of magnetospheric pulsations (ULF waves) is concerned with periods from about 1 second to a few thousand seconds. For magnetotelluric and induction studies, the range in periods is from seconds to hours, and sometimes to days. Secular-variation and CMB studies utilize periods of years, tens of years, and hundreds of years. In these long-term studies, the baseline drifts of the instruments become major sources of error; thus, independent, "absolute" instruments must be used to precisely determine instrument "baselines" to 1 or 2 nanoteslas.

Similarly, a wide range of amplitude resolution is required: from 1.0 picotesla (1.0 milligamma) in the case of ULF waves to 1.0 nanotesla (1.0 gamma) for secular-variation studies.

The specifications cited are well within the reach of current technology; instruments with these resolutions and accuracy can provide key data for studying the important problems listed above.

The technology is available today for implementation of a global network of geomagnetic observatories and magnetometer arrays to address critical problems in the solid Earth and space physics.

Issues and Approaches

Current Status—Surface Platforms

Surface platforms are of mainly two types: magnetic observatories and variation stations. Magnetic observatories are dedicated to recording long-term (years) change in all three components of the magnetic field (as well as shorter-term changes on scales of hours and minutes). Magnetic observatories are primarily distinguished from variation stations by the use of independent absolute instruments at the observatories to accurately determine baselines in order to establish long-term trends (secular variation). Data from magnetic observatories will typically be 1-minute values or hourly mean values with a resolution of about 1 nanotesla (sometimes 0.1 nanotesla). Currently the data are sent to World Data Centers (WDCs); prior to this transmittal, the data are usually not available for 1 1/2; to 5 years, and sometimes not until 10 years. There are about 180 observatories worldwide that send data in digital form to the WDCs. They are mostly in the Northern Hemisphere, with a dense network in Europe. There are very few in the Southern Hemisphere; with the exception of a few island observatories, there are none in the ocean areas.

Variation stations record only variations in the vector components of the Earth's magnetic field and do not attempt to determine baselines. Although some arrays of variation stations are operated on a semipermanent basis in Canada, Alaska, and northern Europe, most are operated on a "campaign" basis. Variation stations are used in studies of ULF and magnetospheric or ionospheric current systems and for induction and magnetotelluric studies of crustal and upper-mantle resistivity structure (such as in the EMSLAB project).

Repeat stations are temporary magnetic observatories with "absolute" instruments that are set up for a few days at repeat sites at intervals of 2 to 10 years (usually 5 years). Data from these repeat stations are used to augment data from permanent observations and satellite surveys in making magnetic charts and spherical harmonic models of the Earth's magnetic field.

Current Status—Seafloor Platforms

Vector magnetic variations have been measured on the ocean bottom with amplitude resolution up to 0.1 nanotesla and time resolution up to about 60 seconds. The data are used in magnetotelluric and induction studies of crustal and mantle resistivity. The platforms have been operated in "campaign" modes for periods of weeks and months (EMSLAB, Barotropic Electromagnetic and Pressure Experiment (BEMPEX) and upcoming studies across passive margins and rift zones). No permanent platforms have been established, and no absolute measurements have been made to establish secular variation of the vector components of the Earth's magnetic field, although there is a nascent Japanese program.

Current Status—Instruments

More than half of the classical observatory magnetometers of a few decades ago have been replaced by digital, electronic magnetometers. The electronic magnetometers themselves are also being improved. Recent developments have resulted in the availability of high-resolution, very stable, self-biasing, ring core fluxgate vector magnetometers with typical characteristics:

- noise: 0.02 nanotesla/hertz @ 0.1 hertz;
- temperature drift: 0.1 nanotesla/°C;
- baseline drift: 5 nanoteslas per year;
- power: 1-2 watts; and
- output: analog and digital.

These instruments can provide analog and digital data with resolution of better than 0.1 nanotesla and accuracy of 1 or 2 nanoteslas at 1.0-second intervals. Lower-power instruments have been developed for special applications.

Total field instruments such as the D.C. polarized proton magnetometer, the Overhauser proton magnetometer, and optically pumped

magnetometers can provide absolute scalar data at sample intervals from 0.1 second to 5 seconds with precision from 1.0 picotesla to 0.1 nanotesla and accuracy from 0.01 nanotesla to 1.0 nanotesla.

Current Status—Data Collection and Distribution

The reporting of results from magnetic observatories to World Data Centers is a major problem. In a recent experiment to see how promptly annual means were sent to WDC-A, for example, it was learned that many observatories were 3 years late. Under the newly established INTERMAGNET program, geomagnetic data from participating geomagnetic observatories are transmitted in near real time via geostationary satellites or computer links to collection and distribution centers known as Geomagnetic Information Nodes (GINs). Four satellites are used (GOES-E, GOES-W, Geostationary Meteorological Satellite [GMS] and Meteorological Satellite [METEOSAT]) which cover most of the globe from 70°N to 70°S latitude. Data consist of 1 minute samples of each of the three components of the magnetic field from a fluxgate magnetometer and of the total field from a proton magnetometer (all with resolution of 0.1 nanotesla). In some cases, 1-hour and 3-hour geomagnetic disturbance indices, similar to the K index, are generated at each site and transmitted via satellite. The data, which include the best available baseline values, are transmitted at 12-minute or 1-hour intervals.

About 25 observatories in North America, Europe, Africa, the Pacific, and Antarctica are now participating in INTERMAGNET. GINs are now operating in Golden, Colorado, United States; Edinburgh, Scotland, United Kingdom; Paris, France; and Ottawa, Canada. Since no GIN can see all of the INTERMAGNET satellites, it is planned to make inter-GIN transfers each 24 hours via computer net so that each GIN will have a complete global geomagnetic data set that is not more than 24 hours old. Users will receive global data sets on-line via telephone-computer link, by E-Mail, or later by CD-ROMs that will be updated at yearly intervals.

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Future Initiatives—Surface Platforms

The existing network of magnetic observatories should be expanded to provide better global coverage, particularly in the Southern Hemisphere. This should be considered because the technology exists today to establish relatively inexpensive, unmanned observatories reporting via satellite or telephone modem. However, the requirement still remains for periodic visits to take absolute measurements for maintaining good baseline control.

Capabilities of available instruments make it possible to have observatory data with good baseline control, resolution of 0.1 nanotesla, and 1.0-second sampling in near real time from a global network. Although the data rates of satellites now used by INTERMAGNET limit time resolution to 1.0 minute, 1.0-second data are available at INTERMAGNET observatories for collection by auxiliary systems or may be transmitted using higher data rate satellite systems.

The same low-power, high-resolution vector magnetometers used at observatories may be coupled with equally low-power data collection systems to produce sets of relatively inexpensive and highly portable array magnetometers. These array magnetometer systems may be used in regional arrays to discover and map anomalous electrical resistivity structures in the continental crust and upper mantle. By augmenting these array magnetometer systems with electric field sensors, MT soundings can later be made over regional structures mapped by the array magnetometer studies. These array systems have the same operating characteristics as those earlier proposed by the Consortium on Array Magnetometers (CAM).

As suggested in the CAM proposal, these same array systems can be used for studies of ULF waves, field-line resonances, and the morphology of magnetospheric source fields and current systems.

Consideration should be given to establishing a publicly funded set of 25 array instruments (such as proposed by CAM) to be maintained by a university member or by a public agency (such as USGS), and available for use by both the solid-Earth and space physics communities. Cooperative use of array instruments should result in the magnetospheric

community's receiving help from the induction community in understanding the significant effects of Earth structure on the characteristics of ULF waves (particularly on polarizations).

Future Initiatives—Seafloor Platforms

To effectively study both the solid Earth and the space above it, magnetic observations must be made over the entire Earth, including the two-thirds covered by the oceans. The technology exists today to put low-power vector and scalar magnetometers with data acquisition systems at permanent sites on the seafloor. These sites could be autonomous and interrogated remotely by surface vessels. Or they could be coupled to surplus transoceanic cables to transmit their data continuously to land terminals. It is technically feasible to take independent absolute measurements on the seafloor using an Earth-seeking gyro for vertical and directional references and using fluxgate and proton magnetometers in a declination inclination magnetometer (DIM) system. The DIM system would be lowered from a surface ship or a submersible, or even left in place and periodically actuated remotely from the surface; for cable sites, the emplaced DIM could be actuated through the cable. The possibilities for these seafloor systems, as well as for obtaining absolute measurements on the seafloor, were seriously covered in papers and discussions at a session during the 1991 IUGG meeting in Vienna and should be further developed.

In a recent study, the Earth was divided into 128 equal area elements of $2,000 \times 2,000$ kilometers (km). Of these, 71 contained some land, leaving 57 "ocean" elements. Some 32 of the ocean elements contained islands, leaving 25 elements as potential candidates for ocean bottom magnetic observatories. Approximately one-half of the land elements now have observatories. Although 2,000-km spacing will satisfy main field modeling, it does not quite meet the needs of secular-variation source studies. The need for 700-to 1,400-km spacing could be satisfied by temporary ocean bottom instruments around a permanent "anchor" observatory.

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Future Initiatives—Global Geomagnetic Indices

Planetary indices of geomagnetic disturbance such as the planetary K-index (Kp), disturbance storm time (Dst), and auroral electrojet magnetic activity index (AE) are currently available to users with delays of weeks (Kp) to years (AE). Although activity indices from a few selected sites are now available through INTERMAGNET and NOAA's Space Environmental Services Center (SESC) in Boulder, Colorado, in near real time, true planetary activity indices are not yet available with a promptness approaching "near real time." Users whose activities are adversely affected by geomagnetic disturbances urgently need real-time notice of the disturbance state of the magnetosphere.

Recommendations

- Selected geomagnetic observatories using suitable low-noise magnetometers should begin to collect three-component data at 1-second intervals for use by the magnetospheric and induction communities.
- Long-period, two-component horizontal electric field measurements (similar to those made at Tucson, Arizona, in the 1920s) should be made at a worldwide network of selected geomagnetic observatories. These data, in conjunction with long-period geomagnetic data, can be used to study deep-Earth resistivity structure.
- Where islands are not available, geomagnetic observatories utilizing three-component magnetometers and total field absolute magnetometers should be established on the ocean bottom. Methods should be developed for taking absolute measurements on the ocean floor. This effort should be coordinated with the IRIS Ocean Seismic Network; in general, efforts should be made to collocate geomagnetic observatories with planned seismic observatories. A task force should be formed to design and

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estimate the cost of the ocean bottom observatory and absolute measurement system.

- Geomagnetic observatory coverage of ocean areas should be planned to take advantage of ocean islands, where possible, since costs of installation and periodic absolute measurements would be much less than on the ocean bottom. Collocation with existing or planned seismic or geodetic observatories should be sought where feasible.
- The INTERMAGNET observatory network should be expanded in the auroral zones (Eastern Canada and Siberia) and in lower midlatitude regions to provide a sufficient array of stations for calculation of real-time AE and Dst indices.
- The planned deployment of six U.S.-and four U.K.-unmanned Automatic Geophysical Observatories (AGOs) in the Antarctic should be encouraged. Recordings with modern low-noise instruments should be maintained at manned sites for both magnetospheric research and induction studies.
- A publicly funded set of approximately 25 three-component array magnetometers and data acquisition systems (with provision for electric field registration) should be obtained. These systems would be similar to those previously proposed by the CAM. The systems would be time-shared by the induction and magnetospheric communities and would be maintained by one of the universities involved or by USGS.
- An adequate supply of state-of-the-art wideband MT systems should be developed and maintained for academic use.
- Selected geomagnetic observatories with low-noise magnetometers should compute dB/dt at 1-second intervals for electric power companies on a campaign basis. Should these data prove useful, consideration should be given to computing a dB/dt index on a permanent basis and transmitting it in real time to electrical power companies to warn of potential damage to electrical power systems from geomagnetic storms.
- A chain of geomagnetic observatories reporting in near real time through INTERMAGNET should be established in the equatorial

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zone to provide corrections for the U.S. Navy POGS satellite and possible future magnetic mapping satellites.

- INTERMAGNET and Solar-Terrestrial Energy Program (STEP) should cooperate closely in establishing complementary global geomagnetic data bases.
- Transoceanic cables that are no longer required should be made available for passive monitoring of electric field potentials.

Airborne/Shipborne Facilities

Enhanced Capabilities

Recent technological advances in airborne/shipborne platforms greatly enhance understanding of the nature and evolution of the lithosphere. For example, the development of optically pumped magnetometers offer an order-of-magnitude improvement in sensitivity over the commonly utilized proton precession magnetometer developed in the middle 1950s. Electronic navigation to meet national map accuracy standards complements these improved magnetometers. Aircraft and ships appear to be available to address the scientific needs outlined in this appendix, except for a long-range aircraft to traverse remote oceanic areas. With the availability of platforms and with the many advances in airborne/shipborne acquisition systems, accurate magnetic data can be routinely collected for a wide range of applications, from the detection of hydrocarbon seepage at a scale of 1:5,000 to fundamental structures related to the formation and evolution of continents at a scale of 1:5,000,000.

Data Acquisition

Ships of Opportunity

The problem of major data gaps or poor data resolution should be addressed by capitalizing on ships of opportunity operated by NOAA, University-National Oceanographic Laboratory System (UNOLS), USGS, NSF, or private industry. The (federal) NOAA fleet is encouraged to routinely acquire gravity and magnetic data. The utilization of willing vessels of opportunity within the merchant and geophysical industries fleet would also help fill gaps. While systematic surveys provide more specific information for analysis, single tracklines available from various vessels over time can provide valuable information. In addition, geographic areas of mutual interest among private industry, government, and academia should be identified and agreements negotiated (1) to share mobilization and demobilization costs; (2) to share data acquisition and processing costs; and (3) to foster a greater synergism through the open exchange of nonproprietary Earth sciences information. Achievement of these objectives will require the identification of key resource people in the respective organizations.

National Airborne Survey

The existing digital magnetic data set of the United States and its continental shelves cannot adequately address many scientific and societal problems. Effects due to datum shifts and nonuniform observation levels result in errors that severely limit the usefulness of the present national data set. Detailed analysis suggests that these data are adequate for a narrow range of anomaly wavelengths (40 to 500 km). Because exploitable mineral and ground water resources occur at depths from 1 meter to a few thousand meters, their delineation requires magnetic anomaly information at wavelengths considerably less than 40 km. Anomaly wavelengths greater than 500 km are important to any regional geological study and to verify and complement satellite field interpretations. Clearly, it is

time for a national commitment to a new magnetic data set of higher quality at all wavelengths.

The compilation of such a magnetic data set requires both the reprocessing of old data and the collection of new data. In limited areas (about one-third of the United States) data were collected with survey specifications appropriate for the geological setting and with calibrations established with long-distance flight-line data. However, two-thirds of the United States contains data collected at an inappropriate survey spacing or altitude.

Canada, Finland, Russia, Zimbabwe, Liberia, and Australia are among the countries that have established cost-effective national airborne geophysics programs. For example, Canada has collected more than 9 million line kilometers of magnetic data at a spacing of 0.8 km, has published more than 9,500 aeromagnetic anomaly maps, and has distributed 30,000 aeromagnetic anomaly maps per year (the most requested item of the Geological Survey of Canada). The Canadian aeromagnetic program has been a very successful endeavor that has led directly or indirectly to the discovery of many ore deposits. The overall cost of the aeromagnetic program has been recovered, many times over, by the general economic benefits to the country that result from such discoveries and from taxes that are subsequently paid to the provincial and federal governments.

In Finland, magnetic and electromagnetic data have been collected at a flight-line spacing of 0.4 km for the entire country. Because the resulting data set proved to be a valuable national resource, the airborne geophysics program was expanded to refly the country at a flight-line spacing of 0.2 km. A highly successful high-resolution aeromagnetic survey program of the State of Minnesota was recently completed using a line spacing of 0.4 km over most of the state. In comparison, the average flight-line spacing in the United States is about 4 km, which is inadequate for most geophysical analyses.

The U.S. national data base clearly needs to be upgraded to modern international standards. The operational platforms and technology exist to carry out this task. Steps should be taken:

- to provide a plan and budget to merge existing data using advanced techniques in the compilation of the second-generation magnetic anomaly map of the United States;
- to assess the quality of existing data over the United States extending to a few hundred kilometers offshore; and
- to provide a cost-benefit study for the replacement of all substandard existing data with new data.

High-Altitude Airborne Survey

Using a suitable aircraft (for example, a B-57), it should be possible to cover the continental United States at an altitude of about 20 km and comparable line spacing in a cost-effective way. Data thus acquired would bridge the gap between low-level and satellite data, define regional magnetic fields, and provide coverage of the continental shelf extending out to a few hundred kilometers offshore. Vector data should also be available for main field modeling. If successful, the project could be expanded to other parts of the world. The survey could be expected to have important interfaces with various geomagnetic disciplines.

An appropriate task group should define detailed requirements and specifications for this program. This task group should define survey specifications, select an appropriate platform, and decide what type of instrumentation should be used. In performing its task, the group should consider costs involved against scientific gains to both the lithospheric and main field scientific communities.

High-Latitude Airborne Surveys

High-latitude aeromagnetic surveys, associated with other airborne surveys, are a central element of the geomagnetic initiative. The Arctic, southern oceans, and Antarctica have special needs. Remote offshore areas such as the Bering Straits and Chukchi Sea should be surveyed by long-range aircraft.

Long-range aircraft, such as the U.S. P3 or Russian Ilyushin 18, are needed to fly low-level surveys in Antarctica over adjacent oceanic crust

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and the ocean continent boundary. Line spacing will generally be wider than ordinarily acceptable for continental surveys. Short-range, ski-equipped aircraft are necessary to fly closely spaced lines and are needed over ice-covered continental areas of Antarctica. Planes currently being used are Twin Otters (in the United States and United Kingdom) or Dornier 228s (Germany) with fuel delivered to the field camps by LC130s (a ski-equipped C130). Aeromagnetic surveys should be conducted in combination with radar ice sounding (2-to-3-km penetration) and airborne gravity as is presently being done by the CASERTZ (Corridor Aerogeophysics South East Ross Transect Zone) program.

Rock Properties

Rock magnetic studies are commonly conducted independently of the required mineralogical, geochemical, and petrological background for linking magnetic property data to interpretation of magnetic anomalies. No single investigator has—or is likely to acquire—the broad expertise and wide range of analytical and experimental facilities that are necessary to produce all the measurements necessary to construct detailed models of lithospheric magnetization. For the study of the geology and geophysics of rock magnetism relevant to lithospheric magnetic anomalies, existing laboratories need realistic support, which includes technical personnel.

New facilities are also required, and, in particular, instruments are needed to measure magnetic properties at elevated pressures and temperatures. Ready access is needed to instruments capable of imaging and analyzing magnetic minerals and associated silicates at micron and submicron scales, including conventional optical and electron instruments as well as such new developments as atomic force microscopes. Furthermore, it is essential that critical magnetic property data measured on given samples be complemented by analyses of other physical and chemical properties of the same samples. These studies may include, but are not limited to, mineralogy, mineral chemistry, geothermobarometry, geochemistry of major and trace elements, radiochronology, elastic parameters, thermal and electrical conductivities, and densities. These

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supporting data would enable the magnetic properties to be placed in a lithospheric context and meaningfully related to magnetic anomalies.

Minimal Survey Requirements

Regional Low-Level Airborne Surveys

Surveys should be flown with high-sensitivity magnetometers and state-of-the-art survey aircraft compensation. Compensation figure of merit of the survey aircraft should be less than 3 nanoteslas. The diurnal variation should be removed using a combination of control lines and base station magnetometers. Over areas where magnetic rocks are close to the surface, a basic flight-line spacing of 1 km or less should be utilized with the control/traverse line ratio being about 1:10. The surveys should be carried out by qualified parties specializing in the aeromagnetic survey technique who would adhere to a set of survey specifications. The survey should be monitored at both the field survey and compilation stages. Draped, gradient, and vector surveys may require more stringent standards. It may be appropriate to include other geophysical sensors (such as very-low-frequency electromagnetic sensors) that would provide additional geophysical information at little additional cost.

Ship Surveys

The optimum marine survey specification should be to acquire data along regularly spaced lines. However, it is recognized that survey standards will often be governed by the primary mission of the vessel and sponsoring organization. In the case of NOAA vessels, line spacing and sample density are usually governed by the requirements to acquire high-quality multibeam sonar soundings. Ideally the direction of survey lines should be based on the orientation of geological structure and, most importantly at low latitudes, by the orientation of the magnetic field. Gradiometer data should be routinely collected to avoid problems with diurnal corrections and external fields at high and low latitudes. For

consistent compilation, it is necessary to reduce the gradiometer data using standardized methods. Because there is a wide range of international groups acquiring data, this could become a major difficulty.

The routine collection of marine magnetic data has not evolved to provide information compatible with the resolution of swath bathymetry systems. As such, information on oceanic crustal structure and processes is lost by the inability to exploit the detailed information contained in the bathymetry in conjunction with analysis of the magnetic anomaly data. Although deep-tow magnetometer technology exists, such systems are expensive and must be towed slowly. A desirable compromise is the development of a mid-depth-tow magnetometer that can be towed at 7 to 10 knots yet provide higher-resolution measurements. Deep-tow measurements are still very useful for studying the ridge axis.

Positioning

For all surveys, positioning systems such as the GPS or the USSR Global Navigation Satellite System (GLONASS), should provide point position (three dimensional for land surveys) to the national map accuracy standard. All map/chart products, whether over land or ocean, should be in compliance with the National Map Accuracy Standards and should be referenced to a recognized geodetic system.

Technology Development

Airborne System Improvements

To achieve accuracies of better than 1 nanotesla in high-resolution aeromagnetic surveys, several issues should be addressed. Aircraft magnetic compensation methods need improvement to fully utilize new high-sensitivity magnetometers. Considerable care is also required in the removal of temporal variations, including secondary fields due to currents induced in the Earth (for example, along coastlines). A viable approach to remove temporal variations may be the deployment of several vector

magnetometer base stations to define the transfer tensor. A study is required to determine the optimum spacing and number of such magnetometers. Precise vertical position control using some combination of barometric, radar, and/or laser altimeters together with satellite navigation is vital.

Magnetometers

The main direction to be encouraged is the development of vector, gradiometer, and vector gradiometer systems, because more interpretational techniques can be applied to the resultant data. For instance, vector or gradiometer systems make possible the immediate recognition of three-dimensional anomalies from a single profile. Algorithms have already been developed to exploit these additional data to interpret the presence of three-dimensional structure from profile data. Further, gradient data can be used to improve interpolation from flight lines onto a regular grid and to relax survey specifications and reduce costs.

Combinations of vector and gradient data have not yet been explored from either an instrumentation or a computational point of view. Given that both have individually shown substantial advantages, the use of the combination should be explored as a long-range development.

Satellite Platforms

Scientific Framework

The need for spacecraft measurements has been defined in the previous sections. In an effort to support these data requirements that pertain to diverse scientific interests and applications (civilian, industrial, and military), the series of present, impending, and planned missions and missions of opportunity has been considered. The specific scientific disciplines relate to the following:

- the magnetosphere, ionosphere, and atmosphere;

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- lithospheric magnetic fields;
- electromagnetic studies of the solid Earth and oceans; and
- main field and core processes.

In addition, there has surfaced a widespread concern for the quality of collected data of any form that are directly affected by the instantaneous condition of the magnetosphere. Pragmatic concerns with regard to communications systems, power grid reliability, navigational ability, and satellite and general space survivability necessitate the continuous measurements of magnetic fields not only in the proximity of the Earth, but also—and perhaps even more importantly—throughout the magnetosphere and in the solar wind. The central theme is the monitoring—and ultimately prediction—of the magnetospheric condition through the modeling and understanding of dynamic processes.

Figure B1-1a is a DE-1 auroral image registering a major magnetic storm on 13 March 1989 (Allen, J., H. Sauer, L. Frank, and P. Reiff, *Effects of the March 1989 solar activity*, *EOS, Trans. AGU*, 70:1479, 1989). Superimposed are magnetic field disturbance data from the field-aligned current system that accompanies such events. These storms are not atypical, especially during the downside of solar maximum. The auroral oval during nonstorm times is commonly around 70° to 75° magnetic latitude (MLAT). Typical magnetic storms can expand the oval to 50° to 60° MLAT; this has been observed consistently in the Upper Atmosphere Research Satellite (UARS) magnetic field data. One example on October 28, 1991, showed field-aligned current disturbances at 45° MLAT (35° geographic latitude!).

It is not just the location of these effects that is significant but the size of the polar cap (the area of open magnetic field lines within the oval), which reflects the increased magnitude of energy stored in the magnetosphere, most of which is dissipated in the ionosphere. This very stressed configuration of the magnetosphere is contained by the entire current system, and the ionospheric auroral oval region can be considered as the focus of that system. The storm processes release this energy and depend not only on solar wind factors (pressure and IMF originating from flare regions as well as other solar and interplanetary processes) but also

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on the inertia, inductance, stored energy, and general internal magnetospheric processes and structure.

Figure B1-1b is an artist's conception of the field-aligned current (FAC) system: The DE-1/HILAT image establishes the correlation between the auroral luminosity and location and the FAC intensity and location. This artist's FAC figure goes further: it sketches the three-dimensional configuration of the FAC system and also shows the correlation of the FACs and the horizontal ionospheric electrojet Hall current. The statistical pattern of low-altitude field-aligned currents is the "focus" of the entire magnetospheric system and its dynamics.

The accompanying ionospheric currents (electrojet Hall currents) increase comparably in amplitude and move in concert with the field-aligned current and the aurora. The two large-scale Hall electrojet currents flow generally in the longitudinal direction over 6 to 10 hours of local time and their dynamic motion, for example in latitude, has the largest inductive effect on the Earth's surface (including conducting artifacts such as transmission lines and pipelines). This Hall current is generally perpendicular to the ionospheric electric field and, and except for motion, time variations, and the end points, is not dissipative. The horizontal ionospheric Pedersen currents that connect the FACs are parallel to the local electric field and are the primary dissipation currents that heat and create the ionosphere in darkness; this energy input is generally larger (up to a factor of 10 for intense storms) than the particle precipitation energy input. The tens of millions of amperes of horizontal ionospheric currents from this March 13, 1989, event overloaded the entire power grid of Quebec and a partial section of Scandinavia's grid, disrupting power for more than 9 hours; similar events disrupt general communication, particularly via satellite.

Specific Scientific and Societal Issues

The following section presents a discussion of the role of satellite platforms in addressing specific scientific issues itemized in the working group reports in this appendix.

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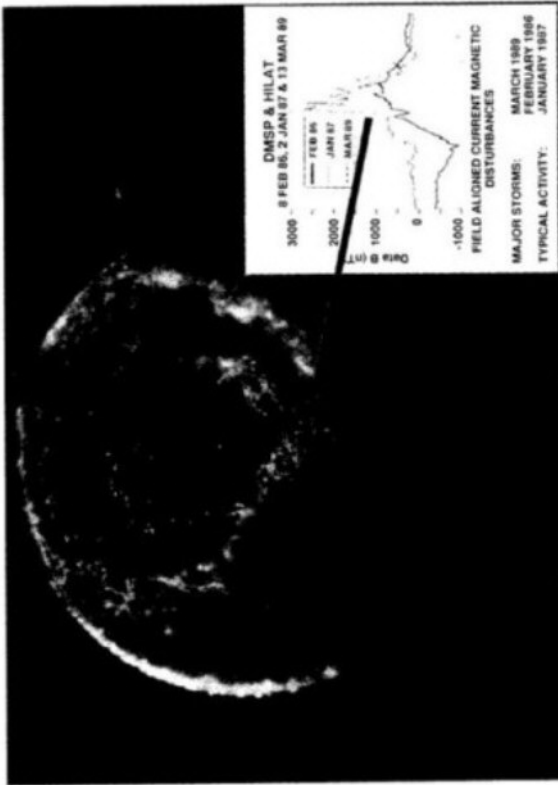


Figure B1-1a

DE-1 auroral image showing a major magnetic storm on 13 March 1989 (from allen et al., 1989; reference given in text). The inset shows magnetic field disturbance data (collected by the HILAT satellite) from the field-aligned current system that accompanies such events.



Figure B1-1b
Artist's conception of the field-aligned current (FAC) system (courtesy L. Zanetti).

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Scientific Issue A1: Magnetosphere, Ionosphere, and Atmosphere

The solar wind couples to the Earth's magnetic field through the processes of magnetic reconnection and viscous interaction. Energy mass and momentum extracted from the solar wind through these processes generates a global convection system that transports magnetic field and particles from the dayside to create a large cometlike tail on the nightside. This convection system, however, is unstable. After merging on the front side, newly opened field lines are transported by the solar wind to the nightside, and temporarily stored in the tail. About an hour later they reconnect forming closed field lines. This process allows the tail-like field lines to collapse earthward accelerating particles into the inner magnetosphere where either they precipitate into the atmosphere causing aurora or they are injected into the Van Allen radiation belts enhancing the ring current. This sequence of events—corresponding to a complete circuit through this global convection system—is called a *magnetospheric substorm*. A *magnetic storm* is produced when a number of substorms occur in rapid succession, building up an intense ring current.

Separation of charges in the moving magnetospheric plasma creates electric fields that are projected onto the ionosphere along highly conducting field lines. These fields drive electrical currents in the ionosphere which—in regions of electric field in conductivity gradients—couple to the magnetosphere through field-aligned currents. Almost all magnetic activity is caused by variations in the intensity of these magnetospheric field-aligned and ionospheric currents.

To explain how these electrical currents affect the Earth's outer magnetic field a quantitative description of the processes that produced them must be obtained. This is accomplished by simultaneously measuring the magnetic fields and particles in the various regions. Upstream monitors in the solar wind provide a description of the solar wind input to the magnetosphere. Magnetometers at geosynchronous orbit detect the changes in locations of the boundary of the magnetosphere, the ring current, and the tail current. Magnetometers on polar-orbiting spacecraft obtain snapshots of the location and strength of the field-aligned currents connecting the magnetosphere to the ionosphere.

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Networks of ground stations make it possible to provide synoptic maps of the ionosphere currents that connect to the field-aligned currents.

Models of solar wind coupling, substorms, and storms are based on data from this broad collection of spacecraft and ground observatories. These models can be used in magnetospheric research to help operational platforms mitigate the adverse effects of space weather or to subtract magnetospheric "noise" from data used in studies of the solid Earth.

Scientific Issue A2: Lithospheric Fields

The first crustal magnetic anomaly maps from Magsat revealed previously unknown, long-wavelength anomalies (400 to 4,000 km). It is not known whether the source region of these anomalies extends below the lower crust to the mantle. The lack of Magsat anomaly resolution has hindered the interpretation of these features. Data from ARISTOTELES improves the crustal anomaly field resolution because the satellite will, at times, be in a low (250 km) circular orbit. In addition, gravity data will be recorded simultaneously. The gravity data will aid in the magnetic interpretation by constraining the density of the source rock. One of the working group recommendations is to promote new satellite magnetic missions with orbits as low as possible in order to define source regions in the lithosphere more precisely.

Derivation of a reliable magnetic anomaly map is the most important tasks. Nonlithospheric "noise" in the map—if unrecognized—may be attributed to magnetization of the lithosphere and may lead to incorrect conclusions regarding the magnetic properties of the lithosphere. Therefore, it is essential to evaluate the noise level at each data-processing stage. A regional magnetic anomaly is usually derived through the following processes:

- **Measurements.** Aside from possible instrument drift and errors, the uncertainty of the location of measurement, especially in the sea, could introduce significant errors to the data.
- **External field component.** The magnetic data are usually collected during the external field quiet periods, but this is not

always possible, especially in the polar regions where the quasi-steady external field is significantly disturbed even during very quiet periods.

- **IGRF removal.** The IGRF models used to remove the core field component may not be accurate on a regional scale, though more recent models derived from Magsat data are probably reliable.
- **Gridding.** This is a nontrivial task, since the sample density along tracks is usually much higher than the track separation.
- **Patching neighboring surveys.** The regional magnetic anomaly maps are derived by patching many survey data.

Continental-scale magnetic anomaly maps have been derived by stitching together smaller-scale surveys recorded over a wide time interval. While important, these composite maps have suffered from an insufficiently determined zero field reference level. ARISTOTELES data, being measured at a constant altitude, would provide a refined core-field reference surface to which those composite data could be related.

Scientific Issue A3: Electromagnetic Induction

The electrical conductivity of the crust and upper mantle is probed by the response of these layers to low-frequency electromagnetic waves, magnetic impulses, and electrical currents in the magnetosphere and ionosphere. The magnetic signatures observed with arrays of magnetometers on the Earth's surface are a summation of signals generated in the ionosphere and magnetosphere and of the induced signals generated in the conducting layers below the Earth's surface.

In order to separate the source signal from the induced signal unambiguously, the source signal must be specified. By increasing the accuracy of the source signal specification, the accuracy of the induced signal will be increased. While models of the ionospheric currents such as the solar quiet and auroral electrojet currents may be useful, the best approach is to specify the source signal based on data from satellites that are in or near the source currents. This requires continuous monitoring of the magnetic field. For complete monitoring of the sources, there must

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be a geosynchronous satellite on the dayside and another one on the nightside. In addition, a low-Earth orbit satellite at high latitudes and another at low latitudes are required. These satellites need to be in operation continuously—both to measure the very low frequency waves and magnetic currents in the source region and to be available at all times that electrical induction measurements might be made.

Scientific Issue A4: Main Field and Core Processes

The Earth's geomagnetic main field, which is produced by dynamo action in the Earth's core, varies slowly (but erratically) with time in such a manner that is predictable for only very short time intervals (on the order of 5 years or less). Based on fundamental physics, dynamo theories to date are inadequate to make any meaningful predictions. Yet nearly all geomagnetic disciplines depend on the ability to accurately isolate the main field from magnetic field observations in order to properly study the spatial and temporal residual or anomalous magnetic field as well as the core itself. Therefore, phenomenological models of the Earth's main magnetic field and its secular variation must be relied upon for this purpose. As input, this requires data from satellites that continuously monitor the Earth's magnetic field on a global scale, in the altitude range of 300 km to 1,000 km. ARISTOTELES in the near term and DMSP/POGS and the NOAA polar satellites upgraded to Magsat quality in the long term will provide the necessary observational platforms for main field and secular field analyses. Other lower-altitude satellites between 150-km to 300-km altitude are needed to resolve the intermediate-wavelength crustal anomalies.

Magnetic Field Satellite Requirements

To address the scientific and societal issues described above, five types of measurements are required.

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Continuous Measurement of the Geomagnetic Field (Magsat-Quality Instrumentation)

The geomagnetic field should be measured continuously with sufficient sensitivity, attitude knowledge of the vector components, and knowledge of the noise to record the field and its secular change over two solar cycles (22 years). This can be accomplished by adding instruments to, or modifying instruments on, existing satellite series such as DMSP, POGS, or the NOAA polar weather satellites. Continuous time series would not only record secular variations but, in addition, the elusive short-term (1-year) main field changes or "jerks."

Low-Altitude Surveys

There have been numerous attempts to study the lithospheric magnetic anomaly field with Magsat data (about 500 km altitude). The wavelength of these anomalies (up to a few thousand kilometers) and their amplitude (from a few nanoteslas to a few tens of nanoteslas) make them difficult to identify with precision in Magsat data. Their amplitude will be increased by several times (depending upon their wavelength) if measurements are taken at an altitude of only 200 km. These anomalies are largely static in nature, so a global survey with a single satellite (with fine spatial resolution), rather than a survey with multiple spacecraft, is required. Multiple spacecraft, however, would assist in a better understanding of the external field transients that would benefit magnetospheric workers, and, indirectly, solid-Earth workers.

Sun-Earth Lagrangian Point Measurements

The magnetospheric research community, including civilian and military agencies, has a need for real-time data specifying the state of incoming solar wind and the state of the interplanetary magnetic field. This information is used in short-term forecasts of the ionosphere and magnetosphere. This need is satisfied by a magnetic field spacecraft at the Sun-Earth first Lagrangian point. The Russian program had included the

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Regatta spacecraft, stabilized by solar sails, to fulfill this need, but construction was stopped due to financial difficulties.

Geosynchronous Measurements

The geosynchronous orbit is well populated with communication, weather, and surveillance spacecraft which occupy fixed locations in the geomagnetic field. If properly equipped with magnetometers, these spacecraft would provide unique opportunities to monitor the effects of the major current systems that create the outer portions of the Earth's magnetic field and sources of hydromagnetic waves propagating through the magnetosphere. It is necessary that there be at least three spacecraft spaced equally in local time. There are presently two NOAA/GOES spacecraft that provide two of the three vehicles needed. Appropriate processing of these data provides important proxies for solar wind conditions when not directly observed by an upstream monitor.

For maximum effectiveness, the Lagrangian and geosynchronous monitors require real-time data archiving and distribution.

"Imaging" the Three-dimensional Ionospheric Current Systems

Spacecraft in low-Earth, polar orbits will pass through the major field-aligned current systems between the magnetosphere and ionosphere within about 15 minutes per hemisphere. These ionospheric-magnetospheric current systems are of keen interest to investigators studying the geospace environment but are "noise" to those trying to measure the Earth's main field and the contribution from static magnetization in the lithosphere. These current systems change rapidly in three dimensions and are found, with different characteristics, at all latitudes. Three or more spacecraft equipped with magnetometers, located at different local time orbits, would show the first-order features of these currents as the solar wind fluctuates. This in turn would help in understanding these complex processes and would provide valuable input to models specifying the state of the magnetosphere and ionosphere (see [Figure B1-1](#)). NOAA and DOD have a series of environmental monitor

ing spacecraft in low-Earth polar orbits. If appropriate magnetometers were placed on these platforms, they would cost-effectively satisfy this operational need.

Present, Planned, and Suggested Magnetic Field Satellite Missions

The operating and planned satellites relevant to this report are reviewed below. Readers should be aware that the status of operating and planned satellites may have changed appreciably between the time of the workshop and publication of this report.

Presently Operating

POGS Series. Polar Orbiting Geomagnetic Satellite, launched by the U.S. Navy in April 1990, (polar orbit 89.98° inclination, 730 km altitude) is providing scalar data that will be distributed to the scientific community through the NOAA/National Geophysical Data Center (NGDC) World Data Center. The field magnitude is accurate to about 10 nanoteslas. Its lifetime is expected to be 3 years; follow-on missions are planned. The purpose of the mission is to provide scalar data for the 1995 epoch DOD world magnetic model of the main field and its secular variation.

UARS. Upper Atmosphere Research Satellite launched by NASA in September 1991 (57° inclination, 600 km altitude). The magnetometer is part of the Particle Environment Monitor that monitors energy input, particles, and current. It was designed with 2 nanotesla resolution and tens of nanoteslas absolute accuracy per axis. UARS is a very stable platform facilitating baseline removal and allowing the remote measurement of ionospheric currents.

NOAA/GOES Series. These spacecraft have operated continuously from 1974 to present; all carry magnetometers. IMP-J, launched in 1972, still provides solar wind and outer magnetosphere measurements and monitors, in elliptical orbits at 35 Re (Earth radii).

Planned Satellites

The following satellite missions are in various planning and funding stages, with various possibilities of being realized.

ISTP. At the time this report was written, the NASA International Solar Terrestrial Program spacecraft were scheduled as followed: Geotail, launch July 1992, equatorial, 100 Re; Polar, launch scheduled for 1993, polar, 4 Re; Wind, launch also scheduled for 1993, first Lagrangian point (L-1 point).

DMSP/POGS. NASA, the Air Force Geophysical Laboratory, and the U.S. Naval Oceanographic Office have been studying the possibility of placing high-resolution magnetometers on the U.S. Air Force's Defense Meteorological Satellite Program satellites. Two of these satellites are always kept in orbit for meteorological observations and, if precision magnetometers for intercalibration were part of the routine instrumentation package, long-term magnetic field measurements would be assured. A magnetometer now carried within the body of the satellite for orientation purposes shows as much as 8,000 nanoteslas of spacecraft-generated noise. Future satellites of this series are identified by "Blocks" with the following characteristics:

- Block 5: Six satellites in the 1994-2005 time period, vector magnetometer with some attitude information, 5-m boom.
- Block 6: Satellites in the 2005-2015 time period, full vector plus scalar capability, 8-m boom, attitude transfer to 1 arc minute, with upgrade to 10 arc seconds possible.

FREJA. A Swedish auroral scientific satellite with fields, plasma, waves, and imaging data. The platform spins at 10 rpm; it has an orbit with $600 \times 1,700$ -km altitude, a 63° inclination, a 2-year lifetime, and a planned October 1992 launch. The magnetic field experiment is boom-mounted and computer-based with 2 nanotesla resolution, attitude to a fraction of a degree, and high sampling rate with band-passed channels for wave measurements. The microprocessor, among other duties, will process the data with fast Fourier transform algorithms, detect storm

events, and store full orbit and burst data in local memory. The goal is tens of nanotesla absolute accuracy in the vector measurements.

Tethers. NASA and the Italian Space Agency plan to start deploying magnetometers on long tethers from the Space Shuttle and from Delta rockets. Most of these instruments will gather data for a few hours or days but, for one Delta experiment in 1994, a tethered magnetometer will be deployed 46 km upward from an altitude of 200 km, then the tether will be cut and the instrument package will assume an orbit at about 500 km altitude. There are expected to be four tethered deployments in the next 2 years.

ARISTOTELES. This NASA/European Space Agency (ESA) spacecraft will carry a French gravity gradiometer as well as scalar and vector magnetometers. It will be launched into an orbit initially at 780 km altitude. After 2 months it will descend to near 200 km and stay there for 6 months. It will then rise to an altitude of 700 km, where it is planned to stay for 3 years. The earliest launch date is 1997, but a 1998 launch date is more likely. The scientific community has expressed the need for a pre-1999 launch to avoid the next solar maximum during 2000 to 2003.

MFE/Magnolia. This was to have been a joint NASA/CNES mission using two sets of fluxgates and total field instruments, launched from a French Ariane rocket. Recently NASA decided to give ARISTOTELES a priority ahead of MFE/Magnolia.

NOAA/TIROS. NOAA operates polar TIROS weather satellites that might provide high-altitude (800 km) platforms for magnetic field measurements.

Oersted. Oersted is a satellite mapping mission proposed by representatives of various agencies in Denmark. It would have a triaxial vector magnetometer and an Overhauser scalar magnetometer for absolute total field measurements. It would also have a high-energy particle detector array and star imagers for accurate attitude determination. It would operate at 600 to 800 km altitude. Several planning meetings have been held with international (including NASA) representation. Exact launch date and orbital configuration are uncertain.

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Other Suggested Missions

Multiple Magsat-Quality Mission. All fields of investigation would benefit from having several Magsat-quality magnetometers in orbit at one time. One approach to this would be to have a Magsat-quality magnetometer and its follow-on overlap by several months.

APAFO. The Advanced Particles and Fields Observatory was selected by NASA and ESA as a U.S./Earth Observing System (EOS) investigation to be flown on the second European Polar Platform. It was a boom-mounted package with vector and scalar magnetometers, collocated star trackers, and particle instruments. At this time APAFO is manifested by ESA but not funded by NASA.

PEGASUS. The Pegasus series of satellites consists of those that can be launched from a high flying B-52 aircraft. Such a procedure may allow low-cost launches of small geomagnetic field satellites in the future. Such a possibility is being considered by several groups in the United States.

Recommendations for Near-Term Missions

1. **ARISTOTELES.** The Magsat mission ended more than 10 years ago. There has been no subsequent solid-Earth (core, lithosphere, crustal) magnetic satellite mission. Therefore, the ESA/NASA ARISTOTELES mission is appropriate because, at various time intervals, this will be a low-altitude (200 km) circular-orbit satellite. Furthermore, the simultaneous acquisition of gravity data will allow synergistic potential field interpretations. The high-altitude second phase of the mission, in which the orbit will progress through all local times every 8 months, will provide valuable data on the main field, secular variation, and external fields. The projected lifetime of the high-altitude phase is 3 years.
2. **ISTP, Geosynchronous, L-1 monitors.** The NASA International Solar Terrestrial Program spacecraft are instrumented with

magnetometers and are scheduled for launch as follows: Geotail, July 1992; Polar, Wind, 1993. These will be located up to 250 of Re equatorial, 4 Re polar and L-1, respectively. The geosynchronous satellites must continue to be equipped with magnetometers, and the L-1 monitor efforts should go forward.

3. **U.S. Environmental Platforms; Encourage Interagency Cooperation.** The DMSP and NOAA Polar orbiting satellite systems provide ideal platforms for continuous measurements of the low-Earth magnetic fields. Interagency cooperation would ensure the optimal applications of these operational environmental satellites to provide routine monitoring of main field and secular-variation field, in addition to ionospheric fields, during both solar quiet and disturbed times. These satellite programs should be upgraded to yield magnetic data of Magsat-quality, or better.
4. **Support International Missions.** Encourage the continued U.S. support and participation in international missions that provide valuable opportunities to significantly enhance the amount of data available to support this initiative. Among the proposed experiments in the international community, Oersted, APAFO, and the European Polar Platform offer particularly exciting missions. Efforts should be undertaken to identify flight opportunities on operational platforms throughout the international community.

Recommendations for Long-Term Missions

1. **Multiple Magsat-Quality Missions to Accomplish Goals.** The most desirable and beneficial to all fields of investigators interested in the geomagnetic field and its disturbances would be multiple spacecraft on the order of Magsat. Different altitudes and multiple, simultaneous platforms would help both modeling efforts as well as the longevity of the overall mission.
2. **Significant Upgrade to DMSP/POGS and NOAA Polar.** On each satellite, Magsat-quality or better is desired for DMSP Block 6 and 7, and NOAA's next-generation polar satellites. It is

necessary to have both vector and scalar instruments on these satellites to intercalibrate. Attitude accuracy is necessary.

- 3. Magnetospheric Magnetic Field Missions.** The mapping of geomagnetic field lines from the Earth's surface to the outer regions of the magnetosphere is not adequate to accurately transfer magnetic disturbance vectors from the magnetosphere to the ionosphere. To solve this problem, a survey of the magnetic field between low-Earth orbit and magnetospheric altitudes is needed. These missions also provide the activity state of the magnetosphere as well as a measure of external fields.

Conclusions

The tradition of magnetic field measurements from the original scientific recordings in the 1600s by Sir William Gilbert has continuously improved and progressed. The progression from solely ground observatory data to combinations with satellite observations culminated in the NASA Magsat mission of 1979-1980, resulting in the extremely accurate IGRF-80 magnetic field model. With the termination of the Magsat mission, this progression is in an apparent hiatus. As a result, the following goals and recommendations are set forth, giving the measurement of core and crustal fields first priority. This is evidenced in the goals as well as in the support of the ARISTOTELES mission.

The list of missions given above has been prioritized in two separate ways that will successfully meet the scientific goals set forth by the proposed initiative. The first proposed mission has been limited to urgent needs, presently available missions, and missions of opportunity. The latter two reflect common interests in magnetic field measurements bridging the various scientific and pragmatic disciplines and concerns. Efforts must be made to avoid possible duplication among agency programs. A synergistic interagency effort is a clear approach, in particular with regard to the DOD and NOAA operational polar platforms.

Finally, the long-term recommendations represent the continuance of high-quality magnetic field measurements satisfying the needs of all of the disciplines involved and the maintenance of the tradition of these important data. All considerations for satellite monitoring of the main field thus far have centered on continuous monitoring with Magsat-quality data. That means vector data with 10 to 20 arc second, or better than 5-nanotesla accuracy, together with absolute scalar data with 1-to 2-nanotesla accuracy. The scalar data are used to calibrate the vector data in-flight. Such are the ideal measurements. In practice, however, there are two ways to compromise these measurements and still acquire very useful data. The first compromise is to monitor the field only at periodic intervals, say at 10-year intervals, rather than continuously. In order for such a compromise to provide data for a really adequate study of long-term core and mantle phenomena, expansion of the surface observatory network as described in a previous section is required.

A second compromise is to acquire less accurate, hence less expensive, data. The least expensive route is to acquire data only from a fluxgate magnetometer. In the case where little or no attitude information is acquired, the data will be analyzed as field magnitude data only. Such are the data from the currently active POGS spacecraft of the U.S. Navy. In the case where attitude information of a few arc minutes is available, the vector data are very useful in mapping fields from field-aligned currents and ionospheric currents, though not for main field modeling. Such are the data from the DE-2 spacecraft which operated from late 1991 through 1992, and such are the data planned for the DMSP Block 5 series. The major difficulty with such data is the lack of absolute measurement. While low-drift-rate fluxgate instruments are indeed available, all are subject to some drift. On a spacecraft, such instruments are subjected to extremes in vibration, radiation, and temperature changes; it is impossible to know what drifts, if any, have occurred. Nevertheless, the DE-2 data were successfully used in one of the better candidate models used in the most recent update of the IGRF. However, three of those who submitted candidate models chose not to use these data.

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Another compromise would be to fly only an absolute scalar magnetometer with no attitude determination. This is more expensive than flying only a fluxgate, because the instrument cost is greater. However, the measurements are not subject to drift and hence are better for main field modeling. A major shortcoming is that the measurements can make no contribution to the study of fields from field-aligned or ionospheric currents.

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B2.

Data Management Systems

New Directions and New Needs

Management of data in the future will be a greater challenge for what have been previously termed "data centers." New developments in technology and new demands by the scientific community, as expressed by the working group reports in this document, for improved services will tax the resources and ingenuity of these organizations. With the advent of distributed computing systems, data centers will not only be repositories of archived data physically residing in such centers, but even more importantly they will become the information and management vehicle that will enable scientists in all disciplines to locate the data they need more easily and efficiently. This is especially important for the needed interdisciplinary studies that will require a relational data base of such files. Such a data base will require a significantly increased level of coordination and cooperation among the centers.

The new demands for access will require modern and efficient approaches to accommodate the increasing volume and complexity of data acquired. With this new confederacy in information management, the centers cannot easily mandate standard formats, but they can help guide the many remote cells in use of data formats and access software independent of the platforms being used.

Appendix B2 was largely developed by the following workshop group: Joe Allen and Herbert Meyers (*Group Leaders*), R. Barnes, J. Cain, W. Campbell, S. Cande, V. Chandler, D. Chapin, R. Clauer, A. W. Green, D. Herzog, W. Hinze, J. Joselyn, J. Kappenman, J. MacQueen, L. Newitt, N. Peddie, J. Phillips, C. Russell, M. Teague, R. Walker.

Key Issues

Magnetism is a pervasive and fundamental area of science that cuts across the traditional boundaries of disciplines that often define and divide groups. Some scientists are concerned with the intense magnetic fields of sunspots and other solar features. Fortunately, these can be observed remotely from Earth, and there are fascinating data that suggest that the maximum magnetic fields of solar active regions have been systematically and monotonically increasing in intensity over at least the past three solar cycles. At the same time, the well-known decline in intensity of the internal dipole moment is reducing the volume and size of the magnetosphere that shields against (or organizes) the influx of energetic charged particles from the galaxy and from the Sun. The frequency and intensity of magnetic storms are also increasing with time. Are these changes interrelated? If so, what is the prospect for the future?

Some workers will be concerned with the heliospheric magnetic field that spreads in waving folds through interplanetary space and sweeps around with the rotating Sun. Others will be mainly interested in changes of magnetic fields sensed by geostationary satellites just inside the magnetopause or at lower altitudes by polar-orbiting spacecraft. Many will be concerned with magnetic field measurements in space at lower altitudes by more satellites so that spatial patterns of geomagnetic field variation may be identified as arising from currents in space, from near-surface sources, or deep in the Earth's interior. Some will be interested in the long-term global field and its slow, almost geological, time scales of change; others in the rapid, local variations or globally organized patterns of external currents that cause rapid change at one or a few sites or that produce significant changes over large regions of Earth.

Finally, there will be the spacecraft operators and electric power system operators or makers of sensitive microelectronics for whom large, rapid changes in the geomagnetic field are a potential source of disaster because of their effects on sensitive technology. All of these groups will have a common need for access to high-quality geomagnetic data collected with accurate instruments at key locations, processed to comparable

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standards over time and space, and reduced to products whose definitions and assumptions are well known and understood.

Data Bases

Of initial concern is the need to identify the sources of geomagnetic data. What data are collected, by which groups, and at what sites? Are data collected in the past adequate in type, quality, and coverage (spatial and temporal); adequately documented to support the conclusions already drawn from them; and adequately documented for them to be combined with newer data to support present and future research? Those same questions can be asked of geomagnetic data being collected today, and for data that will be taken in the future either by temporary, limited campaigns or by worldwide monitoring arrays. Also, as technology changes and costs of maintaining old methods of data collection rise beyond the ability of sponsoring groups to continue supporting them, how can priorities be set for what should be continued and what terminated?

Data Archives

The transition in philosophy of data center function—from management of all data at data centers to distribution of many of the data—brings forward many issues. Well-organized and funded projects that make data available need only keep the centers informed of their directories. Moreover, as such projects mature, and especially after the data collection period is completed, the centers must take a more active role. In the implementation of a project, documentation of data is frequently neglected. Moreover, as a project matures and participants leave, it often happens that this neglect of documentation is never corrected. How can data centers maintain an active role throughout such a project, keep abreast of the activities that generate data, coordinate documentation, and arrange transfer to an archive? How can centers be made aware that some

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data may be at risk of loss to future research and be encouraged to take a hand in their preservation?

Not all data collection efforts are well integrated and organized, especially of internationally produced data. In such instances, the centers need to maintain their traditional role of negotiating standardization of formats and assisting, as possible, to achieve adequate archiving capability of the data produced. Such efforts relate both to primary observations (such as geomagnetic data collected from fixed stations) and to indices derived from such observations. With limited resources, a balance of effort is needed between centralized and distributed components.

Data Access

Data access concepts are of special concern because many data sets exist that cannot be reached by all who need to use them. Limited accessibility for a particular data base may not be a result of a deliberately implemented policy decision, but may result from the fact that plans for collecting the data did not include data processing and availability as important goals. Limited accessibility may be a consequence of the physical characteristics of the media containing the data (for example, analog magnetograms on paper or strip charts held as rolls stored in a closet). Film media (35mm microfilm or microfiche) for many years were a convenient way to capture vast amounts of geomagnetic data and preserve them compactly at an archive so that they could be retrieved and inexpensively copied upon request. However, the requirement for digital data for computer analysis that characterizes research today relegates film records to a secondary role.

Once geomagnetic data are in digital form, how are they to be stored and transferred from one site to another? Are tapes with inherent serial access problems still a viable answer? Has the 8-mm helical scan videotape cassette with its vast capacity become the new medium of choice? What are the relative merits and problems with optical media? What will technology provide next (for example, digital audio tape, optical tape)? How long-lived are the various choices, how universal are

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the recording and playback devices, and how robust but inexpensive are the media? These are key questions. Also, how many users today prefer on-line data bases for real-time or retrospective access, and what type of analysis does on-line access support? How can images and data plots be made accessible on-line together with digital data? The ubiquitous personal computer has revolutionized the collection, processing, exchange, and analysis over the past decade. Now, globally interconnected workstations are clearly the wave of the next decade. As data are made more accessible through the net or on various media, access, display, and manipulation software are essential for efficient utilization. This places a premium on having platform-independent data systems.

Data Products

Much of the driving force that justifies national and international support for programs to collect geomagnetic data comes from a demand for derived data products such as maps, models, or magnetic activity indices. Some models and charts are primarily used for navigation while others describe the main field. External fields in the magnetosphere and ionosphere are interesting scientifically but must be removed to study or to chart the main field. Models of the crustal field and maps of magnetic anomalies have geological importance but can be contaminated by natural fluctuations of external fields. When the complication of secular change is added, it becomes challenging to create accurate models and charts with data that are less than ideal. In addition, changing user needs require higher time resolution and data from locations not previously monitored. Developments in technology have revolutionized the ability to collect and analyze data. Understanding of the physical processes that couple the solar wind and the geomagnetic field has progressed to the point that solar wind data are critical for driving magnetospheric models and making accurate forecasts of impending activity. These advances have created opportunities for significant improvements in data products.

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Components of Data Management

Data Bases

Data are the most fundamental and essential component of geophysical endeavors. However, transfer of data to a data base is frequently a low-priority concern of scientists once the data have served the intended purposes for a particular research project or objective. Often a research project will collect a large amount of data, use only a small portion of it for the intended purpose, and then disregard or dispose of the entire data set. Until recently, few research programs have taken the necessary steps to document their data sets by providing accounts of such factors as the type of data being collected, technical specifications of the instruments that were used, the temporal and spatial resolutions of the observations, or even how the data are being stored, and few research programs have seen to it that the data are archived at some publicly accessible archival center. Data base management is an often neglected aspect of many (if not most) research programs, despite the fact that data constitute the evidentiary pillar upon which science itself rests.

Furthermore, it seems clear that most scientists are aware of only a fraction of the data bases that have been, are being, or will be collected, even within the limited field of geomagnetism. This represents a loss in at least two ways: first, because data may already exist (or be on the way) that could serve the needs of other research objectives; and second, because the mere knowledge of an existing (or developing) data base can serve the serendipitous function of generating new research ideas and promote interdisciplinary cooperation between research groups. Because of the vast proliferation of data sets from land, air, sea, and satellite programs, it is not (currently) possible for anyone to keep track of all the data bases being accumulated in the diverse disciplines within geomagnetism.

Thus, two operational requirements for geomagnetic data bases are as follows:

1. to identify the sources of geomagnetic data from land, air, sea, and satellite that have been, are being, or will be collected from ongoing or temporary observational campaigns; and
2. to address the issues relating to the formatting, storing, documenting, and archiving of data bases.

The following few acronyms (spelled out in Appendix 3 of this volume) represent a small sample of the variety of projects that involve geomagnetic data bases.

EMSLAB	POGS	OEDIPUS-A	IEEY
SYNOP	GOES	AWAGS	STEP
SAMNET	MAGIC	INTERMAGNET	CANOPUS
ISTP/GGS	ULYSSES	CRRES	WIND

Although many of these acronyms are well known, it is unlikely that anyone is knowledgeable about all of these programs. It is even less likely they know the type of magnetic data being recorded, the spatial resolution, sampling rates, instrument sensitivity, status of the data, principal investigator, or how to obtain the data. In addition to temporary campaigns, there are many ongoing geomagnetic data bases that may be more familiar to the research community, such as the USGS magnetic observatory network, the NGDC worldwide digital data collection, and the magnetic models produced by the USGS, U.S. Naval Oceanographic Office (NAVOCEANO), NASA, and IZMIRAN (Russian Institute Terrestrial Magnetism).

Clearly, there is a need to identify, catalog, specify (document), and make known the many diverse projects and programs that involve geomagnetic data bases. Perhaps an organization such as the American Geophysical Union (AGU) could provide the forum wherein the (largely) informational requirement could be fulfilled. Researchers could provide the relevant details to AGU, which could, in turn, publish this information periodically in their transactions (*EOS*). It would be the responsibility of every research program to notify AGU of its activities related to

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geomagnetic (or other) data bases for the benefit and elucidation of everyone in the community.

It is not enough, however, that the scientific community be informed of existing and prospective data bases in geomagnetism. It is also imperative that these data be transferred to standardized formats, on stable media such as CD-ROMs or Magneto-Optical (MO) drives, and be made readily accessible to potential users.

There are almost as many formats for data bases as there are projects acquiring them. Often the choice of formats is arbitrary and determined by the existing data-processing software at the organization is gathering the data. This need not be the case, however, and uniform data formats could be established that would greatly facilitate the ready compatibility of data bases to everyone's data-processing capabilities. Formats could be developed for 1-second, 5-second, 10-second, 1-minute, 1-hour, and so on, temporal resolutions; the magnetic field values themselves could be stored in standardized formats for vector or scalar data, in variation (voltage) or field (magnetic) units, with a variety of degrees of resolution (1 nanotesla, 0.1 nanotesla, 0.05 nanotesla, and so on). Even much of the documentation of data bases could be included in the header portion of the data records, which would ensure that those unfamiliar with the data set would have the best opportunity to be well informed of the nature of the data and any issues relating to their quality. This is certainly not an easy matter to resolve, but the effort needs to be made to standardize the formats of geomagnetic data as much as possible in order to minimize the need for multiple data access software programs, minimize the potential for error in retrieving these data, and maximize the availability and ease of use.

In addition to formats, there is also a need to standardize data base storage media and take advantage of advancements in technology that offer small, high-volume, high-density, low-cost, and easy-to-use data storage devices that ensure the preservation of data bases for decades to come. As was recommended in the NAS/NRC report, *Geophysical Data: Policy Issues*, the scientific community itself should be aware of the problems and take steps to ensure the preservation and integrity of collected data. CD-ROMs and MOs have long lifetimes—too long to be

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accurately determined, but that apparently span decades or more. They are small, relatively insensitive to environmental influences, and can store massive quantities of easily accessible data. Each CD-ROM currently costs less than \$2 to produce and holds approximately 650 megabytes of data. There is an investment cost for the equipment and software to pre-master a CD-ROM for manufacture (mass production), so there would be a need for an organization to assume these responsibilities, particularly in cases where the data are obtained by groups that do not have or cannot afford the costs of such equipment. Because these devices are capable of holding such large volumes of data, criteria would have to be established to perhaps abstract several different data bases onto the same CD-ROM to maximize the use of space and minimize production cost.

Data Archives

It is not possible to revisit the past and reobserve the magnetic field as it was in a certain place years ago. Thus, the record of current and historical observations is critical to ongoing and future research efforts. If the data are not properly archived, research requiring a long history of observations could not be conducted without waiting for a new long history of observations to take place. Moreover, who knows whether features of the magnetic field, such as magnetic jerks and magnetic storms, will be the same during the next century as they were in this one?

The most important new scientific understandings of the nature of the Earth's core processes and their relationship to other phenomena need to have data available covering as early times as possible. Magnetic declination data from ship observations date back at least to the fifteenth century (it should be noted that these data were collected for completely practical, operational reasons, but today they serve as research tools). These need to be ferreted out and added to the geomagnetic archive. Potential contributions from direction and intensity data from archaeomagnetic studies, and paleomagnetic intensity and direction

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observations (lake sediment and lava flows) can be used to extend our knowledge of core processes.

Observations that are less time-dependent, such as aeromagnetic and shipborne survey data, become meaningful only when surveys conducted over many years by numerous institutions become available in an archive for syntheses, analyses, and research. Preparation and analysis of these survey data require access to accurate local, regional, and global magnetic field models, and to dynamic models that provide a reference for moment-to-moment change throughout the day.

The collection and processing of magnetic data represent an investment in resources that becomes more valuable as time passes. Data are an important national resource that with proper care, will contribute to the solutions of numerous scientific and human problems now and in future decades.

Identification of Data to Be Archived

Although it is technically possible to archive all data pertaining to geomagnetism, this may not be economically feasible or necessary. Data from observational systems exist in raw, processed, and interpreted forms. Additionally, the data may exist in several different resolutions. Collections of data at various organizations should be identified and evaluated. Not all data are available in machine-readable form. Major portions of the data need to be digitized, microfilmed, or scanned. Priorities need to be established and decisions need to be made.

Some archival problems and related issues include the following:

- Sensor data are often not available at the full observing resolution. The data that are available are often sampled, averaged, or summarized. For example, observatory data are often processed to obtain 1-minute values, although the digital data collected are usually at much higher time resolutions. Similar conditions exist for aeromagnetics, ship-towed magnetics, satellite observations, and other types of measurements. The higher-resolution observa

tions are generally not now available at national data centers and World Data Centers.

- There are many types of nonstandard measurements made for which there is no recognized archive.
- Many of the older data such as magnetograms and aeromagnetic and ship data are available as paper records. In many cases the data have been manually digitized at sample intervals much lower than present practices.
- Many paper records are deteriorating.

The types of geomagnetic data that need to be considered for archiving include those from repeat stations, satellites, paleomagnetism, archaeomagnetism, observatories, aeromagnetic data, ship-towed data, sea bottom instruments, land surveys, historical compass readings, anomalous compass reading reports, electromagnetic data, rock properties, and perhaps others. For a few of these there are active archiving activities, but for others there are only passive activities or no archive at all.

Identification of Archive Centers

The existence and the programs of the U.S. national data centers and the World Data Centers are fairly well known. They operate as archive centers for U.S. and international programs. Are there, or should there be, other archive centers? In the case of federal organizations, the U.S. General Accounting Office (GAO) and the National Archives and Records Administration (NARA) have specified certain requirements and responsibilities that an archive center must meet. These include provisions for backups, environmental controls, periodic sampling, periodic migration to more modern archival media, and implementation of new technology. There is a trend toward NASA and NSF support of discipline centers at universities where researchers will oversee the data processing and distribution. These are not archive centers, but they offer the opportunity to contribute to the process of making higher quality data available for the archives if their design includes eventual or periodic data transfer.

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Distributed Data Systems

The technology exists to allow a user to obtain data from a distributed system regardless of where the data are stored or the node of entry. Problems include the present difficulty of reliably transferring several gigabytes of data and concerns about long-term security. Recommendations and relationships need to be developed among the nodes, the long-term archive centers, and the funding agencies to assure viability and success of the national archive and data distribution systems. A balance needs to be established between the desire to have data under the control of those actively using the data and the need to protect against the risk that the data will "vanish" when interest and/or support for the data base goes away. Overall stewardship of the geomagnetic archive needs to reside at a single center even though there are many remote nodes performing many of the processing, distribution, and analysis functions.

The National Geophysical Data Center and its collocated World Data Center-A in Boulder, Colorado, are the archive centers for U.S. national geomagnetic data and for geomagnetic data relating to national and international programs, respectively. All data-collecting agencies, funding agencies, and research programs should coordinate with NGDC and WDC-A at the beginning stages of new data campaigns and research programs to assure that adequate provisions and resources will be available for data management activities.

Data Access

This section considers some of the technical issues involved with providing scientific access to magnetic field observations. For this discussion it is assumed that the data are available in digital form. Three major issues must be considered. First, the data must be of high quality. Second, they must be available in a timely fashion. Third, they must be properly archived. Technically, both the data quality issue and the timeliness issue can be addressed most readily through on-line distribution of data. In this approach, data would be placed on-line as soon as they are

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processed. Users can access the data over computer networks. The data need not be located at a central location. They can be stored at any location that is accessible by network. Systems for the distribution of on-line data and for distributed inventory tracking are becoming common. Network access is now worldwide, and the low data rate associated with magnetic field observations (whether from ground observatories or spacecraft) makes it practical to deliver magnetic data electronically. As problems with the on-line data are discovered, they can readily be corrected.

When data are held in a large collection—whether archive or working data base—they must be readily retrievable in order to be accessible. In practice, this means that desired data must be easily identified and called out of the larger mass. This raises to a high level of importance the ability of a system of data base storage and access to provide a user with a fast, simple means of browsing. This might be through a relational data base management system that provides means to search on data criteria, for example, by amplitude or orientation. It might also be through a simple visualization technique that allows a user to display an analog image of a selected length or array of the data. Browse and visualization techniques to provide effective access to the contents of a large data base are essential.

After the data have matured and a sufficient quantity has been accumulated, the data can be moved to permanent archival media. In cases involving many sources, an archival system with random access is desirable. At this writing (February 1992), the only archival random access media are optical media; of these only one (the CD-ROM) has both hardware and logical data standards in place. Logical standards concern naming conventions and directory structures. They make the CD-ROM vendor-independent. Because the volumes of magnetic data are relatively small, the limited capacity of the CD-ROM (650 MB) is not a major concern. A master of each CD-ROM must be generated. A CD-ROM master currently costs about \$800. The price per disk (copied from the master) is less than \$2. CD-ROM readers cost \$300 to \$500. Recently, write-once CDs have become available. On a CD-ROM, magnetic field

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observations can easily be distributed to the wide number of potential users.

Derived Products

Indices

Geomagnetic indices encode the level of short-term fluctuation in the magnetic field above the normal (quiet-day) diurnal variation on both local and global scales. Indices in common use include the K-index family, Dst, and AE. The K index has served the geophysics community well for 60 years, but a simple range index defined over 3-hour intervals is no longer computationally necessary or adequate. New descriptors that measure the amplitude and rate of change of magnetic fluctuations over a range of time scales are needed. Modern data collection platforms allow spectral analysis in near real time. Data sampled at 1-second resolution could be analyzed in place, and the power in specified frequency bands indexed and transmitted over satellite links.

The Dst and AE indices are based on separate networks of observatories and meet the need for global activity indices. However, because some of the stations do not deliver digital data, it takes years to construct the indices, which are presently issued at 1-minute to 1-hour resolutions. In addition, deficiencies in the spatial distribution of the observatories used to derive the Dst and AE indices have been identified. The first three recommendations are these: (1) a new family of indices based on magnetic power spectra at local observatories should be developed; (2) the suite of AE indices should be computed at 1-minute resolution from an improved spatial distribution of digital stations; and (3) Dst should be computed at 1-minute resolution from an improved distribution of digital stations with improved correction for quiet diurnal variations.

For operational use, indices should be available (as nearly as possible) in real time. Accurate forecasts are possible if solar wind data from the forward Lagrangian position (L-1) are used. In addition, solar wind parameters provide the boundary conditions necessary to drive

magnetospheric and ionospheric models. Accordingly, the solar wind plasma and magnetic field data from the L-1 position should be acquired continuously.

The variation observed by a single station in the polar cap can provide a measure of the efficiency of connection of the interplanetary field and geomagnetic fields and can serve as a warning of increasing activity. The polar cap index should be computed at 1-minute resolution.

Models and Charts

Many kinds of mathematical models, charts, and similar products are created from magnetic data. They can be discussed conveniently by considering three categories. The first category includes models and charts that describe the main field and those whose primary use is for navigation. Both kinds may be either national or global in coverage. The second category, models of externally caused fields, includes magnetospheric and ionospheric models. The third category includes models of the crustal field, maps of magnetic anomalies, and data sets consisting of grid values derived from anomaly maps. These three kinds of products and associated requirements are described below.

- **Main Field and Navigation (Global and National).** These products provide the vital information on the variation of the compass that is so essential for safe navigation of aircraft, ships, and boats. They also provide information on the strength of the main field needed by exploration geophysicists for enhancing magnetic survey measurements taken in the search for petroleum and minerals, and information on the change of declination often needed by land surveyors. Currently, NASA, NAVOCEANO, and USGS produce global geomagnetic models. These agencies, along with the British Geological Survey (BGS) and IZMIRAN, participated in the recent (1991) revision of the IGRF. World charts for 1990, based on NAVOCEANO and BGS models, and aimed at satisfying DOD requirements, have been issued by the Defense Mapping Agency (DMA). The USGS will issue world charts for 1990, based on the IGRF and aimed at satisfying the needs of science and commerce. The USGS

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has produced national models for the United States for 1990 and will issue associated charts of D and F. The USGS also provides a dial-in service for obtaining model field elements via terminal and modem.

The main challenge faced by workers in this field is how to create accurate models and charts with data that are often less than ideal. Other challenges include improving forecasts of secular variation; providing better access to models, model information, and associated software; and coping with reduced funding. Good models and charts require good data. Needed are frequent global surveys, like the Magsat satellite survey of 1979-1980, and a well-distributed network of magnetic observatories. Secular-variation forecasts, currently based on empirical analysis, would improve if a workable theory of main field generation were available. The increasing need for greater accessibility to models, model values, and associated software could be met by greater exploitation of modern technology, including network communications.

- **External Field Models.** Models of the externally caused part of the geomagnetic field are useful for correcting ground-based observations and for basic research on the magnetosphere. More accurate, dynamic representations of all of the components of the magnetosphere and ionosphere (including solar quiet, the auroral electrojet, and the field-aligned currents) are needed. These models should provide realistic values of the externally caused field at and near the surface of the Earth.
- **Crustal Models, Anomaly Maps, and Gridded Data.** These products are especially needed for interpreting the geology of the lithosphere. It is vital that the original data upon which these products are based, as well as the digital form of anomaly maps, be saved and made available. The perennial problem of mismatch between maps of neighboring areas must be solved by one or more of the following: regional-scale tie lines, low-altitude satellite surveys, and high-altitude aerial surveys, which would provide long-line data. Furthermore, visualization and interpretation techniques, and the associated software, must be developed and made available.

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Recommendations

- Archive centers must be located in federal organizations that have a long-term commitment to archiving and servicing geomagnetic data.
- Nodes for data processing, quality control, analysis, and distribution are necessary at institutions performing research. However, strong support to the national archive centers must be maintained to provide standard and custom user services and especially to capture and archive data that would otherwise be lost.
- Organizations providing data to a national data center (or node) must provide information on quality control and complete documentation of the data. These should appear as digital records accompanying the data, wherever possible. The nodes and national archive centers must perform quality control on the data in their systems.
- Magnetic maps need to be digitized for those cases where the trackline data are no longer available in a useable form.
- On-line directories and inventories need to be made available. These should describe not only the data held at national centers, but also those existing elsewhere. Such a system should describe the existence of digital data, paper records, maps, and special analyses.
- Survey data need to be provided as total field observations as well as residuals. All corrections applied to the data should be included as part of the data record or within the documentation.
- A rock-properties data base needs to be developed to support paleomagnetism and interpretation of magnetic surveys.
- A task group should be established to investigate the possibility of making some version of classified and proprietary data available for the research community. Reviews of the need for continued restrictions should be made periodically in order to move data into the public domain.
- Data at institutions should not be discarded without first contacting the appropriate national center. The national center, with the

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help of advisory groups, will evaluate the need to archive the data and will seek funds for data rescue.

- Data distributed by nodes or national data centers should include access software and be made available in work station formats.
- Funding agencies should support long-term visits of research scientists to national data centers to perform cooperative analysis of the data and to provide a strong link between the data centers and the research community. Representatives of data centers should periodically visit active research and data collection organizations to assure that the needs of these organizations are being met and to arrange for any special assistance that the data center could offer to support the research and flow of data.
- Institutions must develop an archive policy for those data that are not sent to a national archive center.

B3.

Interagency Communication and Coordination

Introduction

Many federal agencies are involved in the collection and analysis of magnetic data. The needs of these agencies vary greatly, from purely scientific to operational needs, and there is also much overlap among their needs. Thus, it seems obvious that there should be a great deal of communication between the various government agencies, first to define their needs and to discover the areas of overlap, and second to prepare and carry out joint data collection or analysis programs.

In some cases this communication has occurred and joint programs have been conducted. In other cases there has been little communication and the advantage of joint programs has not yet been realized by the relevant agencies. It is the objective of this report to describe the main missions of the government agencies in the field of geomagnetism. Various areas of possible communication and collaboration will be suggested.

National Aeronautics and Space Administration (NASA)

NASA has taken the primary initiative for satellite programs to measure the geomagnetic field. The most recent satellite to have done this was Magsat, 12 years ago. Despite considerable efforts during the intervening time, no subsequent geomagnetic satellite mission has been carried out. One current possibility is to collaborate with the European Space Agency (ESA) to launch ARISTOTELES by mid-1998.

Appendix B3 was largely developed by the workshop participants and was coordinated by Christopher Harrison (*Group Leader*).

ARISTOTELES is a joint magnetic field and gravity mission with a low-elevation phase to measure the crustal field and a high-elevation phase to measure the time-varying core field. The availability of gravity data from this mission would materially help the interpretation of upper-lithosphere magnetic anomalies. If the necessary collaboration with ESA cannot be arranged, the next best alternative would be for NASA to collaborate with the French and Italian space agencies to accomplish a similar mission.

Another possibility is to collaborate with the French space agency to carry out the high-altitude Magnetic Field Explorer Magnolia mission. NASA also has a responsibility for scientific aircraft flights, and there is a possibility of carrying out magnetic field observations for aircraft in the future, under NASA's auspices. Should there be a negative decision on ARISTOTELES by ESA, NASA will consider one of these missions, or an alternative inexpensive magnetic field mission.

The measurement of magnetic fields from satellites is driven by basic scientific needs; NASA has developed a competent group of scientists engaged in the study of the magnetic field of the Earth, from core field modelers to crustal anomaly experts. Major advances have been made in the ability to analyze noisy satellite data, to produce the most accurate magnetic field model possible. Spherical harmonic models of the geomagnetic field produced by NASA are major contributors to the International Geomagnetic Reference Field.

NASA also supports a very strong program of research in the areas of magnetospheric and ionospheric physics. Major new science missions are under development under the International Solar Terrestrial Physics and the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) programs. Smaller missions are also actively under development under the aegis of the Small Explorer (SMEX) program. A vigorous program of rocket and balloon flights directed at upper-atmosphere and ionospheric phenomena is also maintained. In addition, NASA supports a broad program of theory, data analysis, and modeling research in these fields.

Advances have been made in the ability to deal with ionospheric and magnetospheric fields and to deal with the temporally varying portion of the core field. The availability of a superior magnetic field model for

1980, mainly generated by Magsat data, has rejuvenated the study of the magnetic properties of the core and of the core-surface motions thought to be responsible for the secular variation of the Earth's magnetic field. Interest in the crustal component of the field has encouraged study of the rock magnetic properties of candidate rock types thought to be responsible for the long-wavelength magnetic anomalies recorded at satellite altitude.

U.S. Geological Survey (USGS)

The USGS is part of the U.S. Department of the Interior. One of the major tasks of the USGS in the field of geomagnetism is to operate the geomagnetic observatories within the United States and its territories. At the moment, there are 13 observatories in operation. The USGS has been a major force in the creation of INTERMAGNET, an international program to set up state-of-the-art geomagnetic observatories with the ability to transmit digital data in real time to the data centers. CD-ROMs of 1-minute observatory data are available from USGS. Geomagnetic observatories produce important data sets for the generation of geomagnetic reference fields, and USGS has a task to produce such models, which are candidate models for the IGRF. The INTERMAGNET program will eventually expand to about 70 observatories.

The USGS also produces geomagnetic charts of the United States and the world every 5 years. There is also a service to provide model values of the geomagnetic elements by means of an on-line, dial-in service.

Because of the major role that USGS plays in understanding the crustal geology of the United States, there is considerable emphasis on the collection and analysis of crustal geomagnetic field anomalies both on land and over areas of the exclusive economic zone. The USGS conducts low-altitude aeromagnetic studies for mineral and energy assessment, earthquake, and volcanic hazard studies, and a variety of other USGS missions. Paleomagnetic and rock magnetic laboratories conduct geological and tectonic investigations and participate in the interpretation of magnetic anomalies. Despite the fact that USGS, NOAA, and the U.S. Navy have responsibilities for the collection of geomagnetic field anomaly

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data, there is little formal communication among these agencies. There is, however, much informal communication. Because of the need to remove the diurnal variation of the magnetic field from surveys to give an accurate value of the internal field, some effort is spent by USGS to produce more accurate and predictive models for the Sq variation. USGS interest in crustal magnetic field anomalies resulted in cosponsorship of Magsat with NASA. There is still interest in USGS in obtaining a more detailed crustal anomaly data base by flying a satellite in a lower orbit than Magsat.

The USGS can support and coordinate multiagency acquisition of new aeromagnetic data in the United States by use of improved data-merging techniques and by use of USGS geophysical aircraft. These aircraft can fly long baselines to tie more localized surveys together and can also perform low-altitude surveys in areas related to missions of USGS and other federal agencies.

Funding for the acquisition of a second-generation national magnetic map by USGS is problematic at this time because of severe budgetary limitations and because of the broad scope of this type of project. This effort will require participation from a wide base of the geomagnetic community, coordinated by USGS, but involving the support, cooperation, and participation of other federal agencies, state governments, industry, and academia.

The USGS also carries out MT and MV studies for resource assessment. This work is funded in part by DOE because of the geothermal resource implications of the research, and by EPA. Some work is done by USGS to calculate upper-and lower-mantle conductivity by using observatory data.

The USGS does not fund a great deal of work extramurally in geomagnetism, partly because of budgetary cutbacks in recent years. There is considerable informal collaboration with university scientists. Some forms of collaboration, such as the employment of students, is sometimes made difficult by bureaucratic problems. This is certainly an area where practices could be improved, with benefits both to USGS and to the university community.

National Oceanic and Atmospheric Administration (NOAA)

NOAA is part of the U.S. Department of Commerce. It currently operates two series of environmental satellites in geostationary and low-polar orbit. One important NOAA mission is to monitor geomagnetic field activity. Jointly with the Air Force Air Weather Service, NOAA operates the Space Environment Services Center, which is staffed 24 hours a day. SESC monitors the level of activity of the Earth's magnetic field and informs other government agencies, educational institutions, and industrial centers when the amplitude of fluctuations exceeds a preset threshold. High magnetic activity sometimes causes disruption of important systems, such as power grids and communication networks. Some of the data used in this monitoring activity comes from NOAA-managed magnetometers of the Geostationary Operational Environmental Satellites (GOES).

NOAA also issues predictions of geomagnetic activity for similar uses. Because the variations of the magnetic field which are of importance in these predictions and warnings are often caused by solar activity, NOAA scientists also conduct research in solar-terrestrial relationships.

NOAA's weather satellites sometimes malfunction due to magnetic storms; thus, a greater knowledge of these phenomena is important for this agency.

NOAA also has a responsibility for the production of nautical charts of coastal areas, and requires magnetic field information to indicate the magnetic variation (declination) and its change on these charts. The U.S. Navy (see below) has a similar responsibility for charts of oceanic areas. Aeronautical charts are also NOAA's responsibility. NOAA still has a small deep-sea geophysics program and collects towed magnetometer data on these geophysical cruises.

Because of its fisheries responsibilities, NOAA is interested in the magnetic field and its relationship to the navigation and stranding of marine mammals.

NOAA has a major responsibility to maintain data centers related to geophysics and the environment. These centers are responsible for

distributing information from numerous data bases. Included in these data bases are marine magnetic fields recorded by research vessels, information about continental magnetic anomalies, information from satellites such as Magsat and the POGO satellites, aircraft data, and data from geomagnetic observatories. NOAA is also responsible for distribution of magnetic field models, such as the coefficients of the International Geomagnetic Reference Field, and distribution of information about magnetospheric models. Most magnetic field information that is used to develop the IGRF models can be found in the NOAA Data Centers. One problem is that data digitization has not kept pace with data acquisition. A solution to this problem needs to be developed.

U.S. Department of Defense (DOD)

Defense Mapping Agency (DMA)

The DMA has major responsibilities in geomagnetism, including management of the DOD Geomagnetic Data Library. This library contains all data collected by Project Magnet, both classified and unclassified. In association with the U.S. Navy, DMA produces the DOD World Magnetic Models, which are candidate models for the IGRF. These models are developed in collaboration with the British Geological Survey. Operational requirements from the Service Departments of DOD require data to be collected for navigation, directional sensors, magnetic anomaly detection for antisubmarine warfare, magnetic degaussing, targeting, and mine warfare. Most of these requirements can be satisfied by directional capabilities with 1° accuracy.

DMA products include a world magnetic field model, compass roses on maps and charts, world geophysical data charts, and magnetic anomaly detection charts (classified). DMA also responds to special requests from DOD users.

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Department of the Navy

The U.S. Navy runs some major geomagnetic programs. Of these, one of the most important is Project Magnet. This aircraft program collects magnetic field data worldwide using advanced scalar and vector magnetometers. These data are used in the DOD World Magnetic Model. The vector data are especially useful in equatorial areas, where the POGS data (see below) being only scalar, will lead to large Backus effect problems in development of geomagnetic models.

The Polar Orbiting Geomagnetic Satellite is another very important program. This system is currently capable of generating scalar data only, and may suffer from unknown drifts in the fluxgate magnetometers. Starting in 1994, the magnetic field instruments will be placed on the Block 5 DMSP satellites. These are operational meteorological satellites. Although the satellites are oriented in space, the boom on which the magnetometer sensors will be placed will have no attitude transfer system; thus, these satellites will still effectively be only scalar instruments. In 2005, it is planned to mount fully oriented magnetometers on the Block 6 DMSP satellites.

Department of the Air Force

The Air Force mission requires magnetic field measurements as a component of its effort to monitor "space weather." Thus, the primary interest is in the magnetic disturbance vector measured on satellites at the first Lagrangian point (L-1), at geosynchronous orbit, in low-Earth orbit, and as recorded at ground stations. The Air Force has a secondary interest in the Earth's main field only as a baseline from which to measure magnetic disturbances.

National Science Foundation (NSF)

The National Science Foundation funds many programs in geomagnetism—mainly through the Divisions of Earth Sciences, Ocean Sciences, Atmospheric Sciences, and Polar Programs. There is thus support for a range of studies in ionospheric and magnetospheric physics. Theoretical work on core dynamo problems and experimental work on paleomagnetic constraints are major relevant programs. In addition, there is much work on tectonic problems and, although there is not much support for the analysis of lithospheric magnetic anomalies except in oceanic areas, the overall crustal program within NSF provides important constraints for lithospheric models of magnetic anomalies. There is also some support for electromagnetic studies, both of deep Earth and crustal conductivity.

Of particular relevance to the geomagnetic initiative is a proposed new NSF program, Cooperative Studies of the Earth's Deep Interior (CSEDI), which will support research associated with the international SEDI program. The NSF Ridge Inter-Disciplinary Global Experiments (RIDGE) program has considerable involvement from scientists in NOAA (through the Vents program) and USGS.

Interaction between NSF and other agencies occurs in ad hoc arrangements, and there seems to be little difficulty in setting up formal or informal cooperative agreements with other federal agencies, as needed.

Recommendations

- The current efforts to commence a satellite mission (ARISTOTELES) with the European Space Agency should continue. If this mission is not initiated, then other missions should be pursued—such as MFE-Magnolia.
- The later Block 5 DMSP satellites should be upgraded by the addition of a scalar magnetometer at the end of the 5-meter boom, to provide absolute control on the drift of the vector instruments.

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- The Block 6 DMSP satellites should be upgraded to give absolute vector measurements of the Earth's magnetic field to an accuracy of 4 nanoteslas per coordinate. The attitude determination should be accurate to 15 arc seconds.
- Discussions should take place between NOAA and NASA about the possibility of placing magnetometers on the NOAA polarorbiting satellites.
- Educational concerns of geomagnetism should be pursued.

Educational concerns might be pursued in the following ways. Government agencies are encouraged to seek student involvement in their projects whenever possible. This could be accomplished in large part by employment of students during the summer at government facilities. In certain situations, students from nearby universities could work at a government facility during the school year. Appropriate agencies could fund student stipends and expenses through university grants or contracts. Since the number of women and minorities entering professional science careers is still small, special encouragement should be given to these groups. This can be most effectively done at the undergraduate level. Some agencies have student programs at present; they are encouraged to study these programs to ensure that they are effective and easy to implement. (Some programs are known to suffer from rules that are too rigid for effective student involvement.)

Another educational program might entail visits of government scientists to universities to present scientific talks. This program should be restarted by the National Science Foundation. It affords the opportunity to inform and educate students who are not science majors about interesting government research. Programs that inform the nonscientist about major scientific experiments and results are considered extremely important in generating a satisfactory research climate within the country.

- Some of the classified data collected by the U.S. Navy from surface ships would be of great use to the geomagnetic communi

ty. A request should be made to the Navy to release as much data as possible to the NOAA National Geodetic Survey for the appropriate filtering, binning, or culling under classified protocols.

Information of this type even if culled, averaged, or otherwise filtered over a spatial scale of 100 km would be extremely useful to regional and main field modelers. The data derived in this way could be used to improve the Navy's field model.

Of greater value would be data averaged over considerably shorter spatial scales (for example, over a few kilometers). Such data could be used in lithospheric magnetic modeling studies or in determining the age of the seafloor from seafloor spreading anomalies. Basic geological knowledge of this sort would be of great value to the scientific community, especially in areas sparsely covered by unclassified data. Declassifying its data would also be of value to the Navy itself, because the knowledge of the crustal age is of predictive use for the determination of sediment coverage, an important aspect of the acoustic behavior of the ocean floor. These filtered data can then be released to the NGDC with appropriate controls on dissemination, as prescribed by the Navy.

- Steps should be taken to implement a satellite program to monitor the L-1 Lagrangian point, with 24-hour real time transmission of data to the ground.

The effective warning of geomagnetic storms would have immense monetary benefits to the country, and the data obtained would help improve the understanding of the external magnetic field of Earth and so provide a better internal field model. These steps should be taken jointly by NASA, NOAA, DOE, and DOD. ISTP satellites in geostationary orbit should also be used to gather data to study the solar wind.

- Federal agencies (particularly NOAA and NASA) should seek efficient and inexpensive ways of digitizing analog records from geomagnetic observatories. This might be done by subcontracting

to Russian agencies that have the capability of completing this work on time and at little expense.

- The INTERMAGNET program and others involving the setting up of geomagnetic observatories should be expanded. Collaboration between USGS and relevant organizations in other countries should be encouraged. This can be done by providing the state-of-the-art INTERMAGNET instrumentation to less developed countries, and setting up training programs to inform scientists and engineers from these countries how to achieve optimum performance from their instruments.

In order to save on installation and data transmittal costs, new geomagnetic observatories should be collocated with other geophysical observatories, such as the Fiducial Laboratories for an International Natural (FLINN) network, or the IRIS network. Coordination of these geophysical observatories should involve NSF, NOAA, USGS, NASA, DOD, and other relevant federal agencies. The antarctic geomagnetic observatories financed by the NSF Division of Polar Programs should be converted into absolute instruments with help from the USGS.

- A national effort should be implemented to acquire a new airborne and shipborne magnetic map and digital data base of the United States and its EEZ. Such an effort would logically be coordinated by USGS, but it should involve the support, cooperation, and participation of other federal agencies, state governments, industry, and academia.
- A data coordination arrangement should be set up among those federal agencies collecting or holding significant geomagnetic data sets. The relevant representatives should meet often enough to ensure effective communication and collaboration.

Appendix C

Workshop Organization

The Workshop was held at the National Academy of Sciences

Cecil and Ida Green Building

2001 Wisconsin Avenue, NW

Washington, DC

16-20 March 1992

Workshop Leaders

John Hermance (Chair)

William Hinze

Robert Langel

Christopher Russell

Topical Working Group Leaders

James Slavin (The Magnetosphere, Ionosphere, and Atmosphere)

Richard Blakely (Lithospheric Magnetic Fields)

John Booker (Electromagnetic Studies of the Solid Earth and Oceans)

David Loper (Main Field and Core Processes)

Operational Requirements Working Group Leaders

James Heirtzler (Operational Platforms)

Joe Allen, Herbert Meyers (Data Management Systems)

Christopher Harrison (Interagency Coordination and Communication)

Ex-Officio Members

Robin Brett, Chair of the U.S. Geodynamics Committee

Kevin Burke, NAS/NRC

Pembroke Hart, NAS/NRC

BACKGROUND ON OBJECTIVES AND FORMAT

A. Objectives

- To refine the scope and focus of the geomagnetic initiative.
- To identify challenges and future directions in geomagnetic studies and applications, particularly those of an interdisciplinary nature.
- To define unique opportunities in geomagnetic research and development that could benefit from an increased level of interagency coordination.
- To consider the need and possible mechanisms for on-going interagency coordination which are consistent with the mandated mission of the principal agencies involved.
- To develop a plan of action.

B. Size of Meeting

- Large enough to represent the breadth and diversity of the field.
- Small enough to ensure meaningful discussions in a small group environment.
- Approximately 100 participants from the academic, industry, and government scientific community.

C. Selection of Participants

- Participants were selected from a pool of applicants and nominees based on balance of representation among disciplines and the expected scientific participation of the potential attendee.

D. General Guidelines for Pre-Workshop Activity

- Essential material was distributed to the workshop participants before they arrived at the meeting.
- A draft document was circulated to all attendees before the workshop.
- The chairperson of each working subgroup circulated material to subgroup members.
- If appropriate (that is, if certain material was not already circulated, discussed, or otherwise brought to the attention of the meeting participants), attendees were expected to arrive with position statements in hand, ready to be copied and circulated to other participants.

E. Venue for the Workshop

- The Workshop was held at, or adjacent to, the National Academy of Sciences (NAS) Green Building, 2001 Wisconsin Avenue, NW, Washington, DC (Georgetown).
- Plenary sessions were held at the Georgetown Holiday Inn (across the street from the Green Building), a facility that could accommodate at least 100 people.
- Working Group meetings were held in the NAS Green Building where 6 to 8 small meeting rooms were available to accommodate 20 to 40 people each.
- Secretarial support, word processing, and duplication facilities were available throughout the meeting.
- Lodging was available at the nearby Georgetown Holiday Inn.

F. The Working Groups and Subgroups

- The charge to each working group was to articulate and implement the concepts and recommendations of its constituency.

- In general, each attendee was affiliated with at least two different working groups: a "Topical Research Working Group" and an "Operational Requirements Working Group."

G. The Product

- It was planned that a document (called the "proceedings") would be completed by the end of the workshop. This would form the basis of a report to be issued by the U.S. Geodynamics Committee. The "proceedings" would consist of the following elements:
 1. An Executive Summary setting forth the most outstanding opportunities and priorities.
 2. A 35-to 50-page report identifying scientific, operational, and policy issues related to the workshop objectives mentioned above.
 3. A set of supporting appendixes. These might consist of (among other things) those thoughtful statements describing in detail the scientific or the programmatic basis for various elements of the initiative.
- All Subgroups were accordingly requested to develop a one-page summary of their concerns, which they were expected to distribute at the beginning of the meeting.
- All Working Groups were expected to use the one-page Subgroup summaries in arriving at a one-page synopsis of their own. These Working Group synopses would be used by the executive committee (EXCOM) in developing the two-page Executive Summary.

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**MEMBERSHIP OF TOPICAL WORKING GROUPS AND
SUBGROUPS**

**A1. The Magnetosphere, Ionosphere, and Atmosphere
(Chairperson: James Slavin)**

Magnetospheric Processes	Ionospheric Processes	Pulsations
R. McPherron	A. Richmond	M. Engebretson
F. Rich	D. Herzog	R. Clauer
M. Teague	V. Papitashvili	J. Olson
R. Walker	L. Zanetti	V. Patel

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A2. Lithospheric Magnetic Fields (Chairperson: Richard Blakely)

Anomalies	Analysis	Rocks
C. Raymond	V. J. S. Grauch	R. Reynolds
J. Behrendt	J. Arkani-Hamed	R. Frost
S. Cande	D. Chapin	S. Haggerty
V. Chandler	R. Hansen	G. Smith
W. Dewhurst	J. MacQueen	P. Toft
T. Hildenbrand	R. Pawlowski	P. Wasilewski
W. Hinze	J. Phillips	
P. Hood		
P. Taylor		
P. Vogt		

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**A3. Electromagnetic Studies of the Solid Earth and Oceans
(Chairperson: John Booker)**

Regional & Global Studies	Oceans	Materials
P. Wannamaker	A. Chave	A. Duba
W. Campbell	C. Cox	L. Hirsch
G. Egbert	A. W. Green	J. Tyburczy
I. Gough	L. Law	
J. G. Kappenman	B. Narod	
B. Narod	P. Tarits	

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A4. Main Field and Core Processes (Chairperson: David Loper)

Field Models, Inversion, & CMB Proc.	Secular Variations & Reversals	Dynamic Processes & Core Dynamo
J. Bloxham	R. Merrill	P. Roberts
S. Braginsky, J. Cain, M. Fuller, C. Harrison, R. Langel, L. Newitt, N. Peddie, J. Quin, K. Verosub		

(Note: Group did not organize as subgroups)

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MEMBERSHIP OF OPERATIONAL REQUIREMENTS WORKING GROUPS

B1. Operational Platforms (Chairperson: James Heirtzler)

Surface/Seafloor	Airborne/Ship	Satellites
A. W. Green	T. Hildenbrand	L. Zanetti
A. Chave	J. Behrendt	J. Arkani-Hamed
C. Cox	W. Dewhurst	M. Engebretson
I. Gough	B. Donovan	R. McPherron
D. Herzog	K. Gebhardt	P. Mulligan
L. Law	W. Hanna	J. Quinn
B. Narod	R. Hansen	C. Raymond
L. Newitt	P. Hood	F. Rich
P. Tarits	V. Labson	J. Slavin
P. Wannamaker	J. MacQueen	P. Taylor
	R. Pawlowski	
	R. Wold	

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**B2. Data Management Systems (Chairperson: Joe Allen¹;
Herbert Meyers)**

Data Bases	Data Archives	Data Access	Derived Products
D. Herzog	H. Meyers	R. Walker	J. Joselyn
V. Chandler	J. Cain	D. Chapin	R. Barnes
D. Chapin	S. Cande	J. Phillips	W. Campbell
R. Clauer	V. Chandler	M. Teague	D. Chapin
A. W. Green			R. Clauer
W. Hinze			A. W. Green
J. Phillips			D. Herzog
C. Russell			J. Kappenman
M. Teague			J. MacQueen
			L. Newitt
			N. Peddie

¹ J. Allen was the original chair of this Working Group, prior to, and on the first day of, the workshop; he left the workshop on a personal emergency.

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B3 Interagency Coordination and Communication (Chairperson: Christopher Harrison)

Workshop participants

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Agenda
Workshop on the National Geomagnetic Initiative
National Academy of Sciences
Washington, DC
16-20 March 1992

Sunday, p.m. (March 15)	Workshop Organizers (EXCOM, Working Group and Subgroup Chairs arrive. Meeting of EXCOM in executive session.)
Sunday, p.m. & Monday, a.m.	General Participants arrive
Monday 0830-1200 hrs	Pre-Workshop caucus of Meeting Coordinators (EXCOM, Working Group and Subgroup Chairs, Invited Speakers, secretaries, and others)
1300 hrs	Workshop begins.

Plenary Session on the Status and New Opportunities in Geomagnetic Studies

Welcome by K. Burke and W. Hinze on behalf of the NRC and USGC, respectively. Introduction by J. Hermance, and general comments on facilities (secretarial support, word processors, copy machines, small meeting rooms, and so on).

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Invited Speakers

- D. Stevenson** Challenges in the Earth Sciences and Their Relation to Geomagnetic Studies
- R. Langel** Overview of the Geomagnetic Field: The Forest Rather Than the Trees
- W. Hinze** Opportunities and Challenges in Lithospheric Investigations
- R. Walker** Modeling the Magnetosphere
- R. McPherron** Geomagnetic Storms and Things That Go Bump in the Night

Status of Working Group Reports

- J. Slavin** Magnetosphere, Ionosphere, and Atmosphere
- R. Blakely** Lithosphere Magnetic Fields
- J. Booker** Electromagnetic Studies of the Solid Earth and Oceans
- D. Loper** Main Field and Core Processes
- J. Heirtzler** Operational Platforms
- J. Allen** Data Management Systems
- C. Harrison** Interagency Cooperation and Coordination
-

Monday Evening

1930-2130 hrs Preliminary meetings of participants in individual Topical Working Groups (or Subgroups) to present short talks, informally discuss mutual expectations and concerns, and guidelines to achieve meeting objectives. This generated focus to the following morning's activities.

Tuesday

0830-1200 hrs **Meetings of attendees in assigned *Topical Working Groups*.**

Attendees assembled in assigned Working Groups based on **research** topic to discuss (through short talks and informal discussion at the discretion of the Group Chair) the following in terms of the Working Group's specific subfield:

Recent developments in geomagnetic studies
New opportunities
New approaches to solving old problems, which could be implemented through the use of new technology
Specific needs (if any) for interagency coordination
Specific concerns.

By midmorning, each Topical Working Group Chair had developed specific guidelines defining the product needed from each working group. At the discretion of the Working Group Chair, some groups assembled into Subgroup Panels for more specific, focused discussion. In most cases, specific writing assignments resulted in draft text by noon (or by the afternoon plenary session).

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Tuesday

1300-1500 hrs **Plenary Session.**

Each Topical Subgroup reported (through its Chair) on its progress to the entire assembly, followed by a short discussion. At the end of Subgroup reports, a general discussion developed on common issues and concerns.

Preliminary priorities.

(Tight Schedule: 10 minutes per report; maximum = 2 hours total)

1530-1730 hrs **Topical Groups and Subgroups completed writing and/or editing.**

Each Topical Group Chair met with her/his Subgroup Chairs and developed a final consensus statement that was typed and distributed to rest of attendees by midmorning of next day (Wednesday, a.m.).

Tuesday Evening

1930-2130 hrs **Meeting of all Topical and Operational Working Group Chairpersons with Meeting Coordinators to identify needs and priorities.**

Completion of the Topical Working Group Reports and Summaries.

Wednesday

0830-1200 hrs **Meetings of *Operational Needs* Working Groups.**

Attendees assembled into assigned Working Groups based on operational needs.

Each Operational Needs Subgroup discussed the following in terms of its specific subfield:

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Operational platforms
Data management systems
Interagency coordination and communication

At this point, each chairperson had developed very specific guidelines defining the product needed from each Working Group. Specific writing assignments resulted in final text by noon (or by afternoon plenary session).

Wednesday

1300-1500 hrs **Plenary Session.**

Each Operational Needs Subgroup reported on its progress to the entire assembly. Following the Subgroup reports, a general discussion focused on common issues and concerns.

Preliminary priorities.

(Tight Schedule: 10 minutes per report; maximum = 2 hours total)

1500-1730 hrs **Operational Groups and Subgroups complete writing and/or editing.** Each Operational Needs Working Group Chair met with her/his Subgroup Chairs and developed a final consensus statement that was typed and distributed to rest of attendees by midmorning of next day (Thursday a.m.)

Wednesday Evening

1900-2130 hrs **Meeting of all Topical and Operational Working Group Chairpersons with Meeting Coordinators.**

Reports and Summaries of the Operational Needs Working Groups were completed.

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Thursday

0830-1000 hrs

Plenary Session with Agency Technical Managers.

Each Working Group Chair (7) presented a short overview of a relevant section of final report.

(10 minutes per report, including discussion; maximum = 1.5 hour total)

Several agency Technical Managers then discussed with the audience the pros and cons of various mechanisms to achieve interagency coordination.

Thursday

1030-1200 hrs

Meeting of Agency Technical Managers with Interagency Coordination and Communication Subgroup.

Completion of pending writing assignments by general participants and other subgroup chairpersons.

1400-1600 hrs

Plenary Session

The Agency Perspective

Presentations by agency administrators to plenary session.

Discussion of the proceedings and initiative as a whole.

1600 hrs

Concluding remarks.

1630 + hrs

Departure of General Participants (not Meeting Organizers).

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All Working Group Chairs completed writing assignments (including those of their groups), and transferred material to typists.

Friday

0830-1200 hrs

Wrap-up of writing and related tasks by coordinating personnel.

Meeting Coordinators, Steering Committee, and Working Subgroup Chairs assemble final document summarizing proceedings and Executive Summary.

2000 hrs

Steering Committee submitted draft of Workshop Report to the U.S. Geodynamics Committee.

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**Workshop on the National Geomagnetic Initiative 16-20
March 1992**

Attendees

Joseph Allen	National Oceanic and Atmospheric Association/National Geophysical Data Center
Allen Anderson	National Aeronautics and Space Administration
Jafar Arkani-Hamed	McGill University
P. R. Barnes	Oak Ridge National Laboratory
John Behrendt	U.S. Geological Survey
Richard Blakely	U.S. Geological Survey
Jeremy Bloxham	Harvard University
John Booker	University Washington
Stanislav Braginsky	University of California, Los Angeles
Kevin Burke	National Academy of Sciences/National Research Council
Joseph Cain	Florida State University
Wallace Campbell	U.S. Geological Survey
Steven Cande	Lamont-Doherty Earth Observatory
Val Chandler	University Minnesota
David Chapin	ARCO Exploration and Production Company
Alan Chave	Woods Hole Oceanographic Institute
Robert Clauer	University Michigan
Charles Cox	Scripps Institute of Oceanography
Warren Dewhurst	National Oceanic and Atmospheric Administration
Hans Dolezalek	Office of Naval Research
Barry Donovan	U.S. Navy
Alfred Duba	Lawrence Livermore National Laboratory
Timothy Eastman	National Science Foundation, Atmospheric Sciences

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Gary Egbert	Oregon State University
Mark Engebretson	Augsburg College
Joseph Engeln	National Aeronautics and Space Administration
Ronald Frost	University of Wyoming
Michael Fuller	University of California, Santa Barbara
Kim Gebhardt	Defense Mapping Agency
Ian Gough	University of Alberta
V. J. S. Grauch	U.S. Geological Survey
William Green	U.S. Geological Survey
Stephen Haggerty	University of Massachusetts
William Hanna	U.S. Geological Survey
Richard Hansen	Colorado School of Mines
Bruce Hanshaw	National Academy of Sciences/National Research Council
Christopher Harrison	University of Miami
Pembroke Hart	National Academy of Sciences/National Research Council
Eric Hartwig	Office of Naval Research
James Heirtzler	NASA/Goddard Space Flight Center
John Hermance	Brown University
Donald Herzog	U.S. Geological Survey
Thomas Hildenbrand	U.S. Geological Survey
William Hinze	Purdue University
Lee Hirsch	Exxon Production Research Company
Peter Hood	Geological Survey Canada
Leonard Johnson	National Science Foundation, Earth Sciences
JoAnn Joselyn	National Oceanic and Atmospheric Administration
John Kappenman	Minnesota Power
Victor Labson	U.S. Geological Survey
Robert Langel	National Aeronautics and Space Administration/Goddard Space Flight Center
Lawrence Law	Pacific Geoscience Center, Geological Survey of Canada

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David Loper	University of Florida
William Luth	U.S. Department of Energy
John Lynch	National Science Foundation, Polar
Ian MacGregor	National Science Foundation, Earth Sciences
Jeffrey MacQueen	LCT Houston, Inc.
Richard Martino	Defense Mapping Agency
Michael Mayhew	National Science Foundation, Earth Sciences
Robert McPherron	University of California, Los Angeles
Ronald Merrill	University of Washington
Herbert Meyers	National Oceanic and Atmospheric Administration/ National Geophysical Data Center
Richard Mitterer	U.S. Department of Energy
Patricia Mulligan	NOAA/NESDIS
Barry Narod	University of British Columbia
L. R. Newitt	Geological Survey Canada
John Olson	University of Alaska
Ned Ostenso	National Oceanic and Atmospheric Administration
Vladimir Papitashvili	IZMIRAN & STEP Coordination Office
Vithal Patel	Naval Research Laboratory
Robert Pawlowski	Amoco Production Company
Norman Peddie	U.S. Geological Survey
Jeffrey Phillips	U.S. Geological Survey
John Quinn	U.S. Naval Oceanographic Office
Carol Raymond	Jet Propulsion Laboratory
Richard Reynolds	U.S. Geological Survey
Frederick Rich	PL/GPFG, Hanscom Air Force Base
Arthur Richmond	National Center for Atmospheric Research
Paul Roberts	University of California, Los Angeles
Christopher Russell	University of California, Los Angeles
James Slavin	NASA/Goddard Space Flight Center
Guy Smith	St. Louis University
David Stevenson	California Institute of Technology
Pascal Tarits	Institute Physics Globe, Paris

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Patrick Taylor	NASA/Goddard Space Flight Center
Michael Teague	NASA/Goddard Space Flight Center
Paul Toft	McGill University
Ronald Turner	ANSER, Arlington, Virginia
James Tyburczy	Arizona State University
Thomas Usselman	National Academy of Sciences/National Research Council
Raymond Walker	University of California, Los Angeles
Philip Wannamaker	University of Utah
Peter Wasilewski	National Aeronautics and Space Administration/Goddard Space Flight Center
Richard Wold	Terrasense
Lorraine Wolf	National Academy of Sciences/National Research Council
Lawrence Zanetti	Applied Physics Laboratory, The Johns Hopkins University

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Appendix D

Acronyms, Abbreviations, and Special Names

AE	auroral electrojet magnetic activity index
AGO	Automatic Geophysical Observatories
AGU	American Geophysical Union
APAF0	Advanced Particles and Fields Observatory
ARISTOTELES	Applications and Research Involving Space Technologies Observing the Earth's Field from Low Earth Orbiting Satellite
AWAGS	Australia-Wide Array of Geomagnetic Stations
BEMPEX	Barotropic Electromagnetic and Pressure Experiment
BGS	British Geological Survey
CAM	Consortium on Array Magnetometers
CANOPUS	Canadian Auroral Network for the OPEN Program Unified Study (OPEN program has been renamed STEP)
CASERTZ	Corridor Aerogeophysics South and East Ross Transect Zone (Antarctica)
CD-ROM	Compact Disk—Read-Only Memory
CMB	core-mantle boundary
CNES	Centre National d'Etudes Spatiales (France)
CODMAC	Committee on Data Management and Computing (NRC)
COSPAR	Scientific Committee on Space Research (ICSU)
CRRES	Combined Release and Radiation Effects Satellite
CSEDI	Cooperative Studies of the Earth's Deep Interior
DCP	data collection platform
DE-2	Dynamics Explorer
DIM	declination inclination magnetometer

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DMA	Defense Mapping Agency
DMSP	Defense Meteorological Satellite Program
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
Dst	disturbance storm time equatorial magnetospheric activity index (ring current index)
EEZ	Exclusive Economic Zone
EM	electromagnetic method
EMF	electromotive force
EMSLAB	Electromagnetic Studies of the Lithosphere and Mantle Beneath (the Juan de Fuca Plate)
EOS	Earth observing System
EOS	Transactions of the AGU
EPA	U.S. Environmental Protection Agency
ESA	European Space Agency
FAC	field-aligned current
FLINN	Fiducial Laboratories for an International Natural Science Network
FREJA	Swedish satellite program
GAMES	Gravity and Magnetic Earth Surveyor
GAO	U.S. General Accounting Office
GDS	geomagnetic deep sounding
GEM	Global Environmental Monitoring
GGG	Global Geospace Science
GIN	Geomagnetic Information Node
GIS	geographic information systems
GLONASS	USSR Global Navigation Satellite System
GMS	Geostationary Meteorological Satellite (Japan)
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HILAT	High-Latitude Satellite
IAGA	International Association of Geomagnetism and Aeronomy (IUGG)

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ICL	Inter-Union Commission on the Lithosphere (established under the auspices of ICSU)
ICSU	International Council of Scientific Unions
IEEY	International Equatorial Electrojet Year (September 1991 to March 1993; designated by IAGA)
IGRF	International Geomagnetic Reference Field
IGY	International Geophysical Year (1957-1959)
ILP	International Lithosphere Program
IMF	interplanetary magnetic field
IMP	Interplanetary Monitoring Platform
INTERMAGNET	International Real-Time Geomagnetic Observatory Network
IRIS	Incorporated Research Institutions for Seismology
IRM	Institute for Rock Magnetism
ISEE	International Sun-Earth Explorer
ISTP	International Solar-Terrestrial Physics
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geological Sciences
IZMIRAN	Institute of Terrestrial Magnetism (Russia)
K (index)	pseudologarithmic magnetic disturbance index for 3-hour intervals (one station)
Kp	planetary K-index, based on global set of stations
L-1	first Lagrangian point
LITHOPROBE	Canadian program to explore the lithosphere using geophysics, geology, geochemistry, and geodesy
MAGIC	Magnetometer Array on the Greenland Ice Cap
Magsat	Earth's magnetic field satellite (1979-1980)
MARGINS	Margins: A Research Initiative for Interdisciplinary Studies of Processes Attending Lithospheric Extension and Conversion
METEOSAT	Meteorological Satellite (ESA)

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MFE	Magnetic Field Explorer
MHD	Magnetohydrodynamics
MLAT	magnetic latitude
MO	magneto-optical
MT	magnetotelluric
MV	magnetic variation
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NAS/NRC	National Academy of Sciences/National Research Council
NAVOCEANO	U.S. Naval Oceanographic Office
NERC	Natural Environmental Research Council (UK)
NGDC	National Geophysical Data Center (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NOST	National Office of Standards and Technology (NASA/OSSA)
NRC	National Research Council
NSF	National Science Foundation
ODP	Ocean Drilling Program
OEDIPUS	Observations of Electric-Field Distributions in the Ionospheric Plasma—a Unique Strategy
Oersted	Danish national satellite program
OSSA	Office of Space Science and Applications (NASA)
PACEM	Physics and Chemistry of Earth Materials
Pc, Pi	Rapid fluctuations of the geomagnetic field having periods from a fraction of a second to tens of minutes, lasting from minutes to hours. Divided into two main patterns: Pc (continuous, almost sinusoidal, pattern); Pi (irregular pattern). PEGASUS space launch vehicle carried to high altitude by B-52 aircraft
POGO	Polar Orbiting Geomagnetic Observatory

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POGS	Polar Orbiting Geomagnetic Satellite (Navy)
Re	Earth radius
RIDGE	Ridge Inter-Disciplinary Global Experiments
SAMNET	Sub-Auroral Magnetometer Network (UK)
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics Research (ICSU)
SEDI	Studies of the Earth's Deep Interior
SELDADS	Space Environment Laboratory Data Acquisition and Display System (NOAA)
SESC	Space Environmental Services Center (NOAA)
SLR	Satellite Laser Ranging
SMEX	Small Explorer (program)
SMS	Synchronous Meteorological Satellite
Sq	solar quiet (pattern of electric currents on quiet days)
STEP	Solar-Terrestrial Energy Program (7-year program begun in 1990)
STP	solar-terrestrial physics
SYNOP	Synoptic Ocean Prediction
TIMED	Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics
TIROS	Television Infrared Observation Satellite
UARS	Upper Atmosphere Research Satellite
ULF	ultra-low frequency
ULYSSES	NASA/ESA spacecraft to investigate heliospheric phenomena out of the ecliptic plane
UNOLS	University-National Oceanographic Laboratory System
USAF	U.S. Air Force
USGC	U.S. Geodynamics Committee
USGS	U.S. Geological Survey
Vents	Joint NOAA-university study of thermal venting from the seafloor (East Pacific Rise—Juan de Fuca Plate)

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VLBI	very-long-baseline interferometry
VLF	very low frequency
WDC	World Data Center
Wind	solar-wind monitoring satellite (NASA)

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