National Magnetic Anomaly Map

REPORT OF THE
NATIONAL MAGNETIC ANOMALY MAP WORKSHOP
CONVENED BY THE
COMMITTEE FOR A NATIONAL
MAGNETIC ANOMALY MAP
WITH THE COLLABORATION OF THE
SOCIETY OF EXPLORATION GEOPHYSICISTS
U. S. GEOLOGICAL SURVEY
U. S. GEODYNAMICS COMMITTEE
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This report was prepared by the participants
of the National Magnetic Anomaly Map Workshop

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PREFACE

The National Magnetic Anomaly Map (NMAM) Workshop was convened by the Committee for a NMAM in Golden, Colorado, on 17-19 February, 1976 with the collaboration of the Society of Exploration Geophysicists, U.S. Geological Survey, U.S. Geodynamics Committee and American Geophysical Union. The purpose of the Workshop was to prepare a statement of the benefits, objectives, and desirable specifications and requirements of a NMAM and to establish a working plan for producing the map.

The Committee for a NMAM was formed as an _ad hoc_ committee of the Society of Exploration Geophysicists by the Executive Committee of that organization in the summer of 1975 under the title "Ad-Hoc Committee on the Joint SEG-U.S. Geological Survey Aeromagnetic Map of the United States." Broadening of the interests and support of the committee has led to the title change. The committee was established as a result of discussions between J. Dan Skelton, then President of the SEG, and Richard P. Sheldon, Chief Geologist of the U.S. Geological Survey, concerning the common interest of their two organizations in the preparation of a NMAM and eventually a North American magnetic anomaly map. Subsequently, the Committee has become affiliated with the American Geophysical Union and includes members representing expertise in magnetic map preparation and a variety of users plus representatives of the U.S. Geological Survey and other interested federal agencies. The Committee also serves, in effect, as a working group providing advice to the U.S. Geodynamics Committee. The basic function of the Committee is to encourage preparation of a magnetic anomaly map. The Committee has agreed to recommend standards for the map, develop interest in it, and marshal the forces to bring the map to completion.

The Committee or sub-committees of the Committee met several times during the Fall of 1975 to discuss various aspects of developing a NMAM, but few major problems were solved. An extended period of concentrated effort was needed to discuss and resolve the major issues facing the Committee. The Workshop provided this opportunity and this report is a written record of the conclusions of that three-day meeting. The 29 participants of the Workshop (Appendix I) included members of the Committee for a NMAM plus several experts in magnetics from the U.S. Geological Survey.

The discussions of the workshop centered around 25 questions grouped into five general topics: (1) Objectives of the NMAM, (2) Status of magnetic mapping, (3) Desirable characteristics of the NMAM, (4) Preparation of the NMAM, and (5) Implementing the NMAM. Prior to the Workshop several participants were designated as discussion leaders of the questions and were asked to prepare written position papers on them. During the workshop several committees were formed to consider particular problems and questions that arose during the discussions and to report back to the Workshop on their findings. Recorders were assigned to each of the five general discussion areas to take notes of the discussions and to synthesize these with the position papers into a record of the Workshop. These recorders, C. E. Helsley, R. H. Higgs, A. J. Navazio, R. D. Regan, and R. J. Wold, and with the Committee Chairman, W. J. Hinze, are responsible for the preparation of this report.

This report serves as a formal record of the proceedings of the Workshop. But more than that we believe it should serve as a starting point for the marshalling of the interest and support of the geoscience community behind the preparation of a NMAM which will serve scientific and applied objectives of the nation and which will eventually lead to a North American magnetic anomaly map. The recommendations contained herein are the consensus obtained from the Workshop participants and, therefore, are not necessarily the opinion of individual participants nor the official stand of the collaborating organizations. A draft of this report was received by all participants after the Workshop. The important recommendations regarding the preparation of the NMAM were accepted by the Workshop without dissent.

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SUMMARY AND RECOMMENDATIONS

Our country's urgent need to find new sources for minerals and energy and its need to know more about the planet on which we live could be greatly assisted by preparation of a national magnetic anomaly map - a map which will provide an accurate representation of the earth's anomalous magnetic field. It is startling to note that the United States is one of the few major industrial nations that has a strong mineral resource base which has not commissioned a detailed airborne magnetic survey of the country for the purpose of preparing a national magnetic anomaly map. The preparation of this map, together with a consistent data set, will be of great value in encouraging petroleum, mineral, geothermal, nuclear fuels and ground-water exploration, will provide useful data for engineering and site evaluation, and will foster new scientific studies of our earth. In view of the significant role that magnetic observations at sea have had in developing the concepts of plate tectonics, it is anticipated that the scientific studies resulting from this effort will be very productive as indeed has been the case in other parts of the world.

The national magnetic anomaly map program represents an investment of permanent value. The dollar value of the map in terms of benefits accrued cannot be estimated with meaningful accuracy, but other countries' experience with similar maps indicate that it will pay for itself many times over from the taxes obtained from resource deposits discovered directly or indirectly as a result of the map. More than that it will be of great importance in maintaining the quality of life in the United States by aiding exploration for energy and mineral resources which are declining at an alarming rate. Probably no other set of geophysical data is as useful in the study of a wide variety of geologic and geophysical problems.

Thus, the Workshop concluded that every effort be made now to produce a national magnetic anomaly map and consistent data set from an aeromagnetic survey flown specifically for that purpose. This map will be used in geological mapping of surface and subsurface magnetic rocks, in locating economic resources both energy and mineral, and in mapping magnetic provinces and tectonic grain. In view of the number of years required to complete the national magnetic anomaly map survey, an interim national map and quasi-consistent data set is to be prepared from existing available data and magnetic data currently being collected by the Energy Research and Development Administration as part of the National Uranium Resource Evaluation Program. A special recommendation developed at the Workshop specifies the desired aeromagnetic characteristics of this latter survey. Finally, in order to obtain a national magnetic anomaly map in the next few years, a colored photo-mosaic of available magnetic data should be prepared at a scale of 1:2,500,000.

Specifically, the National Magnetic Anomaly Map Workshop recommends the following:

1. EVERY EFFORT BE MADE TO PRODUCE A NATIONAL MAGNETIC ANOMALY MAP AND CONSISTENT DATA SET FOR THE PURPOSE OF GEOLOGICAL MAPPING OF SURFACE AND SUBSURFACE MAGNETIC ROCKS, IN LOCATING ECONOMIC RESOURCES BOTH ENERGY AND MINERAL, AND IN MAPPING MAGNETIC PROVINCES AND TECTONIC GRAIN. THIS MAP SHOULD BE PREPARED FROM A SPECIALLY DESIGNED SURVEY WHICH HAS AN AVERAGE TRACK LINE DENSITY OF 2 KM.

2. WHILE THE SPECIALLY DESIGNED SURVEY IS BEING FLOWN AND THE MAP PREPARED, AN INTERIM MAGNETIC ANOMALY MAP AND QUASI-CONSISTENT DATA SET SHOULD BE PRODUCED FROM THE AVAILABLE DIGITAL MAGNETIC DATA AND ANALOG DATA CONVERTED TO DIGITAL FORM. THESE DATA SHOULD BE SUPPLEMENTED AS EXPEDITIOUSLY AS POSSIBLE WITH THE ERDA MAGNETIC DATA SET NOW BEING COLLECTED UTILIZING THE RECOMMENDATIONS MADE BY THE WORKSHOP.

3. IN RESPONSE TO THE INTEREST OF THE GEOSCIENCE COMMUNITY FOR AN IMMEDIATE NATIONAL MAGNETIC MAP ALBEIT INCOMPLETE AND DERIVED FROM INCONSISTENT DATA, A PHOTO-MOSAIC OF EXISTING MAGNETIC DATA SHOULD BE PUBLISHED AT 1:2,500,000 SCALE. THIS MAP WILL SERVE THE PURPOSE OF LOCATING SOME OF THE MAJOR MAGNETIC ANOMALIES AND TECTONIC TRENDS OF THE UNITED STATES.

4. THE THREE-STAGE NATIONAL MAGNETIC ANOMALY PROGRAM SHOULD BE BROUGHT TO THE ATTENTION OF APPROPRIATE GEO-SCIENCE ORGANIZATIONS AND FEDERAL AGENCIES AND EVERY EFFORT SHOULD BE MADE TO OBTAIN THE NECESSARY FUNDING TO ACHIEVE THE PROGRAM.

5. A WORKING ADVISORY COMMITTEE, COMPOSED OF RE-PRESENTATIVES OF THE SPECTRUM OF THE GEOSCIENCE COMMUNITY, SHOULD BE ESTABLISHED TO TAKE OVERALL GUIDANCE OF THE MAGNETIC ANOMALY PROGRAM. IN ADDITION, AN EDITORIAL ADVISORY COMMITTEE SHOULD ASSIST THE EDITOR OF THE PHOTO-MOSAIC MAP IN SELECTING AND EDITING DATA FOR THE MAP.

INTRODUCTION

Magnetic methods have had a long and successful history of mapping the earth's crust for both scientific and applied objectives. With the general availability of sensitive airborne magnetometers after World War II, magnetic mapping of broad areas became economically feasible for geologic purposes. Subsequent development of more sensitive magnetometers capable of absolute measurements and digital recording have opened new vistas for magnetic exploration of the earth. As a result, extensive areas of the earth's oceans have been mapped magnetically and many countries have been mapped aeromagnetically or have on-going programs to achieve that goal largely for the purpose of fostering mineral and energy resource exploration and production (Appendix II). The United States is <u>not</u> one of these countries. It has not organized a national magnetic anomaly map program despite the dominant role that the U.S. has had in post-1940 magnetic instrumentation developments, the dependence of the U.S. economy on raw materials derived from the earth, and our strong scientific position.

At the present time approximately 50 percent of the U.S. is covered by available magnetic surveys conducted by federal agencies (primarily the U.S. Geological Survey), states, and academic and oceanographic institutions. Additional areas covered by private industry surveys are generally not available. Unfortunately the existing magnetic data have serious limitations in the preparation of a national magnetic anomaly map (NMAM) because of inconsistencies and deficiencies in the surveying and reduction procedures of data collected over a 30 year time span by a variety of individuals and organizations. Furthermore, the available data are not contiguous and, therefore, the use of the data in a regional sense is limited.

The importance of a NMAM has been known and stressed for a long time. In 1966 the Society of Exploration Geophysicists' Executive Committee urged the U.S. Geological Survey to complete such a map. Similar resolutions were sent by the American Institute of

Mining Engineers and the American Geological Institute. In 1968 Isidore Zietz of the U.S. Geological Survey made an excellent case for a NMAM in an article published in Geotimes. Despite this interest and the documented exploration and scientific uses of a NMAM the U.S. has not initiated a program to achieve this goal. It is imperative that this situation be rectified immediately for the best interests of the nation. The objectives and benefits that will accrue to the U.S. from a NMAM as discussed in this report provide compelling justification for this strong stand. Furthermore, magnetic surveying technology has reached a level that will provide a high quality map which will have a long useful life.

Realizing the urgency of preparing a NMAM and because several years are required to prepare it, recommendations are made for preparing interim NMAMs. The importance of interim maps which will be prepared from available data should not be underestimated, but it is clear that they cannot reach the degree of significance or range of usefulness inherent in a NMAM prepared from a survey designed for that purpose. Furthermore, it should be emphasized that a NMAM will neither bring an end to magnetic surveying in the U.S. nor eliminate the usefulness of existing detailed magnetic maps observed with modern instrumentation and survey procedures. On the contrary, the NMAM, it is anticipated, will act as a catalyst for additional detailed surveys and for reinterpretation of existing high quality data.

OBJECTIVE OF THE NMAM PROGRAM

The objective of the National Magnetic Anomaly Map Program is the accurate representation of the earth's anomalous magnetic field on maps of regional scales. Maps of this nature have an application to a wide variety of applied and scientific studies. Although a regional magnetic anomaly map cannot provide the information available from magnetic surveys conducted for specific purposes, it is invaluable in providing a basic framework to specific studies, in selecting areas for more detailed investigations, and in studying broad-scale geologic features.

A related objective is the preparation of a consistent magnetic anomaly data set covering the United States and adjacent marine areas which will be available to industrial, academic, research, and governmental agencies. This data set will greatly increase the potential uses of the magnetic anomaly data by providing the capability of data enhancement and interpretation by computer analysis and computer map preparation at essentially any scale.

USES OF THE NMAM

The utility of the NMAM and associated data set can best be illustrated by describing the principal applications of magnetics to both applied and general scientific purposes.

Petroleum Exploration

Extensive use of magnetic data has been made in the search for petroleum-bearing districts and deposits in the United States and much of the information that can be interpreted from magnetic data in the U.S. is useful in petroleum exploration programs. Petroleum is nonmagnetic and most commercial accumulations of petroleum occur in sedimentary rocks that are also essentially nonmagnetic; therefore, the application of magnetic survey techniques to the search for petroleum is indirect. Sedimentary rocks are usually underlain by magnetic basement rock that produce magnetic anomalies. These magnetic anomalies can be defined by aeromagnetic surveys and interpreted in terms of the depth to the basement rock surface and consequently the thickness of overlying sedimentary rocks. The magnetic data can also be used to determine relief on the basement surface that may be directly related to structures favorable for accumulation of gas and oil in overlying sedimentary rocks. Thus, with magnetic data it is possible to identify areas with potential for occurrence of petroleum and to provide information on thickness of sedimentary rocks plus some information on possible structures in sedimentary rocks.

Presence of igneous extrusive rocks interbedded with sedimentary rocks or igneous rocks intrusive into sedimentary rocks may be important in the exploration for oil or gas. Magnetic data are very effective in indicating the presence, delineating the boundaries, and in determining the depth of igneous rocks.

The National Magnetic Anomaly Map will have direct application on petroleum exploration in:

a) Allowing for better definition of the background or regional field which, when removed, would better define local magnetic anomalies.

b) Determining locations and extents of tectonic elements and fixing tectonic grains; and, possibly, better establishing relative times of occurrence of tectonic events.

c) Providing better locations of basement elements which may or may not be offset from their surface geologic expressions.

d) Emphasizing to management the importance of magnetic data in an all-out search for energy sources.

e) Creating interest in untested and under-explored areas.

f) Guiding explorationists in planning detailed surveys.

The regional magnetic survey of the East Coast continental shelf and coastal plain flown by the U.S. Navy more than a decade ago provides an example of the potential application of the NMAM. This survey established the tectonic grain, mapped the significant "East Coast Magnetic Anomaly," and showed several anomalies having potential economic implication. Partially as a result of this survey, interest was stimulated in offshore exploration of this area. Later when the area was opened for exploration, the survey was used as the basis for 1) locating both aeromagnetic and marine gravity/magnetic detailed surveys over areas of special interest and 2) establishing parameters (e.g. spacings and directions of lines, elevations of flights) for these follow-up surveys.

Mineral Exploration

In the search for mineral deposits aeromagnetic data have both direct and indirect application. Aeromagnetic surveys provide a direct indication of ore bodies containing substantial amounts of magnetite or other magnetic minerals. Numerous iron-ore bodies have been found through magnetic surveys. Examples of such discoveries are the Lyons ore body near Yerington, Nevada, and the Pea Ridge, Missouri, deposit. Aeromagnetic surveys are an effective means of mapping and evaluating the economic potential of Precambrian iron formations. In Minnesota, aeromagnetic maps have been used in defining the area known to be underlain by iron formation.

One of the greatest values of the NMAM in the exploration for mineral deposits is in the study of magnetic features related to mineral deposits but not produced directly by ore bodies. Regional magnetic surveys are useful in establishing regional lithologic setting, character of mineral districts, intrusive provinces, and in delineating batholiths and major structural trends and crustal features, all of which are important for developing the framework for detailed mineral exploration. For example, in the Boulder Batholith area of Montana, the valuable ore deposits at Butte and mineralized areas to the north are indicated by magnetic minima which are caused by a deficiency of magnetic minerals related to the mineralization. Considerable effort is being devoted to recognizing regional patterns in the distribution of mineral deposits and regional magnetic surveys provide the best continuous and uniform set of data over large areas to aid in this recognition.

Geothermal Applications

Magnetic anomalies associated with geothermal systems have been identified in several areas of the western United States. These anomalies take different forms. In Yellowstone National Park and at Steamboat Springs, Nevada, magnetic lows are produced by alteration zones associated with active or fossil hydrothermal systems while in the Imperial Valley of California a magnetic high is produced by igneous rocks apparently associated with the Salton Sea geothermal system. Indirectly magnetic surveys are used in geothermal exploration to indicate the thickness of basin fill in an area such as the Rio Grande Valley and the extent and depth of geothermal reservoirs in volcanic areas of the Pacific Northwest.

The regional distribution of thermal anomalies in the crust appears to be controlled by regional tectonic patterns that are as yet not well understood. Regional aeromagnetic anomalies are key elements in developing an understanding of these features. For example the Yellowstone-Eastern Snake River Plain-Northern Nevada geothermal anomaly has a pronounced magnetic expression. Obtaining complete magnetic coverage of the western United States would be a major contribution to the development of regional tectonic models which would serve as guides to selection of areas for more intense geothermal exploration.

Regional aeromagnetic data are being used to determine the bottom of the magnetic portion of the crust and thus to map what is presumed to be the Curie isotherm surface. Regions where the Curie isotherm is relatively high in the crust are normally regions of high heat flow and thus promising areas for geothermal exploration. The technique has been successfully tested in the region of Yellowstone National Park.

Nuclear Fuels Exploration

Under the pressure of future demand for nuclear fuels, exploration must develop new resources in known districts and must expand beyond these districts and similar "Sandstone" environments. In established districts magnetic data provide tectonic-structural information related to uranium occurrences. Information includes basin configuration, definition of source area of sediments, and faults which may be related to favorable ore trends. Geological environments known to contain significant deposits of nuclear fuels elsewhere in the world (e.g. granite massifs of France, pegmatitic alaskitic gneiss of Southwest Africa, Precambrian erosional surfaces in the metamorphic rocks of Canada and Australia and the peralkaline intrusive complexes of southeastern Greenland, Brazil, and South Africa) must be assumed to have some favorability for uranium in the United States. Magnetic data, even of regional nature, are valuable in identifying and mapping these potentially favorable environments. Furthermore, a national magnetic map will encourage the development of regional, if not global, tectonic concepts from which uranium exploration models will evolve to foster innovative approaches to the solution of the nuclear fuel supply problem.

Ground-water Studies

With the increased emphasis on appraisal and development of total ground-water resources of large regions, regional geophysical studies have become increasingly important to ground-water investigations. Ground water is now being developed from great depths in several basins in the western United States and magnetic data are useful in determining depth and structure of these basins.

In large areas of the northwestern United States basalt flows are important aquifers. Magnetic data have proven useful in determining extent, thickness and depth of burial of major basalt aquifers in this region. A successful example is the study of Gem Valley in southeastern Idaho.

Earthquake Hazards and Site Evaluation

Regional magnetic studies are not normally useful in engineering geology studies of specific sites but can be of considerable value in investigations of earthquake hazards. Magnetic data have proven very useful in determining location and attitudes of faults in several areas including faults of the San Andreas system in California. The data will sometimes indicate the total lateral displacement of faults offsetting magnetic units. Ground motion response of seismic waves is determined by the underlying rocks. Regional magnetic surveys are effective in determining the thickness of poorly consolidated sediments over a magnetic basement and in mapping major lithologic units in the basement.

Recent research in the eastern United States indicates that the large historic earthquakes of this region (New Madrid, Charleston, Cape Ann) occur near the boundaries of large mafic intrusions within the basement. Apparently these earthquakes are localized by the mechanical properties of these mafic masses as contrasted with the surrounding felsic rocks. Magnetic surveys are effective tools in locating these mafic bodies and, thus, are important in studies of earthquake hazards in eastern United States.

General Scientific Uses

Recent revolutionary discoveries about the origin, destruction, and regeneration of sea floor material throughout the world's oceans and the role of sea floor spreading in producing earthquakes and effecting movement of continents were made possible in very large part by magnetic surveys. These findings about the evolution of the earth, based on detailed measurements of the earth's magnetic field at sea, point out the enormous potential usefulness of similar surveys over land areas. This has been confirmed by recent studies wherein magnetic measurements have contributed substantially to our understanding of the earth's crust.

Regional aeromagnetic surveys provide nearly continuous uniform data over any type of terrain. The data reflect the geology from the surface to tens of kilometers below the surface. No other set of geophysical data is as useful in the study of a wide variety of geologic and geophysical problems. In large areas of the country aeromagnetic maps can be used directly in the preparation of lithologic maps. In Precambrian terrain lithologic units often have characteristic magnetic expression which is used to map the units where exposures are poor or do not exist. Key magnetic patterns are used to map structure in areas of poor exposures. Because the magnetic properties of metamorphic rocks reflect the metamorphism of these rocks, magnetic data can be used in studies of regional metamorphism. Regional surveys have demonstrated that large blocks of basement rock have characteristic magnetic expression. Although the complete significance of some of the regional magnetic patterns is not yet fully understood, magnetic data are probably the most effective tool in studying basement lithology. It is estimated that magnetic data provide the only practical means of obtaining comprehensive geologic information on basement lithology over as much as 80 percent of the region east of the Rocky Mountains.

Magnetic surveys are effective in determining geometry of sedimentary basins and in defining major masses of extrusive and intrusive igneous rocks. For example, using the geometry of an intrusive mass inferred from magnetic data, it is possible to infer the spatial stress patterns produced by the forceful intrusion of the mass. The relationship between intrusive masses is often apparent from regional magnetic surveys.

Another, and possibly more important, application of aeromagnetic data is in the geologic investigation of the broad Atlantic continental shelf. A thorough understanding of the magnetic anomaly-geology relation of land areas is vital to the use of magnetic surveys in marine investigations. As in the case of the buried basement of the central and coastal United States, magnetic data offer the greatest promise as a means of mapping the geology of the uppermost basement rocks of the continental shelves.

BENEFITS EXPECTED

The NMAM program represents an investment of permanent value that will have beneficial impact on numerous activities and elements of our society involving many groups in all parts of the United States. The applied uses of the NMAM as cited in the previous section are important in encouraging the exploration and development of the mineral resources that this nation needs to maintain the quality of life in the face of present or impending national shortages of energy and other mineral resources. In addition, the NMAM will provide valuable geological information that can be used in environmental and siting problems across the country. The dollar value of the map cannot be estimated with meaningful accuracy. The experiences of other countries with similar programs are the best guides to the benefits to be expected.

L. W. Morley, Geological Survey of Canada, has made the following statement relative to the Canadian magnetic program (written communication, 1969):

"The Geological Survey of Canada, in combination with the provinces has already spent $12 M dollars on airborne magnetometer surveys and published over 5,000 maps. The complete cost of this program has been more than paid for by the government revenue derived from a single mine discovered, as a direct consequence of an aeromagnetic survey, in the second year of the program in 1949. This was the iron mine at Marmora, Ontario. How many mines were discovered indirectly by these maps would be very difficult to find out since every mining company uses them along with government geological maps. How the companies use them and what exploration tactics are employed are closely-guarded company secrets.

In the final analysis, one of the best ways to judge the worth of a product, such as a map, is to see how often and for how many years it is used and referred to. Many of the 5,000 aeromagnetic maps of Canada have been reprinted a second time after an initial printing of over 2,000, 20 years ago. It is fully expected that these same maps will find use 30 years from now."

A country-wide aeromagnetic survey recommended, designed and managed by the U.S. Geological Survey for Liberia was made with funds supplied by an AID loan. The geophysicist responsible for developing the use of these data in Liberia reports the following:

"The Government of Liberia contracted an 87,000 mile aeromagnetic and total count gamma radiation survey through funds supplied by a loan from the U.S. Agency of International Development. The cost was about $900,000. The survey was flown with NS lines spaced 0.5 miles over land and 2.5 miles over the continental shelf; flight elevation was 500 feet. The main purpose of the survey was to assist in a program of regional geologic mapping although mineral exploration possibilities were an important consideration. The survey took 2½ months to complete (November 1967-January 1968) and data compilation was completed about 15 months later. Preliminary forms of the maps were made available to oil companies interested in the offshore area and as a direct result of these data and interpretive reports open-filed by U.S.G.S., the Government of Liberia entered into oil lease negotiations with several companies. About three-quarters of the continental shelf area has been leased to date and signature bonuses and 1-year lease payments to the Government of Liberia have surpassed the entire cost of the survey.

The oil exploration area is only a small fraction of the total survey and mineral exploration is just commencing. At least one anomaly has been identified as an ultramafic intrusive body and shallow trenching by a company has already revealed evidence of nickel and cobalt, commodities not previously known in Liberia. Iron mining is the main industry of the country and the survey has extended by a large extent the known location of iron formation and will undoubtedly contribute to an increase in iron ore reserves. Many obvious targets for mineral exploration are indicated by magnetic anomalies in areas which otherwise would not have been easily identified. The survey has attracted the attention of the petroleum and mining industry and representatives of companies throughout the world are visiting the U.S.G.S.-

Liberian Geological Survey office to discuss the survey results on a weekly basis."

The information obtained from the NMAM program would greatly benefit both the government and the public as a whole. From a research standpoint the magnetic data would add a new dimension to our knowledge of the crustal structure of the United States. Hopefully, such knowledge would contribute to further studies of the occurrence of natural resources and may aid in the development of new mineral and energy sources.

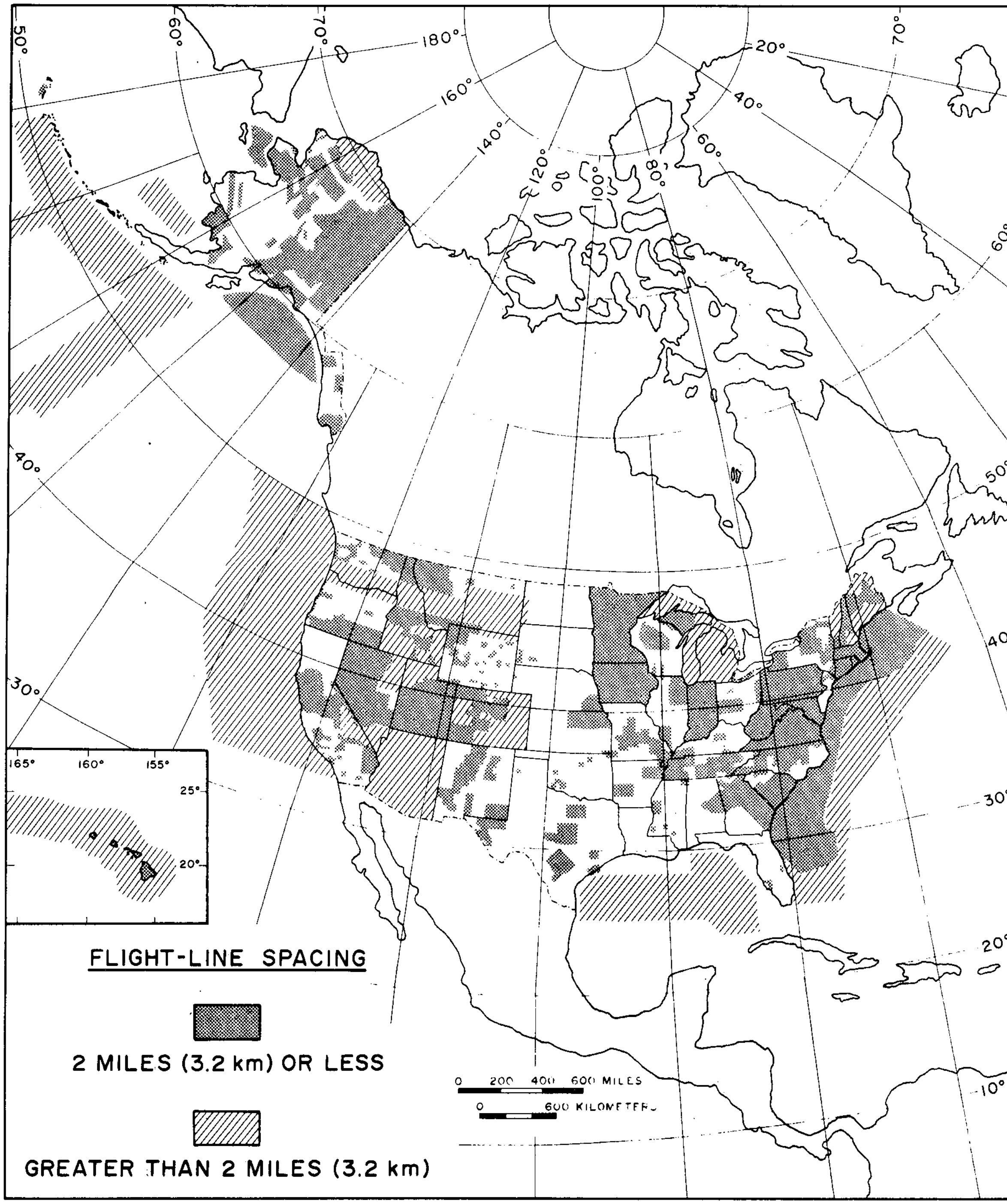

FIGURE 1. Magnetic Coverage of The United States.

CURRENT STATUS OF MAGNETIC ANOMALY MAPPING

Magnetic anomaly data of widely varying quality and track spacing are publicly available for approximately 50 percent of the U.S. These data have been primarily observed by the U.S. Geological Survey, with minor but significant contributions by other federal and state agencies, universities, and research organizations. Magnetic coverage of the U.S. and adjacent marine areas is shown on Figure 1. Approximately 4.1 M square km of the contiguous 48 states is covered by magnetic data (52 percent of total) and 4.7 M square km are available for the 50 states. Approximately 60 percent of these data was obtained at line spacings of less than 3 km with the balance obtained at spacings of up to 10 km. The private magnetic coverage of the U.S. that may be made available to the public is impossible to estimate, but perhaps some data may be released by private industry for up to one-half of the area currently not covered by public magnetic data.

About 75 percent of the available data was obtained with fluxgate magnetometers measuring only relative changes in the total magnetic intensity and the observations are in analog form. Approximately 75 percent of the U.S.G.S. controlled surveys west of the Mississippi River was flown at a constant barometric elevation. A comparable percent of surveys in the eastern U.S. was flown at either 150 or 300 meters above the ground. More than 90 percent of the magnetic coverage was obtained from aircraft flying either north-south or east-west flight tracks. The major exceptions are magnetic surveys of West Virginia and parts of several other southeastern states which were flown NW-SE. With the exception of the East Coast, marine magnetic data generally are derived from ship surveys with widely spaced track lines (30 km). Portions of the East Coast have a detailed aeromagnetic survey with sufficient accuracy to meet the specifications of the NMAM. Probably less than 10 percent of the total U.S. is covered by surveys meeting these specifications.

The only major magnetic survey currently underway in the U.S. today is a result of the National Aerial

Reconnaissance Survey being conducted by the Technology Development Division of ERDA. The principal goal of this survey is fostering the uranium production potential of the U.S. by delineating new exploration regions. As a result emphasis is placed on radiometric techniques and the survey is planned to maximize the quality of these methods. However, ERDA, realizing the potential benefits that can be accrued by combining magnetic observations with the natural radiometric survey, has included magnetics in the suite of parameters being measured. ERDA has worked closely with the Committee for a NMAM in setting standards and procedures for the magnetic observations. A list of recommendations to ERDA adopted at the Workshop is presented in Appendix III. This survey, which is scheduled for completion by January 1, 1980, will significantly improve an interim NMAM for only a modest expenditure (less than 1 percent of the total proposed budget), but will not serve the purpose of providing data for a high quality NMAM without a significant increase in the budget.

The experience gained from the Federal-Provincial Aeromagnetic Survey Program of Canada and the status of this program are germane to the U.S. NMAM program and future plans for a North American MAM. The present Federal-Provincial Aeromagnetic Survey Program since its inception in 1960 has compiled 7.5 M line kilometers of data including data observed prior to 1960 by the federal government. These data have played an important role in developing Canada's mineral resources and have had a considerable influence in promoting the use of the magnetic method overseas by Canadian contractors.

From the Canadian experience we derive the following conclusions which are helpful in planning a U.S. NMAM:

1) A constant set of survey specifications is highly desirable for the entire program.

2) A scale of 1:5,000,000 or 1:2,500,000 for the map permits the data to be depicted on one or two map sheets which illustrates regional geologic information and provides the explorationist with a means to look

for new concepts or geologic implications for resource discovery.

3) A series of map scales at regular intervals as now planned by the Canadian government is important to meet the diverse use of magnetic data.

4) When the U.S. NMAM is completed a North American MAM can be compiled including available Latin American magnetic data which will permit a broad-scale view of the North American continent and will complement other North American geoscience maps.

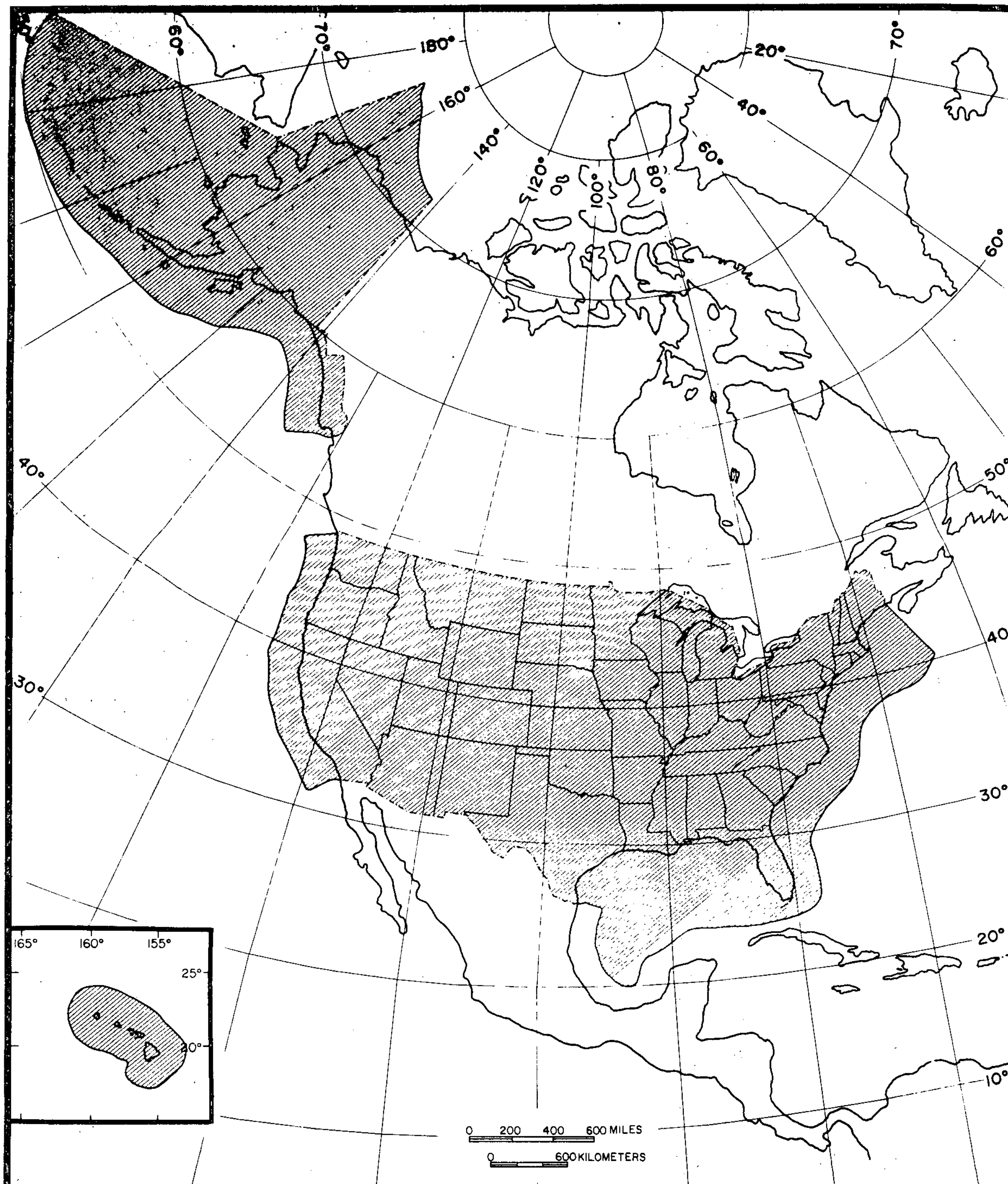

FIGURE 2. Proposed Aeromagnetic Coverage of The United States.

PROPOSED NMAM PROGRAM

The previously identified uses and potential benefits of a NMAM make it clear, particularly at this time, that the U.S. needs a NMAM program to prepare a map and related data set in the near future. Much of the publicly available magnetic data of the U.S. has limitations for the preparation of a NMAM because of inconsistencies and deficiencies in the surveying and reduction procedures of data collected over a 30 year period by a wide range of organizations and personnel. Inconsistent and low-quality data will seriously reduce the potential usefulness of the NMAM. Furthermore, magentic data obtained from the private sector and from present and planned national surveys designed for other purposes generally will not serve the ultimate goal of a NMAM. Therefore, a national magnetic survey is proposed as a basic element of the long-range objectives of the NMAM program. However, considering the length of time that is required to organize and conduct the survey and prepare the map and the urgency of preparing a NMAM, an interim NMAM is proposed, which in turn will be preceded by a photo-mosaic magnetic anomaly map of the U.S. These intermediate steps will provide information and data in a useful form for much of the U.S. and adjacent marine areas.

National Magnetic Anomaly Map

A NMAM should be prepared of the entire land area of the U.S. plus marine areas to a distance of approximately 200 km beyond the edge of the continental shelf in the Atlantic, Pacific and Arctic Oceans and should cover the Gulf of Mexico and Bering Sea approximately to the international boundaries as shown in Figure 2. In cooperation with the Canadian government, the NMAM should extend at least 10 km across the Canadian border to tie into existing and planned magnetic surveys in Canada. A similar arrangement should be made with the Mexican government in order to tie together the surveys of the two countries. In addition, aeromagnetic surveys of the U.S. should be calibrated over the Canadian calibration range in order to tie the surveys. Ultimately, a North American Magnetic Anomaly Map should be produced, but only when a consistent data set for the U.S. is available.

The consistent data set is defined as data taken at uniform specifications and reduced by a single set of procedures. The NMAM should be prepared primarily from a survey conducted over a continuous time span which has the following specifications:

Flight-line Spacing -	Average spacing of 2 km. May be reduced to 1 km in some areas and increased in other areas to a maximum of 5 km.
Flight-line Direction -	Perpendicular to geologic/magnetic grain where feasible.
Flight Elevation -	Mean terrain clearance of 300 meters with special considerations for mountainous areas and deep sedimentary basins.
Magnetometer Characteristics -	Sensitivity of 0.25 gammas with 2 gamma noise envelope in "hardrock" areas; 0.25 gammas with 1 gamma noise envelope in "softrock" areas. Total field measuring.
Positioning -	80 meters.
Diurnal Control -	Monitor temporal variations with a magnetometer ground station at the local base of operations to avoid flights during periods of magnetic disturbance. Level by intersections with tie line spacing of 1 in 10.
Figure of Merit (Magnetic interference due to aircraft) -	6 gammas absolute

Digital Data Tapes - Should contain:

- Total field
- Anomaly field
- Date, time, latitude, longitude
- Elevation - radar and barometric
- Line and other bookkeeping information
- Diurnal trace from ground station

Option - Consideration should be given to obtaining total radioactivity data in selected areas, and consideration should be given to utilizing new instrumental developments such as gradiometers, vector magnetometers, cryogenic magnetometers, etc.

The data should be compiled onto contour maps of scales of 1:250,000, 1:1,000,000 and 1:2,500,000. Other map scales could be developed to match state and national geologic maps as necessary. The basic contour interval on the 1:250,000 scale map should be 10 gammas with 2 gammas in low-gradient areas such as the Gulf Coast area. Other contour intervals should be used as necessary.

Interim NMAM

The optimum survey for the purposes of the NMAM described above will provide a consistent data set of sufficient detail and accuracy to meet the needs of the U.S. However, it is apparent even under the best of conditions that this map and data set will take several years to complete. In the interim, a temporary quasi-consistent data set should be prepared and a national magnetic anomaly map should be compiled and published at a scale of 1:250,000 from this data set. A quasi-consistent data set is composed of measurements taken at non-uniform specifications and reduced or processed by acceptable procedures to produce an equivalent data set. The source of this data set includes existing publicly available data held by the U.S.G.S., private industry data contributed to the program, and the aeromagnetic data currently being collected by ERDA as part of the National Uranium Resource Evaluation Program. Digital data from these sources and analog data converted to digital form will be processed to develop the quasi-consistent data set. The theory and technology are available to efficiently produce this data set. However, this data set does not meet the standards required of the NMAM previously described because of lower quality of much of the original data, generally inadequate flight line spacing, and inherent problems in converting analog to digital data. Despite the limitations of the interim NMAM and the quasi-consistent data set, these data will be of considerable use to the geoscience community.

Photo-mosaic NMAM

The geoscience community has considerable interest in an immediate NMAM even though it may be incomplete and prepared from inconsistent data. Therefore, it is recommended that a colored photo-mosaic of existing magnetic maps should be compiled at a scale of 1:1,000,000 and published at 1:2,500,000 with a consistent coloring scheme. The limitations of this map should be made clear to users and should include a warning that the map should not be reproduced at larger scales. The selection of data for this map is a subjective process, but every attempt should be made to use data consistent with surrounding data. All available data, including data acquired from private industry and released to the public, should be considered in the preparation of this map. The quality of the data should be graphically shown on the map and an overlay should accompany the map showing specifications of the various data sources. The photo-mosaic NMAM even with its limitations will serve the purpose of locating some of the major magnetic anomalies and tectonic trends of the U.S.

IMPLEMENTATION OF THE NMAM

The acquisition of a consistent data set and the preparation of the NMAM are major undertakings requiring the investment of considerable resources. In order to ensure that a NMAM meeting the required specifications will be prepared in a reasonable time frame, it will be necessary to explain the program and publicize the economic and scientific benefits of the map to gain the support required to complete the program. Meanwhile, advantage should be taken of available data for the preparation of a photo-mosaic map and of surveys planned or in progress that, together, can be used to prepare an interim NMAM. To effect the completion of the NMAM, a broad range of plans and estimates must be made by various groups and organizations. In this implementation section, the Committee for a NMAM proposes preliminary plans necessary to start the NMAM program.

Resources

The photo-mosaic NMAM will be compiled by utilizing currently available data from federal and state agencies, universities, and petroleum and mining companies. Data from petroleum and mining exploration industries will be solicited and acquired for the NMAM by the Committee. A sub-committee is already at work on this task and plans to achieve its goals by 1977. Currently available data are in a great variety of formats and have various track densities, altitudes above terrain, navigational accuracies, equipment sensitivities, field removals, etc. Criteria for selection of data to be used in compilation of a mosaic map must be carefully chosen to ensure that the map will be accurate and useful at the publication scale. An advisory committee will be appointed to develop criteria for the selection of data and to edit the map.

A number of surveys are planned or are in progress which can be used to improve the coverage and quality of the NMAM. Current surveys of the U.S.G.S., many in co-operation with other governmental agencies, meet the specifications necessary for producing a high quality NMAM. Detailed surveys are also being conducted by the

U.S.G.S. and others in ocean areas off the East Coast and these data will be available for incorporation into a high quality NMAM and the production of a consistent data set for detailed analysis.

ERDA is currently conducting a radiometric survey over the conterminous U.S. and Alaska to support the National Uranium Resource Evaluation Program. The survey aircraft are collecting magnetic data which will be incorporated into the interim NMAM. The basic survey is scheduled to be completed by 1980. Flights are conducted at a nominal 120 meters above terrain on an average track line spacing of 8 km but range from 3 to 20 km. The primary goal of the ERDA survey is to obtain radiometric data, as a result surveying is done on all days suitable for radiometric operations including days of high magnetic disturbance. Thus not all magnetic data obtained in this survey will be usable and gaps will occur in the data. It is anticipated that during the period of the ERDA survey, approximately 50 percent of the days will have undesirable temporal magnetic disturbances (k_p exceeding 1+). However, the Committee for a NMAM has made recommendations to ERDA in hopes of obtaining high quality magnetic data for the production of a quasi-consistent data set.

The Naval Oceanographic Office (NAVOCEANO) under its World Charting Programs plans to conduct a low-level ($\sim$ 450 meters) vector airborne survey of the U.S. with north-south tracks at 100 km spacing to update and improve the density of vector data for development of a more accurate world model. Total intensity data (sensitivity of $\sim$0.02 gamma) obtained in this survey could be used to help tie currently available data and data obtained in the future. This surveying may also tie into Canadian data to help implement a future North American magnetic anomaly map.

The National Aeronautics and Space Administration Ames Research Center also has the capability to conduct airborne vector magnetic surveys. Their most suitable aircraft available for this purpose is a CV990. This aircraft cannot operate efficiently below 6 km altitude, but vector surveys conducted at that altitude or higher would be useful in comparing with low-level NAVOCEANO vector data and the planned vector magnetometer satellite data for the development of a highly accurate mathematical model of the geomagnetic field over the U.S. This would allow for the development and removal of an accurate regional field for the NMAM.

To produce an anomaly map it is necessary to remove a regional or common reference field from all survey data. In preliminary photo-mosaic maps a variety of regional fields have already been used, primarily the International Geomagnetic Reference Field, Epoch 1965.0. Graphical methods of removal have been employed for many of the small area maps. It is impractical to attempt to remove a standard regional field in preparing the mosaic map because of the current status of these maps.

The Committee for a NMAM does not intend to specify a particular reference field at this time, but does reccommend that a mathematical model with coefficients of degree and order 12 or a new model derived from or "tuned" to the survey data be used in the preparation of the NMAM. A thorough analysis and understanding of the model should be achieved prior to its use. The development of a consistent data set will permit the removal of any regional field, thus providing the option of selecting the field on the basis of the intended use of the anomaly map.

A single national repository should be assigned the responsibility for maintaining the magnetic data files used in the compilation of the NMAM and for providing further distribution of data to requestors. The National Geophysical and Solar-Terrestrial Data Center (NGSDC) of NOAA, Boulder, Colorado, currently maintains data files of this type and is considered the most suitable agency for this purpose.

Estimated Cost

Much of the cost of the NMAM survey involves contracts let under competitive bidding. The cost of the surveying including basic data reduction and compilation is estimated at $6 per line kilometer, although this figure may be decreased by 10 percent or more because of the magnitude of the program.

The land area of the U.S. (excluding Hawaiian Islands and other islands) is approximately 9.3 M square km. On the basis of an average track line density of 2 km, the number of line kilometers of data necessary to cover this area is 4.7 M. Much of the coastal area extending approximately 200 km from the continental shelf plus the Gulf of Mexico could be covered by an average 5 km line spacing totaling approximately 1 M profile kilometers. Estimating that 10 percent of the total area is already covered by high quality data, the cost of the survey would be approximately $30 M. An additional 10 to 20 percent would be required for program management, publication costs, development and testing of regional field models, data handling by a national repository, and grant money available to government and university scientists for regional scientific studies. The grant money should be administered by a government agency, such as the National Science Foundation, with the advice and counsel of a committee of scientists with expertise in magnetic interpretation and related disciplines.

The cost of the interim NMAM and quasi-consistent data set can be estimated by considering that: 1) 40 percent of the U.S. is covered by data in analog form and thus must be digitized, 2) 10 percent is already in digitized form, and 3) 25 percent additional land coverage can be obtained from private industry largely in analog form. Using these resources the cost of the interim map covering 75 percent of the U.S. is approximately $0.6 M.

The photo-mosaic NMAM requires less processing of data, thus, its cost is considerably less than the above NMAM or the interim NMAM. The cost of this map covering approximately 75 percent of the land area of the U.S., will be approximately $135,000.

Thus the entire NMAM program that is proposed can be achieved for approximately $35 M distributed over a 10 year time span--a modest cost considering the potential value of the results.

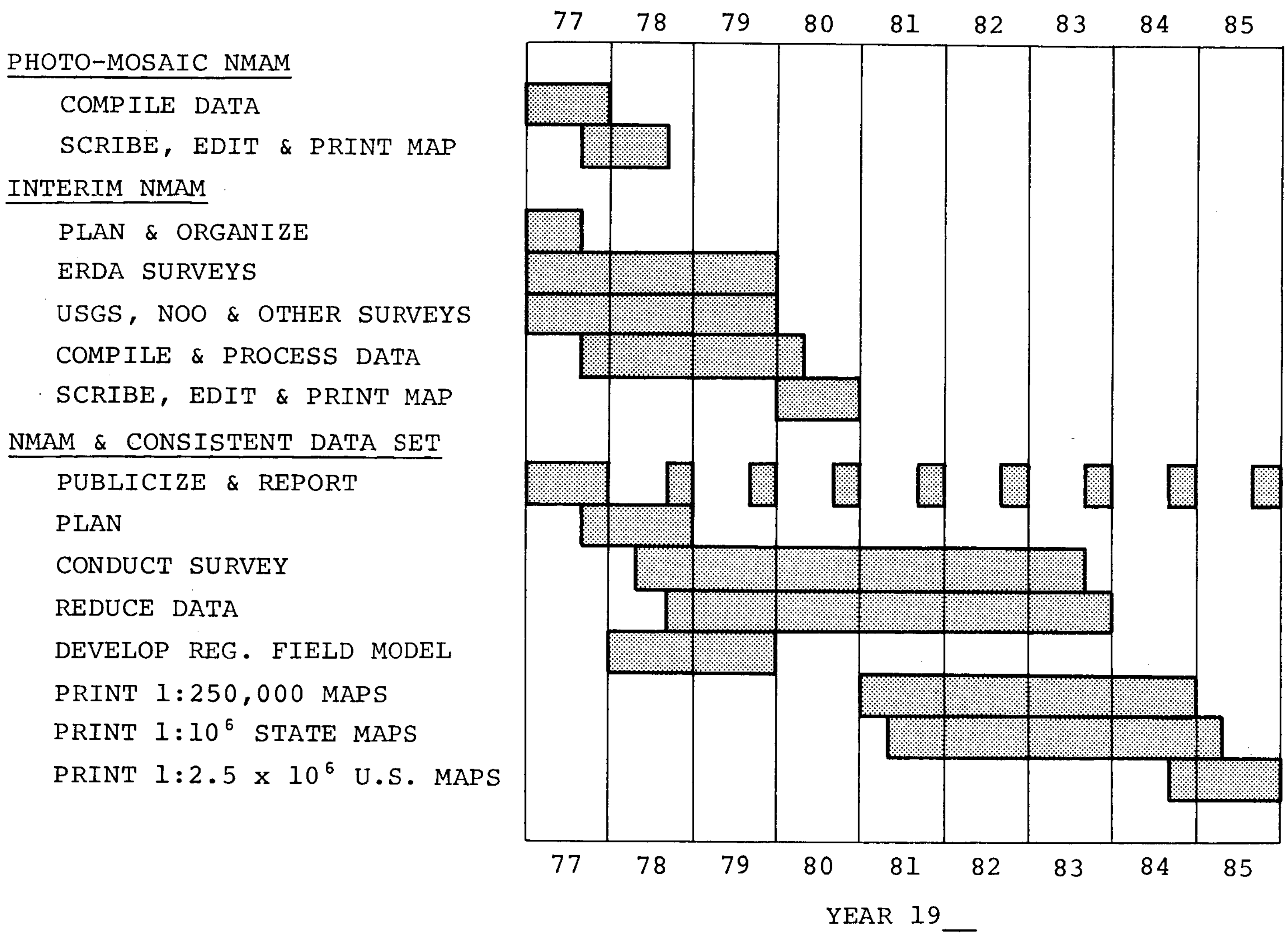

FIGURE 3. National Magnetic Anomaly Map: Time Schedule and Implementation Plan.

The participants of the NMAM Workshop were selected on the basis of their knowledge of magnetic anomaly map preparation and interpretation. Thus most discussions were concentrated on technical matters.

Effort must now be expended to develop the funding necessary for the NMAM program. The first step is to publicize the program to the geoscience community through appropriate journals and report on the results of the Workshop to a variety of organizations, soliciting their endorsement of the program and aid in carrying it out. It seems clear, that because of the magnitude of the program and the broad range of potential uses of the NMAM, that the major source of funding must be the federal government.

Program Time Schedule

The time schedule and implementation plan illustrated in Figure 3 must be regarded only as estimates subject to modification. It is anticipated that funding will commence in 1977 for all three phases of the program, but costs will be relatively low the first year. As illustrated in Figure 3, the publication of the three stages of the NMAM are estimated for 1978, 1981, and 1986. There are alternatives to this time schedule that may be considered depending on when funding is available and at what level. For example, if the NMAM survey is funded at a sufficiently early date at a high rate, it would be possible to complete that program by 1984. In that case the need for the interim NMAM should be re-evaluated; particularly the maps at scales larger than 1:2,500,000.

The level of funding anticipated over the 10 year time span of the program is shown in Figure 4. Expected expenditures start in 1977 at $0.5 M reaching a maximum of $6 M by 1980 and continuing through 1983 when the NMAM survey is completed. Funding levels decrease to $1 M or less for the final three years of the program.

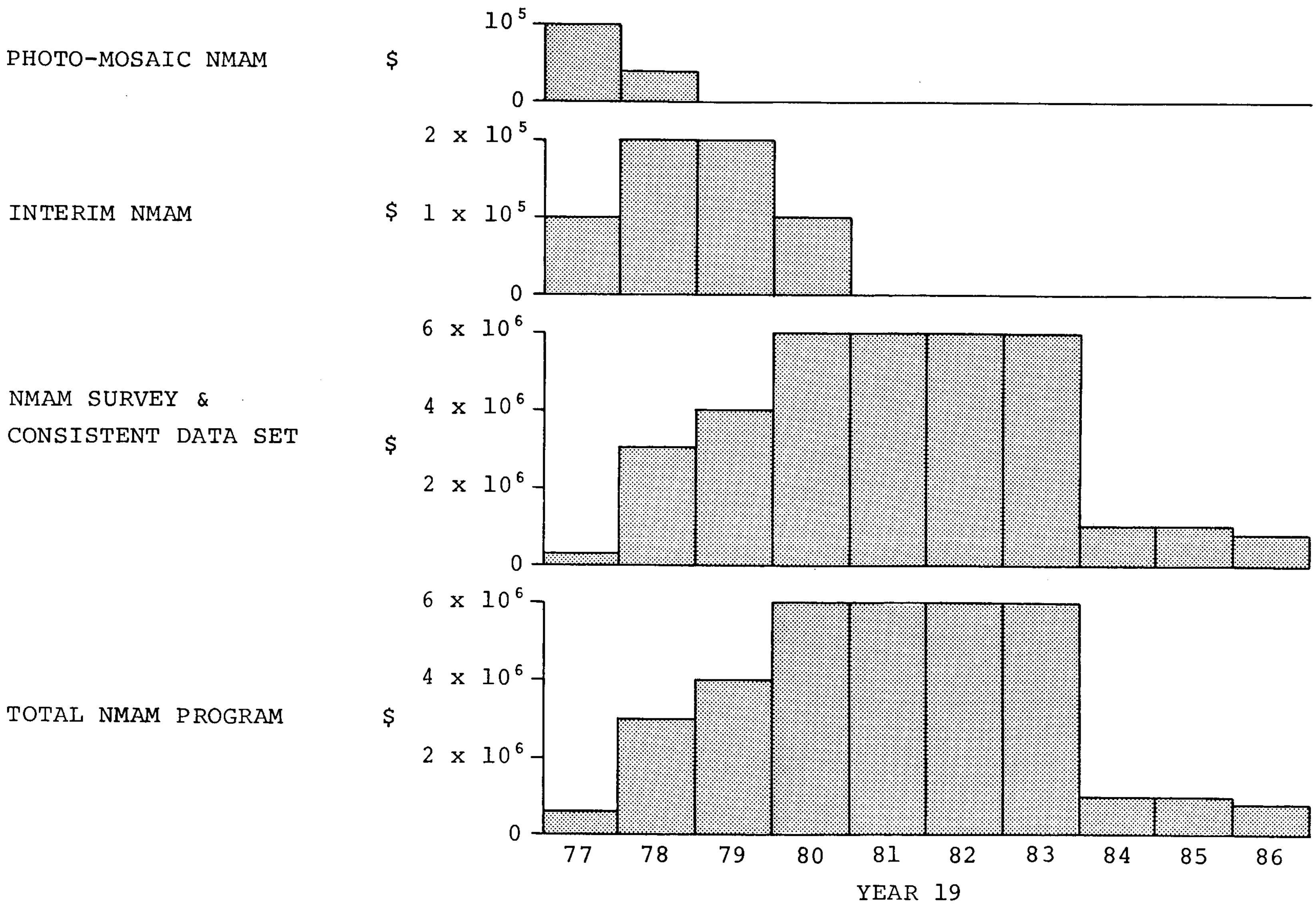

FIGURE 4. Estimated Funding Required for a Ten-Year National Magnetic Anomaly Map Program.

Advisory Committees

An editorial advisory committee is recommended to aid in selecting data and editing the photo-mosaic NMAM. A general NMAM advisory committee should be established to provide over-all guidance for the program and should advise the operating managers of the program on specifications, progress, priorities and related subjects. This committee should be representative of the geoscience community and should consist of specialists in both magnetic anomaly map preparation and interpretation.

APPENDIX I: Participants in the National Magnetic Anomaly Workshop, 17-19 February, 1976.

L. R. Alldredge	U. S. Geological Survey
J. C. Behrendt	U. S. Geological Survey
*J. W. Berg, Jr.	National Academy of Sciences
B. K. Bhattacharyya	U. S. Geological Survey
*J. C. Cain	U. S. Geological Survey
W. H Campbell	U. S. Geological Survey
*J. D. Corbett	Cities Service Minerals Exploration Corporation
*Phillip Dodd	Energy Research & Development Administration
*M. D. Fuller	University of California at Santa Barbara
R. H. Godson	U. S. Geological Survey
A. W. Green, Jr.	U. S. Geological Survey
*C. E. Helsley	University of Texas at Dallas
J. R. Henderson	U. S. Geological Survey
*R. H. Higgs	Naval Oceanographic Office
*W. J. Hinze	Purdue University
*P. J. Hood	Geological Survey of Canada
*E. J. Iufer	National Aeronautics and Space Administration
M. F. Kane	U. S. Geological Survey
*J. F. Landau	Gulf Research & Development Corporation
*P. L. Lawrence	Mobil Oil Corporation
D. R. Mabey	U. S. Geological Survey
*R. F. McMahon	Chevron Oil Company
*A. J. Navazio	LKB Resources Inc.
*M. S. Reford	Geoterrex Ltd.
*R. D. Regan	U. S. Geological Survey
*K. L. Svendsen	National Oceanic & Atmospheric Administration
R. E. Sweeney	U. S. Geological Survey
*R. J. Wold	U. S. Geological Survey
*I. Zietz	U. S. Geological Survey

*Member or associate of Committee for a NMAM; additional members not in attendance at Workshop: S. P. Gay, Jr. and J. R. Heirtzler.

APPENDIX II: Countries That Are Engaged In or Have Completed a NMAM Program of All or Major Parts Of Their Country.

Algeria
Argentina
Australia
Bolivia
Botswana
Brazil
Canada
Czechoslovakia
France
French Guiana
Great Britain
Guyana
Iran
Ivory Coast
Japan
Liberia
Nigeria
Surinam
Uruguay
U.S.S.R.
West Germany
Zambia

APPENDIX III: Recommendations to Improve the Quality of Magnetic Data on the ERDA National Airborne Reconnaissance Survey.

In order to insure that magnetic data collected on the ERDA National Radiometric Reconnaissance Survey are of the highest quality and of as wide-spread utility as possible the following recommendations are submitted.

A. Recommendations requiring only minor alterations of present programs

1. The general survey track orientation should be East-West in the contiguous United States and North-South in Alaska to aid in delineating the major magnetic features.

2. Total field intensity measurements should be made once each second at 1/4-gamma sensitivity. The magnetometer should be out of the influence of the aircraft's magnetic field.

3. Survey tracks should be limited to a length of approximately 200 kilometers, spaced no greater than 16 kilometers apart, with cross-ties on a ratio of 1:5. (The current plans call for 190 kilometer long tracks; the additional 10 kilometers of track should be surveyed as an overlap into adjacent survey areas to aid in producing a consistent data set.)

4. Both radar altimeter and barometric pressure data should be recorded in digital form so that complete control on altitude and terrain clearance can be obtained for subsequent upward continuation of the data to a common plane.

5. A calibration area should be established for determining the absolute accuracy of the installed magnetometer equipment. This should be supplemented by surveying an 8 to 10 kilometer base calibration line at the beginning and end of each survey flight and before moving to a new area. Also the frequency oscillator

of the proton precession magnetometer should be checked routinely with an external calibrated frequency reference and adjusted as necessary. The absolute values that should be achieved are:

Time: ±0.5 seconds
Position: ±65 meters
Total Intensity: ±5 gammas
Altitude: ±6 meters
Height above terrain: ±2 meters

B. Recommendations requiring some increase in scope of present program

1. Magnetic temporal variations should be monitored during each survey by establishing a magnetometer ground station at the local base of operations (airfield, regional office, etc.). These magnetometer base stations should be self-contained proton precession magnetometers with digital recording of total field intensity at 1/4-gamma sensitivity at 4-second intervals. (Costs: about $10,000/unit). These stations should be located as close to the survey area as possible, preferably no more than 300 kilometers from any survey track.

2. A more ideal method of monitoring the magnetic temporal variations would require the deployment of two magnetometer ground stations in each survey area. Stations should be located so that one is within 100 kilometers of any survey track. The units can be "leap-frogged" from one survey area to another as the survey progresses. This system, although highly desirable for determining the spatial coherence of magnetic temporal variations particularly in the auroral zone of Alaska, would require additional major expenditures. The initial capital investment for 6 survey teams with 12 base stations would be approximately $120,000, but may require an additional man in each survey team for maintaining and deploying the units - at a total additional cost of about $150,000 per year for 6 survey teams.

APPENDIX III

C. Recommendations requiring a significant increase in scope of the present program

1. In order to approach the goals of the National Magnetic Anomaly Map, the survey track spacing should not exceed 5 kilometers. This recommendation should be considered only if it is necessary to increase radiometric coverage because the cost of radiometric surveying is considerably greater than comparable magnetic surveys. Increasing the track density will be particularly valuable in areas where present magnetic coverage is limited and will be especially useful in producing an improved consistent magnetic data set.

2. The survey should not be flown during the periods of magnetic disturbance when the temporal variations exceed 3 gammas per minute (non-linear).

D. Data Format: Contractors should record all data in digital form with time (GMT) to the nearest second. The final data tape for magnetics should be separated from the radiometric data and should contain the following information

1. Survey Data
   a. Aircraft Identification Number
   b. Year, Julian Day, Hour, Minute, Second
   c. Best Geographic Position (Latitude and Longitude to the nearest 1/1000th of a degree)
   d. Total Intensity to nearest 1/4-gamma at 1-second intervals
   e. Altitude (barometric) to nearest 3 meters
   f. Height above terrain (radar altimeter) to nearest 0.5 meter.

2. Base Station Data
   a. Station Number
   b. Location of Station (Latitude and Longitude to nearest 1/1000 degree)

c. Year, Julian Day, Hour, Minute, Second
d. Total Intensity to nearest 1/4-gamma at 4-second intervals

E. Disposition of Data

Contracts should include the requirement that magnetic tapes of both survey and base station data as outlined in paragraph (D) above be furnished to:

National Geophysical and Solar Terrestrial Data Center
U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Data Service
Boulder, Colorado 80302

who will act as the National Repository for these data and will provide for further distribution to requestors.