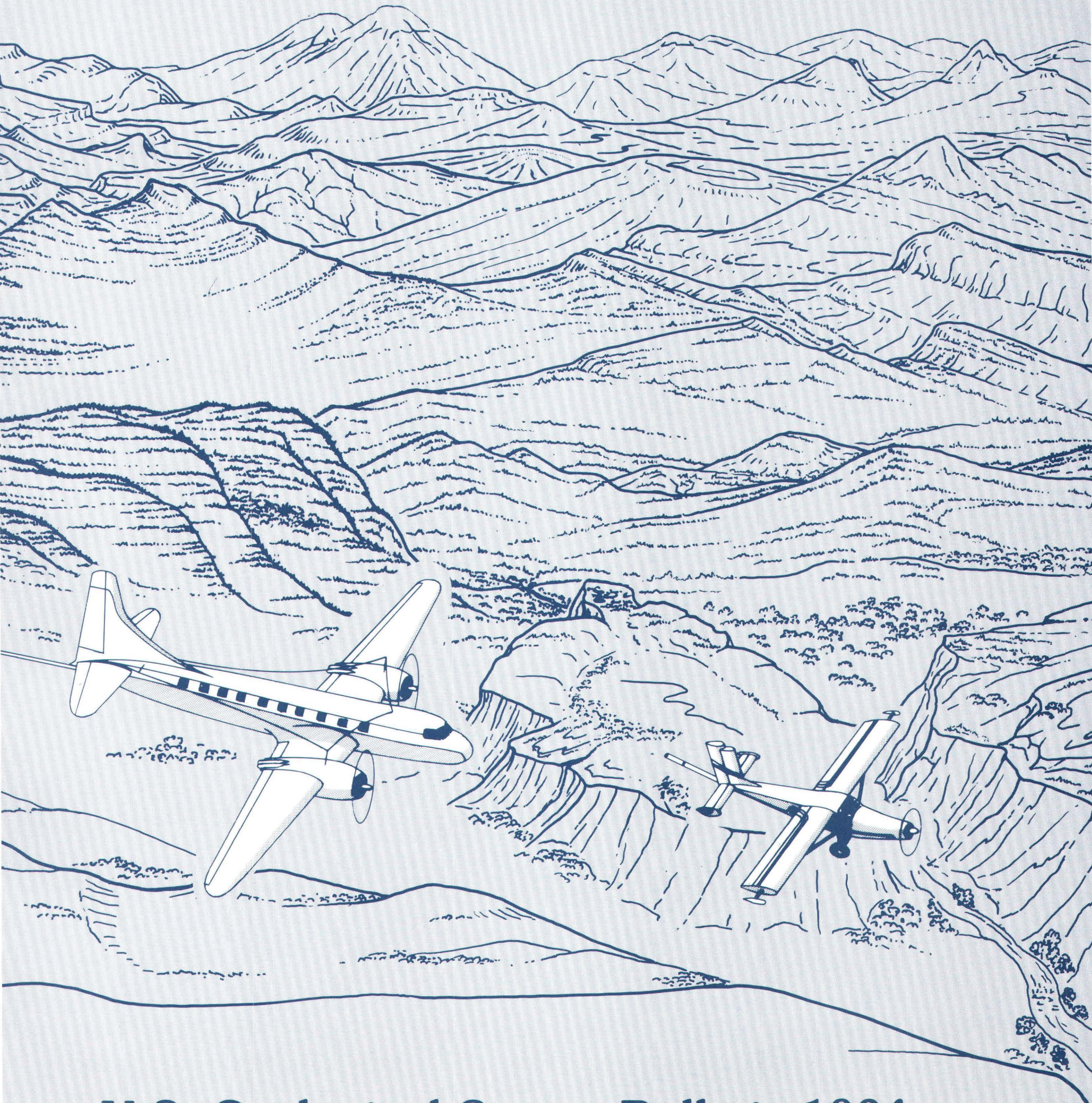
Geologic Applications of Modern Aeromagnetic Surveys



U.S. Geological Survey Bulletin 1924

Front Cover: Past and present U.S. Geological Survey aircraft used for geophysical surveys are depicted flying over terrain typical of the foothills west of Denver, Colorado. The aircraft, in order of age (from left to right), are Beechcraft Model 17, Staggerwing; Douglas DC-3; Convair CV-240; and Fairchild Porter PC 6/C-H2.

Cover design by Art Isom, U.S. Geological Survey.

Geologic Applications of Modern Aeromagnetic Surveys

Edited by WILLIAM F. HANNA

Proceedings of the U.S. Geological Survey workshop on Geological Applications of Modern Aeromagnetic Surveys held January 6-8, 1987, in Lakewood, Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1924

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1990

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

U.S. Geological Survey Workshop on Geologic Applications of Modern Aeromagnetic Surveys (1987 ; Lakewood, Colo.)
Geologic applications of modern aeromagnetic surveys ; proceedings of the U.S. Geological Survey Workshop on Geologic Applications of Modern Aeromagnetic Surveys, held January 6–8, 1987, in Lakewood, Colorado / edited by William F. Hanna.
p. cm. — (U.S. Geological Survey bulletin ; 1924)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:1924
1. Aeromagnetic prospecting—Congresses. 2. Geomagnetism—Canada—Congresses. I. Hanna, William F., 1938– . II. Title. III. Series.
QE75.B9 no. 1924
[TN269]
557.3 s—dc20
[662'.153] 90–3272
CIP

FOREWORD

A workshop entitled "Geologic Applications of Modern Aeromagnetic Surveys," sponsored by the U.S. Geological Survey, was conducted January 6–8, 1987, at the Sheraton Hotel Conference Center, Lakewood, Colo. Because of severe constraints on time, space, and budget, attendance at the workshop was restricted to invited members of academia, private companies, National laboratories, and State and Federal governmental agencies. The workshop was originally promoted on short notice by the late Frank C. Frischknecht, in concert with Thomas G. Hildenbrand, Lindreth E. Cordell, and Gary L. Raines. Hildenbrand, who inherited the administrative responsibilities of Frischknecht, subsequently spearheaded a major effort to promote airborne electromagnetic and remote sensing techniques as well, in later workshops dedicated to these methods. Thus, this proceedings volume on the magnetic technique is one of three such workshop volumes documenting the value of and the need for a national aerogeophysical program. A list of attendees for the present workshop and their respective affiliations is provided in Appendix A.

The first half of the workshop was devoted to oral presentations made by a select number of participants; the second half was devoted to working group sessions identified by geographic area or by topic and involving all participants. Titles of presentations and the compositions of working groups are summarized in Appendix B. Although this proceedings volume does not include narratives for all presentations made during the workshop, it does contain a few additional reports relevant to the subject of the workshop.

The motivation for the workshop was based on the strong commitment of the U.S. Geological Survey to develop knowledge about efficient techniques for assessing mineral, fuel, and ground-water resources as well as geologic hazards. Some of the most efficient of these techniques are those which utilize airborne systems because of speed of coverage and almost unlimited accessibility. The subject workshop focused on a technique that has a proven track record and that has been extensively developed, utilized, and promoted by the U.S. Geological Survey over a 45-year period: aeromagnetic surveying.

Many advances have been made since the original implementation of aeromagnetic surveys, some of which relate to development of new instrumentation and others of which relate to the formulation of new concepts that bear on data acquisition, processing, interpretation, and display. Some of these current and emerging technologies were highlighted in presentations made during the workshop; others were discussed in working group sessions or were addressed informally in conversations among workshop participants.

William F. Hanna

Editor

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INTRODUCTION

Need for Aeromagnetic Data and a National Airborne Geophysics Program

By Thomas G. Hildenbrand and Gary L. Raines

The U.S. Geological Survey (USGS) pioneered airborne geophysical exploration (Hanna, this volume). In 1943 James R. Balsley, a USGS geophysicist, recognized the potential importance of a magnetic airborne detector (MAD) for geophysical exploration. This device, which was developed by the Navy to detect submarines, utilized a self-orienting fluxgate magnetometer. In 1944, after a few modifications were made to the MAD system, the USGS flew the first airborne geophysical survey; 10,000 line miles of magnetic data were collected over Naval Petroleum Reserve 4 in the northernmost part of Alaska. In the following 44 years, airborne geophysics evolved into a major component of earth science. Today aircraft are capable of acquiring a wide variety of critical geophysical data (for example, gravity, magnetic, electromagnetic, radiometric, spectral, and thermal), which are critical to solving National resource, environmental, and geologic hazards problems.

Historically the USGS has conducted (fig. 1) or contracted with private industry to conduct airborne geophysical surveys that involve the yearly collection of thousands of line miles of data (fig. 2). A disturbing trend in the number of line miles flown has occurred, however, over the past 13 years. The USGS has progressively decreased its geophysical data collection effort from 150,000 line miles in 1975 to less than 1,000 line miles in 1988. This proceedings volume stresses the utility of airborne geophysical data and thus the need for a national airborne geophysics program to reverse this trend in USGS data collection by systematically acquiring geophysical data to address important National needs.

Manuscript approved for publication, December 13, 1989.

OTHER NATIONAL AIRBORNE GEOPHYSICS PROGRAMS

Canada, Finland, the U.S.S.R., Zimbabwe, Liberia, and Australia have established cost-effective national airborne geophysics programs. For example, Canada has collected over 6 million line miles of magnetic data, published over 9,500 aeromagnetic anomaly maps, and distributed for many years 30,000 aeromagnetic anomaly maps per year (the most requested item of the Geological Surey 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 and its overall cost has been recovered many times over the years through 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" (Hood, this volume). In Finland, magnetic and electromagnetic data have been collected at a flight-line spacing of ¼ mi for the entire country. Their national airborne geophysics program includes reflying their country at a flight-line spacing of ⅛ mi.

In comparison, the average flight-line spacing in the United States (fig. 3) is about 3 mi, which is inadequate for most interpretational needs. In figure 4, the amount of information that can be derived from aeromagnetic data along flight lines spaced ¼, 1, and 3 mi apart is shown for a small area in Minnesota. The 3-mi-spaced magnetic data show only broad features with little structural information. The 1-mi-spaced data hint, for example, of structures that trend northwest. Clearly the ¼-mi-spaced data provide a greater wealth of information essential to the interpretation of lithologies and structures in this area, particularly the northwest- and east-trending mafic dikes.

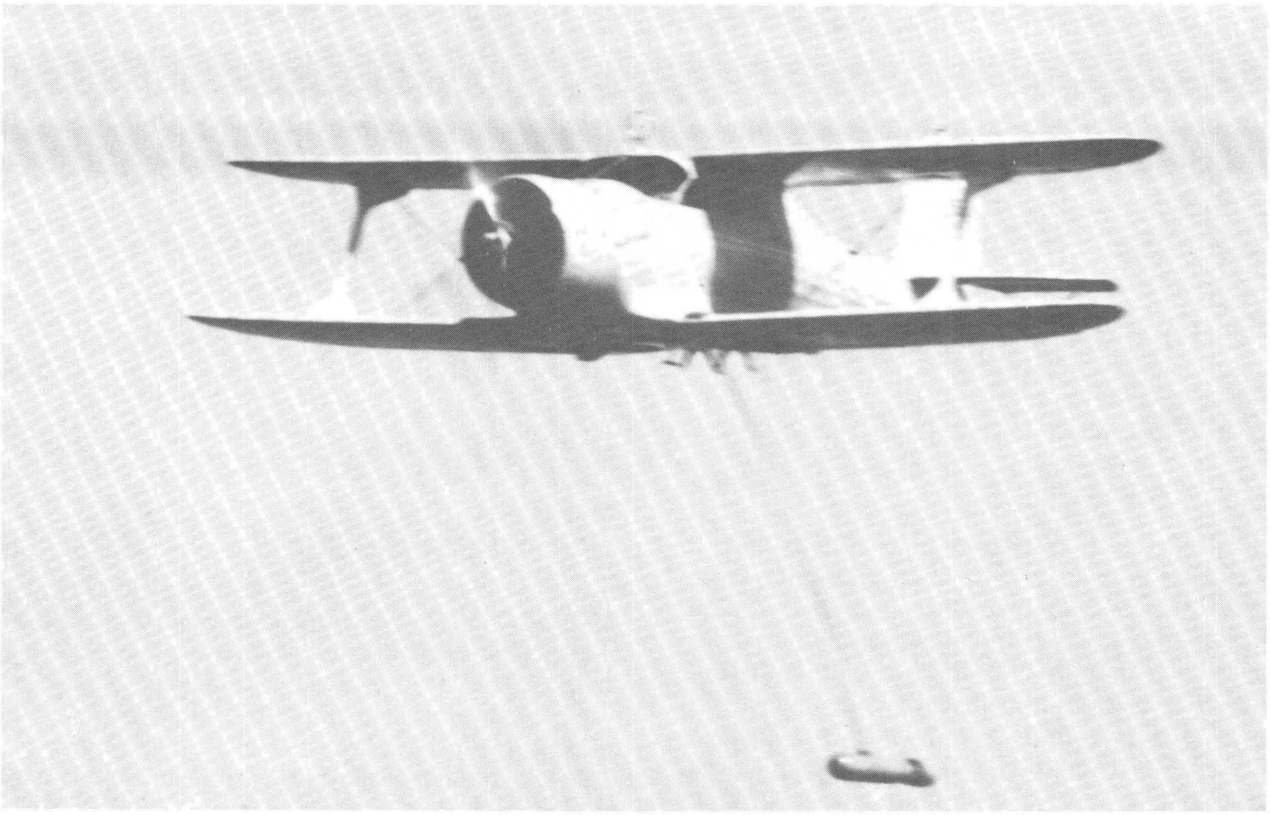

Figure 1. Biplane flown by the U.S. Geological Survey in 1947 to collect magnetic data. Towed "bird" contained fluxgate magnetometer.

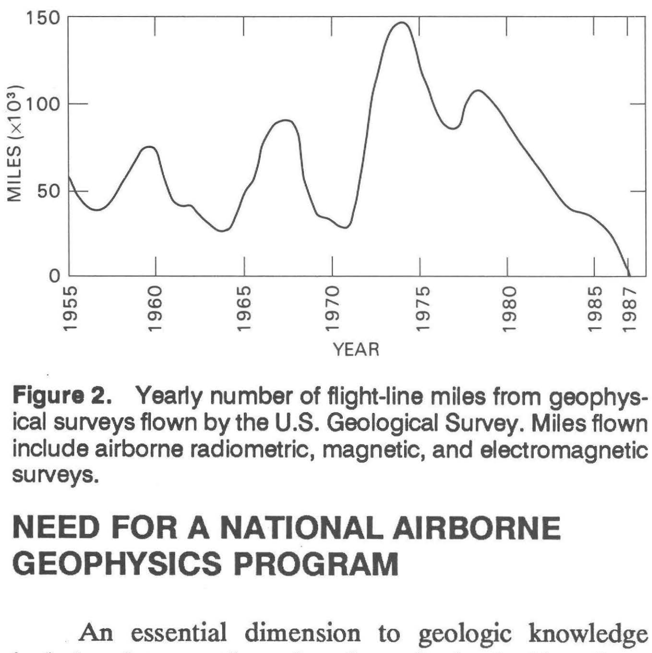

Figure 2. Yearly number of flight-line miles from geophysical surveys flown by the U.S. Geological Survey. Miles flown include airborne radiometric, magnetic, and electromagnetic surveys.

NEED FOR A NATIONAL AIRBORNE GEOPHYSICS PROGRAM

An essential dimension to geologic knowledge includes data on the subsurface obtained either from extrapolation of surface geology or from direct measurement by geophysical methods. Exploitable mineral and ground-water resources occur at depths that range from 1 ft to a few thousand feet. Petroleum resources generally occur at greater depths (as deep as a few miles). Geologic hazards such as landslides and volcanic eruptions are associated with processes that may occur over an even greater range of depths.

High-quality maps that are derived from surface geologic observations are important and necessary for many purposes. Commonly it is possible to extrapolate surface geology into the near subsurface with adequate accuracy. Nevertheless, the time has long since passed when surface geologic mapping alone meets most needs. Vast parts of the United States are covered by surficial deposits that prevent observation of the bedrock. Surface exposures of flat-lying rocks in the Midcontinent and elsewhere provide few clues about underlying structures.

Most geologic information is obtained from studies at scales that range from 1:24,000 to 1:250,000. For investigations at these scales, airborne geophysics provides a more universal approach to subsurface investigations than any other type of method. There are several reasons for the broad capabilities of airborne methods:

(1) Aircraft are suitable and commonly optimal platforms for acquisition of critical geophysical data, including data on potential fields (magnetic and gravity) and electromagnetic fields. Electromagnetic field data include audio, very low and radar frequencies to thermal and near infrared

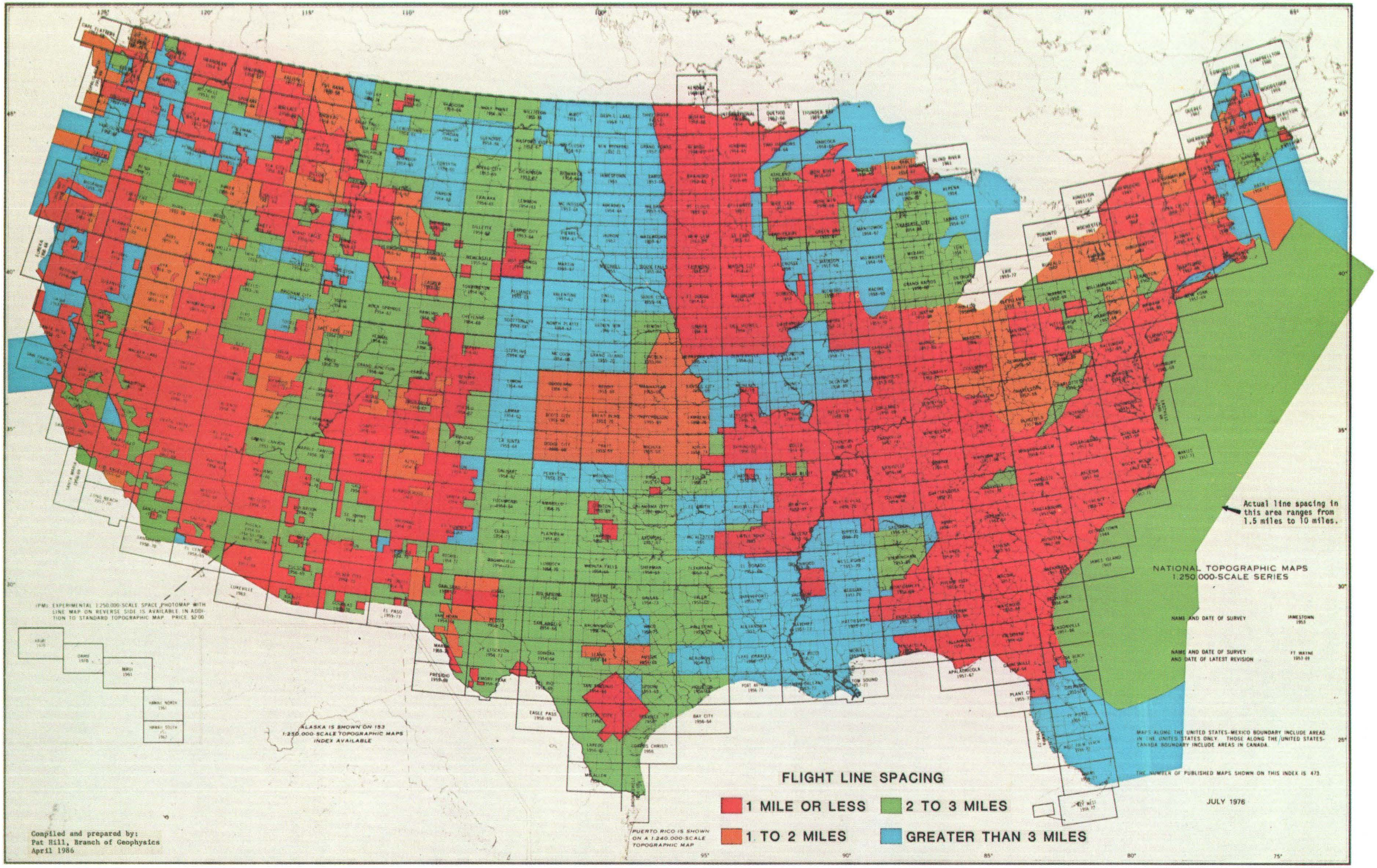

Figure 3. Aeromagnetic coverage map of the conterminous United States, showing the best flight-line spacing from geophysical surveys flown prior to April 1986. Compiled by U.S. Geological Survey, 1986.

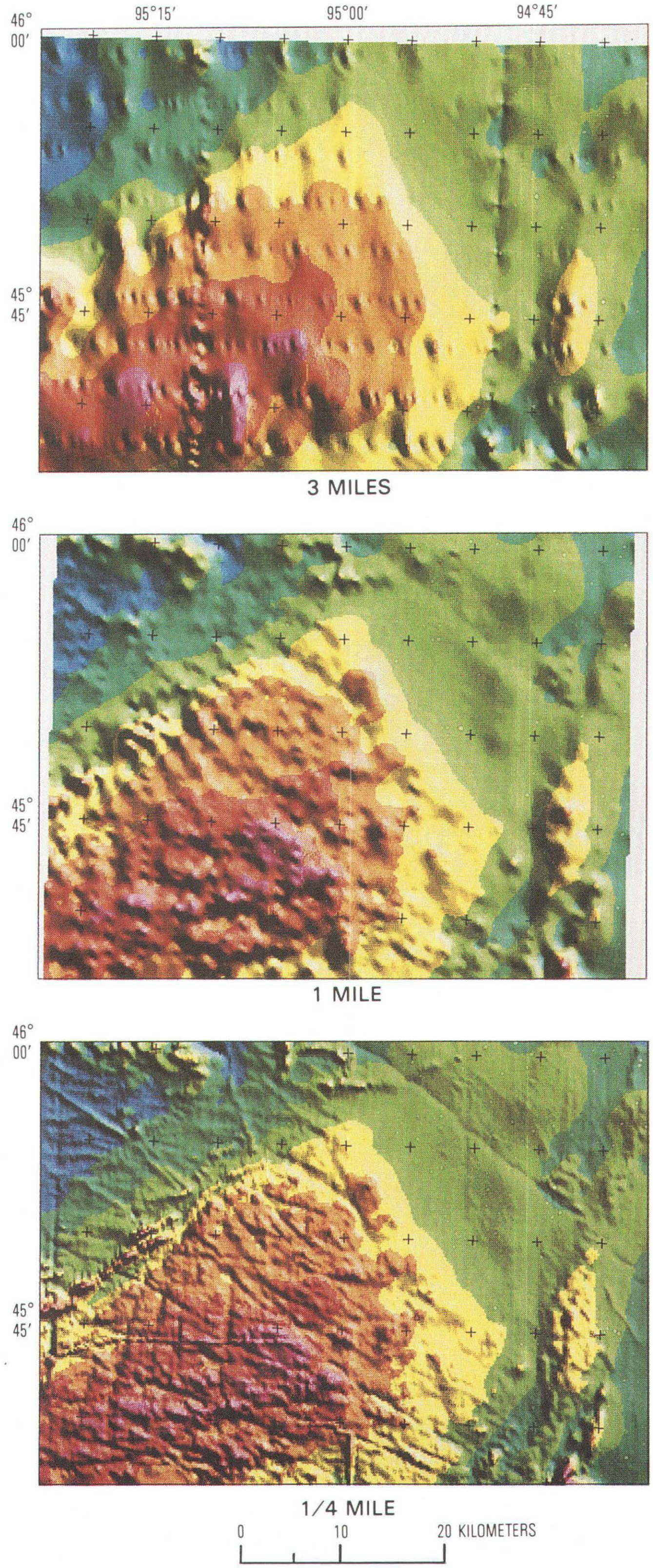

Figure 4. Interpretive resolution versus flight-line spacing. Shaded aeromagnetic anomaly maps (illuminated from the northeast) shown at three flight-line spacings from surveys of the same area in central Minnesota (magnetic-field intensities increase from green to red). The 3-mi-spaced data set (top) was compiled from the National Uranium Resource Evaluation (NURE) aeromagnetic survey, which was flown at a spacing of 3 mi and at 400 ft above the ground. The Minnesota Geological Survey, with funding from the Legislative Commission on Minnesota Resources, conducted an aeromagnetic survey of the same area at a flight-line spacing of ¼ mi (bottom) and at 450 ft above the ground. The aeromagnetic anomaly map from 1-mi-spaced data (middle) was derived by using every fourth flight line of the ¼-mi-spaced data.

frequencies, and visible-light and gamma-ray spectra. Some sensors can be used simultaneously, thereby obtaining information on surface and subsurface variations of several rock properties in a single survey.

(2) The horizontal resolution of data obtained by low-flying aircraft is more than adequate for mapping at scales as large as 1:5,000. Images of large swaths can be obtained in a single pass by high-flying aircraft for small-scale mapping. Through use of several sensors, information is obtained over a continuum of depths from the surface to tens of miles below the surface.

(3) Aircraft data are now collected in digital form and are thus suitable for immediate computer processing, analysis, and display by geographic information systems. The results form a uniform and consistent data set that can be accessed and reinterpreted as often as needed to provide information on new problems or as geologic concepts change.

(4) Data can be collected by aircraft over areas that are inaccessible on the ground because of natural causes, such as rugged topography, or man-made causes, such as restrictions imposed by private ownership.

(5) Airborne geophysics is very cost effective when applied to large areas. Generally no other set of ground-based methods can supply equally useful information at such low unit costs.

The importance of airborne geophysics was recognized in past decades as can be seen by the relatively large data-acquisition programs of the USGS during 1950–1980. Twenty or thirty years ago the rate of acquisition of aeromagnetic data far exceeded USGS capabilities to interpret and fully utilize the data. Now, however, airborne data acquisition by the USGS is at an all time low and available data are seriously inadequate.

Rejuvenation of airborne studies is timely both in terms of unsatisfied need for subsurface information and new technological developments which greatly enhance the capabilities of the various methods. Recent improvements in sensors offer order-of-magnitude improvement in resolution (both spectral and spatial) over the best devices available a few years ago. Improvements in electronic navigation for aircraft from the Global Positioning System will be operational in the near future.

In coordination with government agencies, academic institutions, and private industry, the long-term goal of a national airborne geophysics program should be to obtain systematic, digital airborne geophysical data for the United States. Data acquisition should focus on the needs of National programs, including mineral and organic fuel assessments, earthquake and volcano hazards, and environmental issues.

KEYNOTE PAPERS

Aeromagnetic Survey Program of Canada, Mineral Applications, and Vertical Gradiometry

By Peter J. Hood[1]

Abstract

A regional aeromagnetic program has been carried out in Canada for the past 40 years and now covers about 60 percent of the land area and a considerable portion of the surrounding continental shelves. The basic specifications utilized throughout have been to fly at a 305-m mean terrain clearance along flight lines spaced 805 m apart. In the mountainous areas of the country the survey technique utilized is to fly a given area at a constant barometric elevation. This procedure results in contour maps that retain the continuity of the total-field contours between the survey areas flown at different heights, albeit with some loss of detail.

The areas surveyed include the economically important greenstone belts of the Canadian Shield which comprise about 25 percent of the area and most of the mineral deposits of the Superior Structural Province. The aeromagnetic program has been credited with a prime role in a number of mineral discoveries in the shield and elsewhere in Canada. These include, in addition to the direct discovery of iron ore, a pathfinding role in the discovery of massive sulphide deposits of the base metals, which commonly contain the magnetic mineral pyrrhotite. In recent years, magnetic survey results have also been of great assistance in gold exploration programs, particularly in delineating the underlying geology in the vast drift-covered areas of the Canadian Shield which commonly have minimal outcrop. Alkaline syenite-carbonatite complexes, which may contain niobium and tantalum mineralization, are easily recognizable because they usually generate bulls-eye magnetic anomalies. On the continental shelf of eastern Canada, reconnaissance aeromagnetic surveys have successfully delineated areas underlain by sedimentary rock with hydrocarbon potential.

Vertical gradiometer techniques have been developed by the Geological Survey of Canada to provide more definitive aeromagnetic survey coverage, which is used in detailed geological mapping programs, many at 1:20,000 scale. The Geological Survey of Canada initially built its own inboard fixed-wing system on a Beechcraft Queenair aircraft using optical absorption magnetometers in the early 1970's. A substantial experimental survey program was then carried out to demonstrate the efficacy of the gradiometer technique before a technology transfer was made to airborne survey contractors. More recently the Geological Survey of Canada has fostered through research and development contracts the development of helicopter-borne towed-boom systems for use in mountainous terrain. The results in such rugged areas as the Gaspe Peninsula of southeastern Quebec have demonstrated the success of this new airborne geophysical survey technique.

PREVIOUS WORK

In 1947, aeromagnetic surveys were commenced by the Canadian Federal government as an aid to both geological mapping and mineral exploration programs. For a number of years the Geological Survey of Canada (GSC) operated its own survey aircraft, and during the 10-year period 1947–1956, inclusive, an average of 40,000 line miles were flown each year. During this period of time the value of the aeromagnetic survey technique as a geologic mapping tool for the Canadian Shield was clearly demonstrated; in addition the program received a considerable psychological boost in the early years as a result of the discovery of a 20-million-ton iron deposit at Marmora, Ontario, beneath 120 ft of Ordovician limestone. This aeromagnetic survey was flown by Aero Service, Inc., in 1949 and was jointly funded by the GSC and the Ontario Department of Mines. Lang (1970) carried out a cost-benefit analysis of the Marmora discovery and estimated that the 1949 aeromagnetic survey cost about $45,000, whereas production and reserves at the Marmoraton property to the end of 1969 amounted to $198 million. Lang stated that this figure of $198 million was much more than the total expenditures by the GSC from 1842 to 1969!

[1]Geological Survey of Canada, Ottawa, Ontario, K1A 0E8.

The prime area of interest in the execution of the Canadian aeromagnetic survey program was the well-mineralized part of the Canadian Shield which surrounds Hudson Bay. The shield area is in general quite flat because the rocks have been eroded for millions of years both by the normal process of weathering and to a considerable extent by the various glaciers that have occurred throughout geologic time.

In 1960, the need for an accelerated aeromagnetic survey program became increasingly apparent to the Director of the Exploration Geophysics Division, Dr. L.W. Morley, and led to a combined Federal/Provincial aeromagnetic survey plan being proposed in which the cost was shared equally between the Federal government and the various provinces. In retrospect it is clear that the timing of the proposal was propitious for the following reasons (Hood and Ready, 1976):

(1) The aeromagnetic method had become an established survey technique which could be carried out by contract survey companies for a reasonable price. In addition, the survey industry was actively seeking Canadian government work to provide some stability in their operations and thus to ensure a continuing Canadian airborne geophysical survey capability. It is of some interest that the Canadian airborne geophysical survey industry subsequently grew to become the largest in the world in terms of overall capabilities and was consequently able to obtain a large proportion of international business.

(2) A pilot program had been carried out by the GSC itself which demonstrated the value of the aeromagnetic survey technique as an aid to geologic mapping and to mineral exploration. Thus, because the GSC had a cadre of personnel who were themselves technically competent in the technique, it was possible to draw up an objective set of contract specifications and subsequently to ensure that these specifications were adhered to through field and office inspections.

(3) It was anticipated that government-funded surveys of the Canadian Shield would provide an orderly, standardized coverage with common specifications in comparison to that which would result if the surveys were carried out by various private mining companies; in any case, the end products of such surveys by private companies would remain proprietary. It was also recognized that standardized coverage would permit large areas to be compiled in order to produce regional aeromagnetic survey maps.

(4) Outside agencies both in the private sector and in the provincial governments were enthusiastic about the proposed aeromagnetic survey program.

At the 1960 Mines Ministers Conference held in Quebec City the resolution to proceed with the present Federal-Provincial aeromagnetic survey plan was unanimously approved. The aeromagnetic survey of the Canadian Shield proceeded as planned, and the rate of survey flying jumped 8.5 fold from 40,000 line miles per year prior to 1958 to 340,000 line miles per year after the inception of the program. However, a number of factors combined to reduce the average production rate to a lower level of 165,000 line miles per year in subsequent years. These factors included the poorer operating and weather conditions in northern Canada, where the later surveys were conducted; fewer landing strips in northern Canada, which increased the percentage of nonproductive flying; the fact that the magnetic diurnal variation is generally much greater in northern Canada due to the auroral zone; and the fact that there was a high rate of inflation, which gradually increased the cost of the surveys due to a cost-of-living factor that was included in the payment schedule. Because the amount of money budgeted for aeromagnetic surveys remained essentially constant until 1978, the rate of production of aeromagnetic maps decreased inversely as the cost-of-living factor increased. In 1978, the budget for aeromagnetic surveys was halved, and this caused a further reduction in the rate of data acquisition.

The Federal/Provincial aeromagnetic survey program appears to be more generally approved of by the mineral exploration industry than any other recent Canadian government program. The data from these surveys are much used in the planning of mineral exploration programs (Roth, 1975). The aeromagnetic survey program is credited with a prime role in a number of discoveries in Canada and a lesser role in others (Pemberton, 1966). Most mineral deposits are located in the so-called greenstone belts which are fairly readily delineated by aeromagnetic surveys because the belts produce regional magnetic lows (Morley and others, 1967; Grant, 1985). The greenstone belts comprise about 25 percent of the area of the Superior structural province; thus, 75 percent of the area of the Superior Province may be eliminated as nonmineralized and nonprospective by carrying out aeromagnetic surveys. The delineation of iron formation is relatively easy from aeromagnetic surveys, and there are many iron-ore discoveries; for example, in Ontario alone, deposits were delineated at Agwa, Briarcliffe, Bruce Lake, Kakabeca Falls, Lake St. Joseph, and North Spirit Lake. In addition, because there appears to be a close relationship between the occurrence of sedimentary iron formation and stratiform massive sulphide deposits in a sea-floor spreading environment (Stanton, 1976; Grant 1985), a follow-up survey of distinctive anomalies on aeromagnetic maps in such areas has led to significant discoveries, such as the Brunswick No. 12 orebody in the

Bathurst mining camp (Ward, 1958). Moreover, because pyrrhotite has very strong magnetic properties, base-metal sulphides that contain significant amounts of pyrrhotite will also produce distinct magnetic anomalies; these anomalies appear to be more prevalent on the aeromagnetic maps of the Canadian Shield than was expected. In British Columbia, aeromagnetic anomalies ultimately led to the discovery of the Island copper mine in northern Vancouver Island and the Cariboo Bell copper mine in the intermontane zone.

Alkaline syenite-carbonatite complexes, which may contain niobium and tantalum mineralization, generate circular to elliptical magnetic anomalies (Dawson, 1972). The recognition of such features on aeromagnetic maps led to the discovery of the Big Beaverhouse, Schryburt Lake, and Alpha-B alkaline complexes in Ontario. In addition, the Memegos and Lachner Lake alkaline syenite-carbonatite complexes in Ontario and the St. Honore complex in Quebec were all identified by aeromagnetic surveys.

The major geological benefit of the regional aeromagnetic survey of the Canadian Shield has been the outlining of the major units and a better understanding of the tectonic history of the shield, which has resulted in a refinement of the boundaries of the various age provinces. Much of the Canadian Shield is covered with glacial overburden, which was deposited during the last ice age, and about 30 percent of it is covered by lakes. Thus, the percentage of outcrop available to the geologist is commonly less than a few percent of the total area. With the use of aerial photographs and aeromagnetic maps, the geologist can prepare a preliminary geologic map that can be used to plan geological traverses and, in general, to carry out field work efficiently. The location of geologic contacts can usually be more accurately estimated using aeromagnetic contour maps, especially where outcrops are sparse. Consequently, the aeromagnetic survey data have been of great benefit to the geologic mapping program of the GSC.

In concluding this summary of previous work, it should be recognized that the Canadian Federal/Provincial aeromagnetic survey plan has also had a considerable influence in promoting the use of the method overseas. Consequently the so-called Canadian specifications for aeromagnetic surveys have been adopted for many overseas surveys, and this has helped the Canadian airborne geophysical survey industry to obtain a considerable amount of overseas work. In addition, aeromagnetic surveys funded by the Canadian International Development Agency (CIDA) were carried out in Botswana, Brazil, Cameroon, Guyana, Ivory Coast, Lesotho, Mali, Niger, Nigeria, Pakistan, Upper Volta, and Zimbabwe by Canadian companies on behalf of the national geological surveys of these countries or equivalent organizations.

AEROMAGNETIC SURVEYS IN THE MOUNTAINOUS REGIONS OF CANADA

The mountainous regions of Canada generally border the coastal areas, such as the northern coasts of Baffin Island and northern Labrador and the Cordillera of western Canada. These mountainous areas have posed special problems in aeromagnetic surveying because (1) it is generally impossible to conduct drape-flown surveying, even using Short Takeoff and Landing (STOL) fixed-wing aircraft; (2) it is difficult to maintain a constant elevation over the steep terrain; and (3) safety considerations are more restrictive here than over flatter terrain.

In the early 1970's, the GSC contracted out helicopter-borne aeromagnetic surveys in southern British Columbia, but the resultant cost was rather excessive, and alternative techniques using fixed-wing aircraft were sought. In 1973, a test was carried out in the Kamloops area of British Columbia over an area where the mountain peaks reach an elevation of about 1,830 m (6,000 ft). An aeromagnetic survey was flown by the GSC at a constant barometric elevation (CBE) of 1,980 m (6,500 ft) using its twin-engine Beechcraft Queenair aircraft equipped with an inboard optical-absorption magnetometer. The same area had been drape-flown in 1967 by a contractor using a fixed-wing aircraft equipped with a fluxgate magnetometer.

It was apparent that the amplitude of the variations of the 1967 drape-flown fluxgate profile was greater because of the lower survey elevation, but in general there was excellent correspondence. Some short-wavelength features were only apparent on the 1973 CBE profile as an inflection on the side of a larger anomaly, which indicates that there was some loss of detail. However, in subsequent analysis of the data, it was found to be mathematically more valid to downward continue constant barometric altitude data, which are obtained in a given horizontal plane, than to apply the continuation technique to the constant terrain clearance data. The exercise also confirmed the widely held view that topographic effects are of much less importance than magnetization changes in the underlying rocks. However, the contoured maps from the Kamloops test clearly indicated that useful data could be obtained by conducting aeromagnetic surveys of mountainous terrain at constant barometric elevation. In addition, there were two rather cogent reasons for adopting the CBE technique for the Canadian aeromagnetic survey program, which is entirely contracted out to airborne geophysical survey contractors. Firstly, better quality maps will result from the CBE technique in spite of some unavoidable loss in detail. This is because:

(1) The control and traverse lines will always cross at the same height, which will permit a more accurate leveling procedure to be carried out.

(2) Errors in positioning the aircraft will be minimal because the camera will always be pointing vertically downward. The accuracy of any Doppler system that is utilized will be improved.

(3) The noise on the magnetic data due to miscompensation effects will be minimized because aircraft maneuvers, such as pitch, will be minimal in straight and level flight.

Secondly, the cost of the aeromagnetic surveys will be lower for CBE surveys than for drape-flown surveys because CBE surveys are logistically easier to fly and the production is greater for the following reasons:

(1) A STOL-type aircraft is not required, and therefore a less expensive and faster aircraft can be utilized.

(2) The amount of aviation gasoline used will be considerably reduced because the aircraft will not have to climb up and down over the mountains.

(3) Typically, in mountainous areas there can be fog or mist in the valleys until midmorning which might prevent flying drape-flown surveys.

(4) The flight lines can be spaced somewhat farther apart because the average terrain clearance will be greater for most of the survey area.

(5) There will be fewer reflights because it is easier to fly evenly spaced parallel lines.

(6) Flight-path recovery is simpler at the higher elevation.

(7) The safety factors are much higher.

(8) There are physically less fatiguing conditions and no airsickness problems for the aircrew.

Subsequently the CBE technique has been applied by the GSC to aeromagnetic surveys in northern British Columbia, northern Labrador, and Baffin Island, which have considerable topographic relief. In planning the 1981–82 aeromagnetic survey of northern Labrador, the first item to be considered was the flight-line direction, which should always be oriented at a high angle across the main geologic strike. It was clear from the geologic maps of northern Labrador published by the GSC at 1:250,000 scale that the predominant strike direction was north-south. Accordingly, the flight-line direction was chosen to be east-west. The second item to be considered was the division of the area into survey blocks to be flown at CBE. This was done using the published topographic maps at 1:250,000 scale which indicated that the Labrador Highlands are as high as 1,200–1,800 m (4,000–6,000 ft). The coastal fiords are bounded by cliffs that can be more than 600 m (2,000 ft) high.

The Labrador aeromagnetic survey was divided into 14 individual blocks oriented in an east-west direction that could be flown at CBE (fig. 5). It was decided to survey the inner area, which is remote from the coastal mountains, at 300 m (1000 ft) mean terrain clearance (MTC) because it was feasible for a normal survey aircraft to do so. In carrying out such planning exercises, it should be appreciated that the flight lines can usually be positioned to straddle isolated peaks so that the whole area does not have to be flown at a higher elevation.

Because of the increased terrain clearance of the survey aircraft over most of the Labrador survey area, it was decided to increase the line spacing from the standard 800 m that is utilized over the Canadian Shield to 1 km. For the sake of surveying efficiency, the same flight-line spacing was designated for the MTC area so there could be continuity of the flight lines. The control-line spacing was set at 10 km, and the allowable magnetic diurnal variation from a linear mean was set at ±10 gammas between control lines. The typical survey aircraft flying at 140 knots takes less than 2 ½ minutes to fly 10 km. The tighter specification (instead of the more usual 14 km) was chosen because the survey area is located in the auroral zone where the diurnal variation is usually quite large. The basic sensitivity of the magnetometer utilized was set at 0.25 gamma, which was well within the capability of good, commercially available proton-precession magnetometers. It is generally accepted that standard (or low) sensitivity surveys are those in which the sensitivity is 1 gamma or more, medium sensitivity surveys are those in which the sensitivity is between 0.1 and 1 gamma, and high sensitivity surveys are those in which the sensitivity is 0.1 gamma or less. Thus, this survey was a medium-sensitivity aeromagnetic survey. The noise envelope of the magnetometer data was set at 0.5 gamma.

Figure 6 shows one of the 102 resultant 1:50,000-scale total-field aeromagnetic maps, which is located in the central part of the survey area immediately south of lat 58° N. On the published maps the east-west flight lines were printed in blue, and the fiducial points were numbered along the survey lines (black is the only color used on figure 6). The total-field contours were printed in red, and the basic contour interval was 5 gammas. The thicker contour lines on the map are 100-gamma contours. Topographic contours (200-ft intervals) and drainage appear on the published maps as a gray base. Lakes are stippled with grey dots. The portion of this particular sheet that is shown in figure 6 is at the intersection of three blocks which were flown at three different elevations, namely 300 m (1,000 ft) MTC and 1,070 m (3,500 ft) and 1,220 m (4,000 ft) CBE above sea level. It can be seen that, in general, the wavelength of anomalies in the area flown at 1,220 m (4,000 ft) CBE are greater than those in the area flown at 300 m (1,000 ft) MTC, but the continuity of the individual anomalies across the elevation boundaries is surprisingly good.

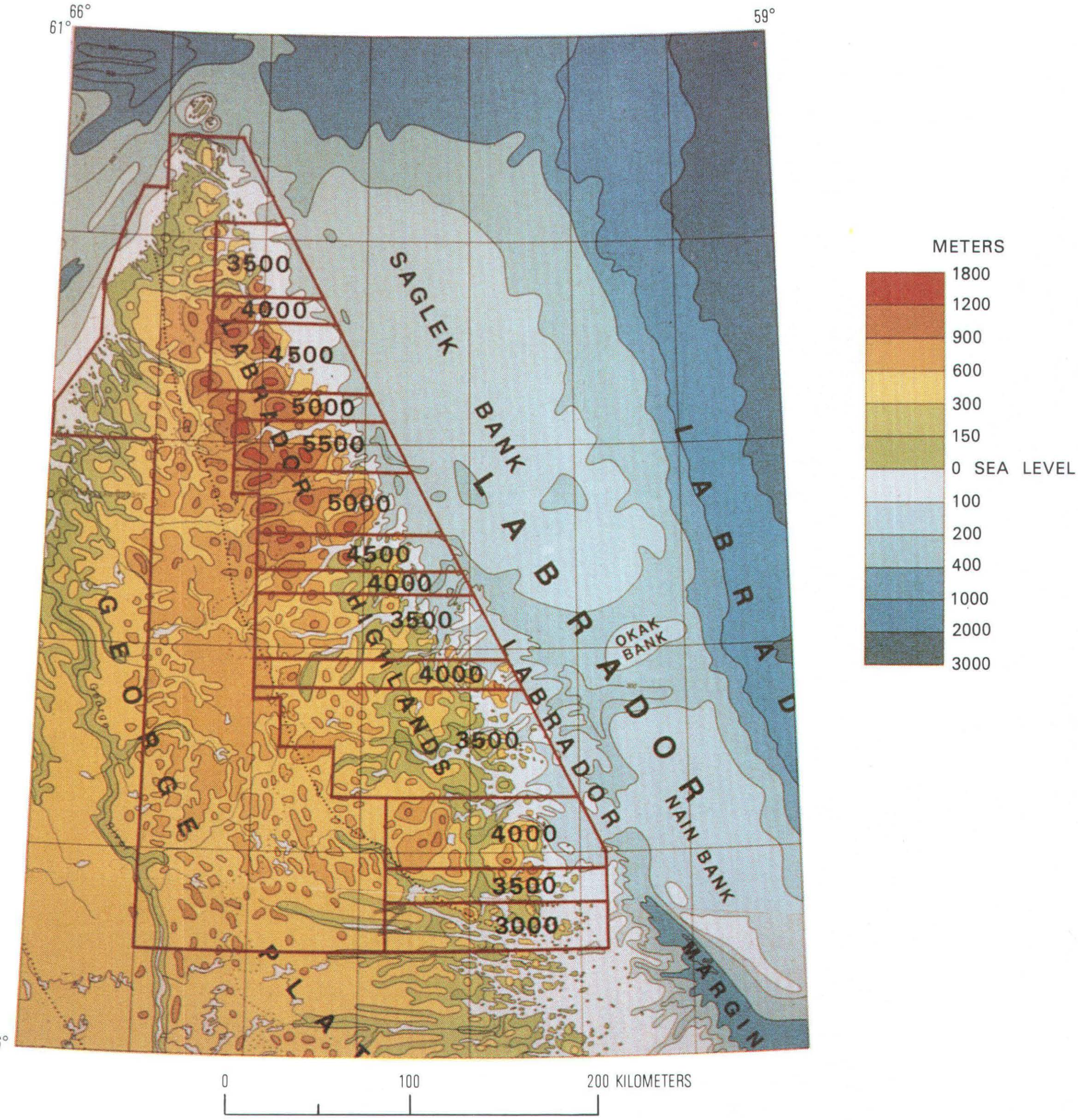

Figure 5. Map showing 1981–82 aeromagnetic survey of northern Labrador. The survey area has been divided into 14 individual blocks, each flown at a given constant barometric elevation, plus an inner area flown at 805-m mean terrain clearance.

Figure 7 shows the central portion of the Hebron sheet which includes the area around Saglek Fiord. The survey aircraft were mostly based at the airport south of Saglek Bay, which has been extensively utilized for offshore survey operations by oil companies. A linear anomaly strikes in a north-northwest direction across the junction of Saglek and Ugjuktok Fiords and tends to disappear over the water where the anomalies pinch considerably. This is due to the fact that the rock has been eroded away by glacier movement in the formation of the fiord. A similar effect is also seen for the linear anomaly that crosses farther to the east along Ugjuktok Fiord. Thus, there is an inverse topographic effect which indicates that the anomalies are mostly produced by the magnetic effects of the upper kilometer of crust. Nevertheless, it remains clear from the experimental evidence that this is another example where magnetization changes are much more important than topographic effects in the production of magnetic anomalies.

The results of the 1981–82 aeromagnetic survey of northern Labrador were also published in the 1:1,000,000-scale magnetic anomaly map series of the GSC (Dods and others, 1985). Figure 8 shows the resultant magnetic anomaly map which is a residual total-field anomaly map in which the core field of the Earth was removed from the measured data using the International Geomagnetic Reference Field. The basic

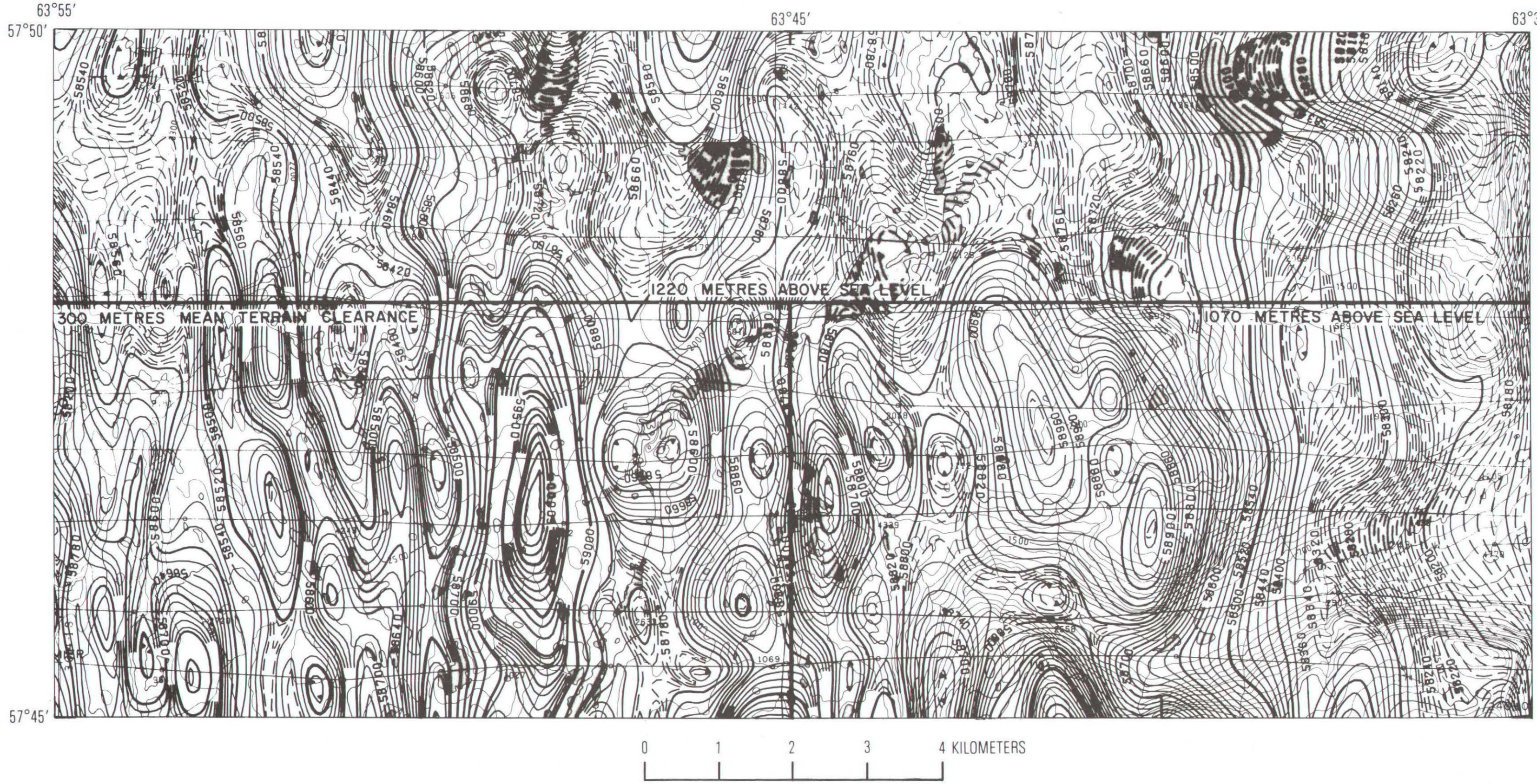

Figure 6. Part of the 1:50,000-scale Lac Lomier aeromagnetic map (GSC Map 6322G, published 1983, NTS 14E/13) from the 1981–82 Labrador aeromagnetic survey showing the contours for three adjacent areas flown at the constant barometric elevations of 300 m, 1,070 m, and 1,220 m above sea level.

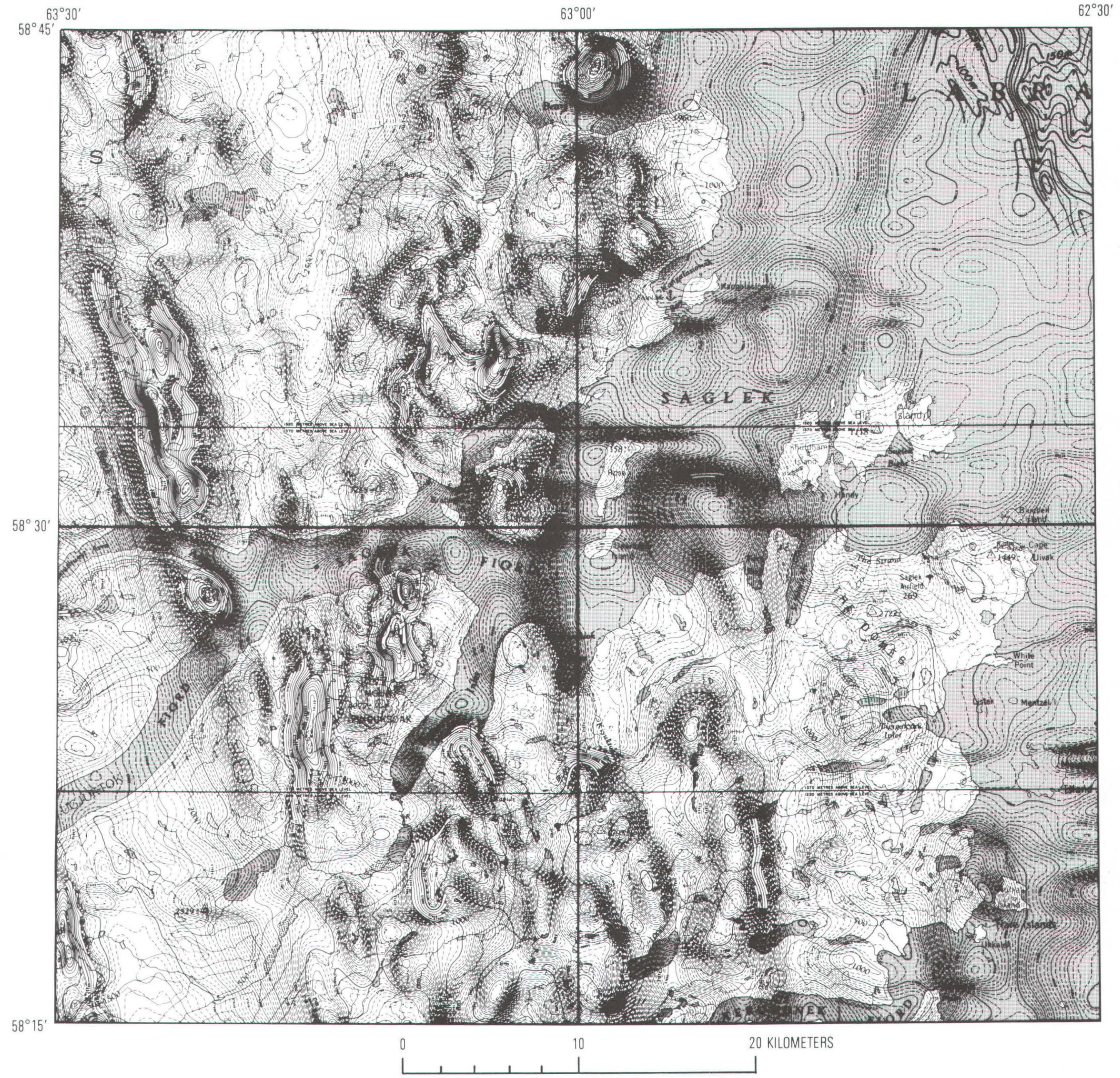

Figure 7. Central portion of the 1:250,000-scale Hebron aeromagnetic map (GSC Map 7473G, published 1983; NTS 14L, K) showing the contours in the area around Saglek Fiord, Labrador.

color interval for the map is 25 gamma in the central portion of the color scale.

Both aeromagnetic and marine data were utilized to compile the map, and no height corrections were made. It is clear from this map that the data have not been affected by the variety of survey elevations that were utilized because the survey boundaries are not marked by level discontinuities which would easily show on a colored map. The continuity of the north-northwest-striking geology is clearly apparent. The blue area is mostly underlain by nonmagnetic mylonitized gneiss, whereas the adjacent high area (red) to the west consists of more magnetic granulite.

One of the techniques for bringing out the distinctive patterns in an aeromagnetic map that provides useful structural information is the shaded-relief technique (Dods and others, 1985). This technique simulates the shadows thrown by a magnetic relief model when illuminated by a low-angle light source. Features that have low amplitude and that strike at right angles to the direction of the illumination will be preferentially delineated by the resultant shadows. The technique can

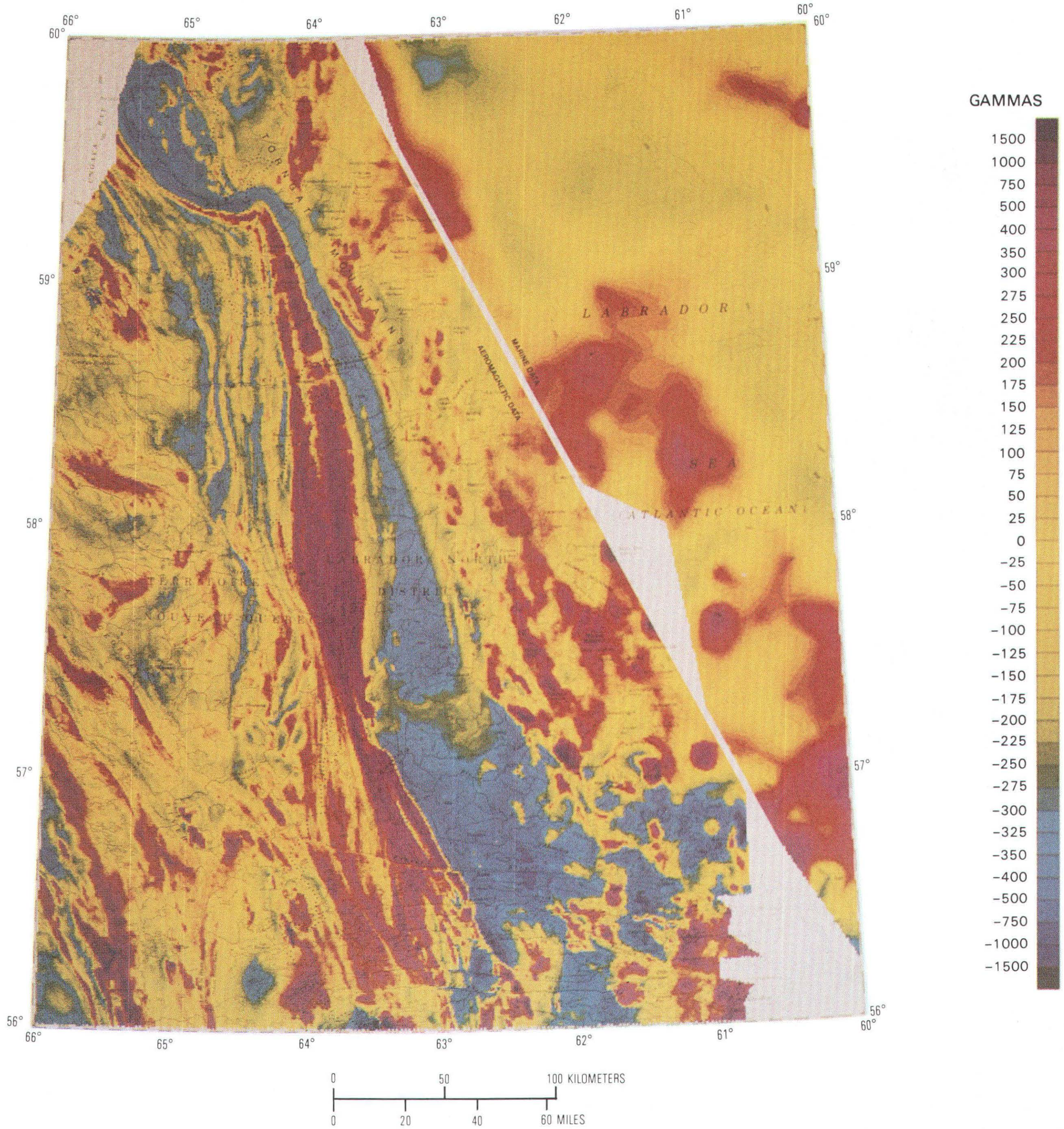

Figure 8. Torngat Mountains magnetic anomaly map at 1:1,000,000 scale (GSC Map 20M, published 1985).

also be used to bring out any misleveling of the data; the preferred direction of illumination to bring out any level shifts would be parallel to the flight lines because these will normally be at right angles to the geologic strike. Figure 9 shows the resultant shaded-relief map for northern Labrador in which the direction of illumination is from the south. No misleveling effects can be detected. The structure of the various geologic formations that underlie northern Labrador is very apparent.

Thus, the GSC experience indicates that in the first phase of a national aeromagnetic survey program, areas of rugged topography are most efficiently surveyed at CBE using fixed-wing aircraft.

PRESENT WORK

The status of the aeromagnetic survey coverage to the end of 1986 is summarized in figure 10. To date, a

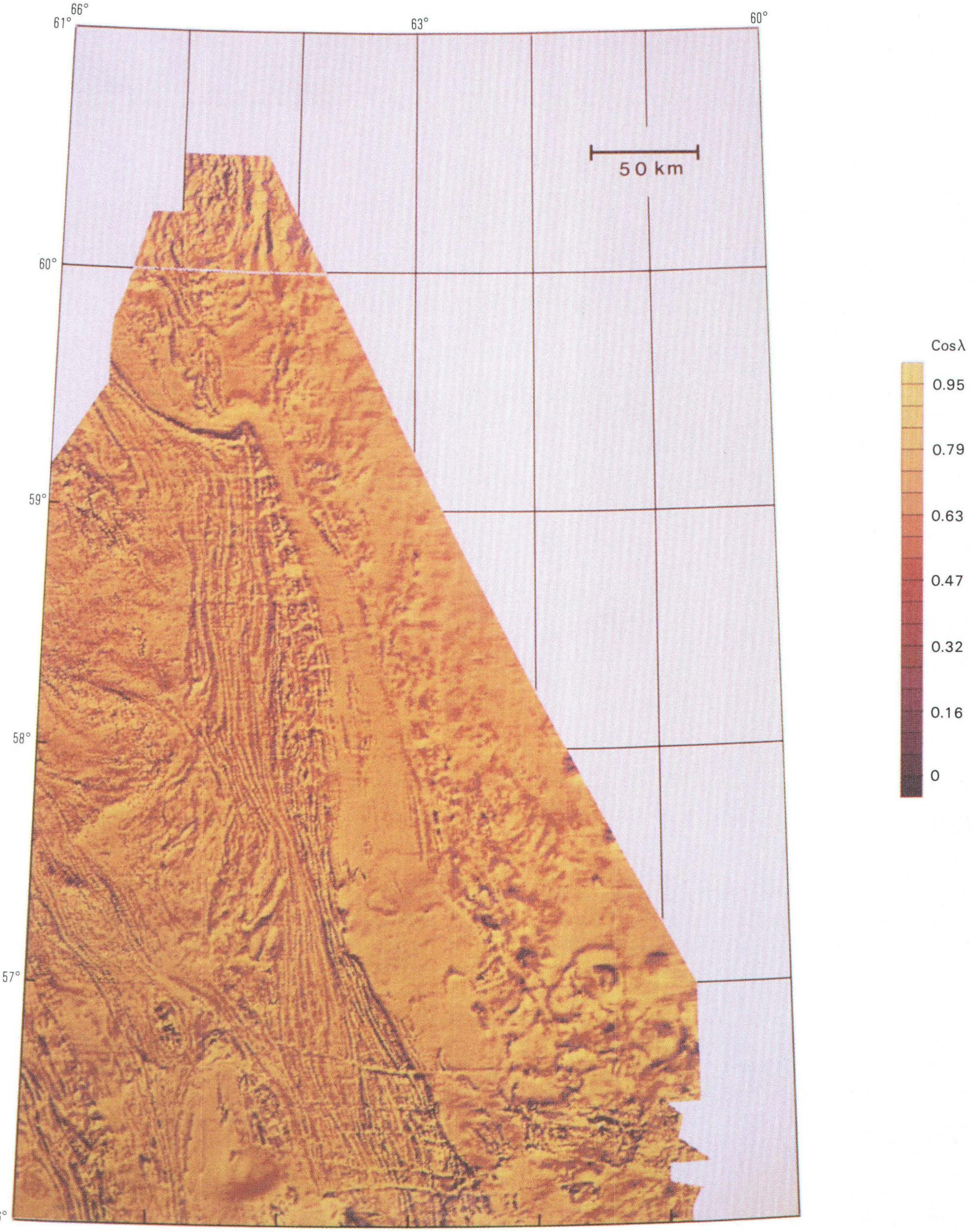

Figure 9. Shaded-relief map of northern Labrador with the direction of illumination from the south.

total of about 8,600,000 line kilometers of regional coverage have been flown in Canada, and aeromagnetic maps covering all of Newfoundland, Labrador, New Brunswick, Quebec, Ontario, and the Canadian shield areas of Manitoba, Saskatchewan, and Alberta have been issued. The provinces of Prince Edward Island and Nova

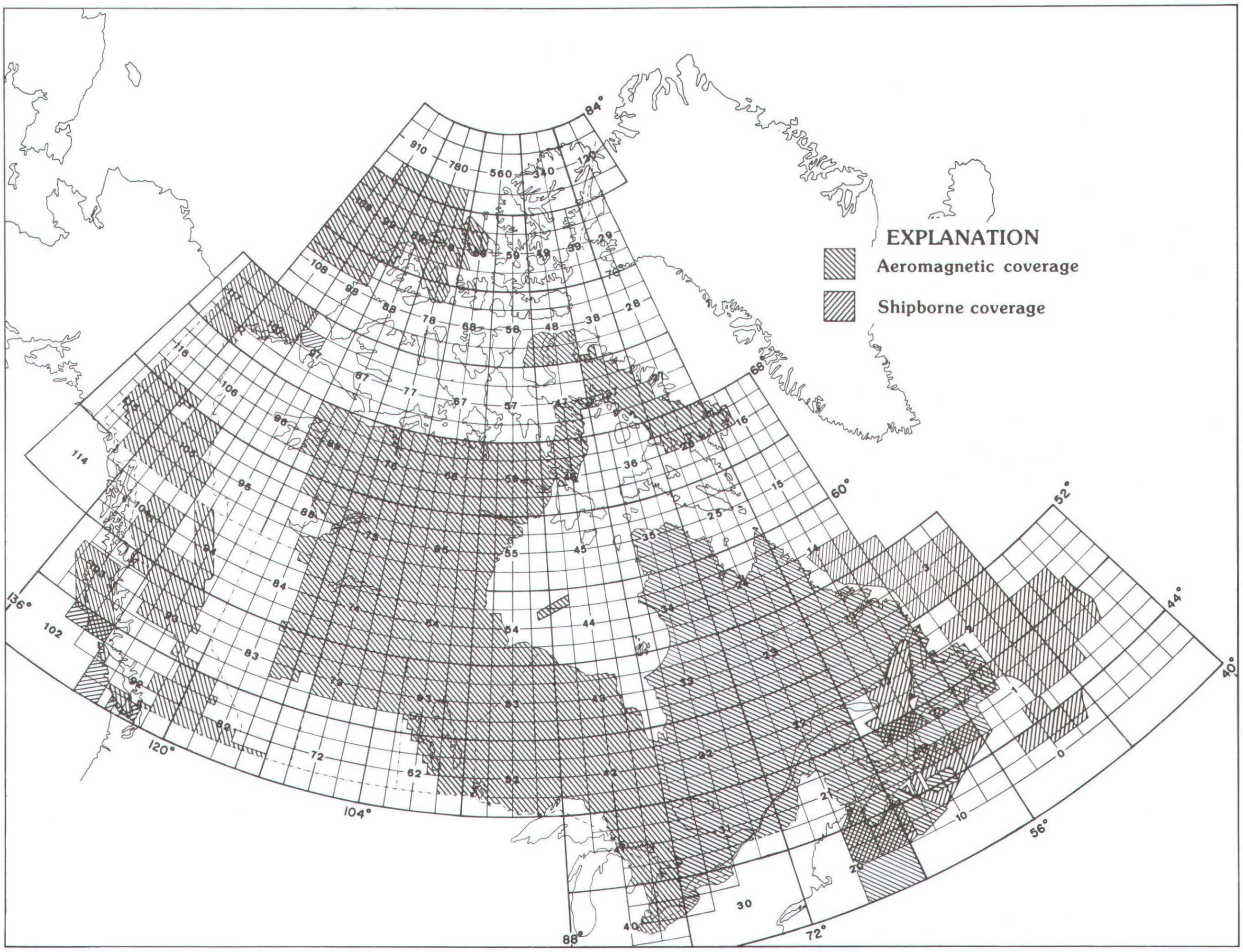

Figure 10. Aeromagnetic and shipborne magnetometer coverage map of Canada to December 31, 1986.

Scotia were surveyed prior to the start of the Federal/Provincial program. At the present time, more then 9,500 aeromagnetic maps at various scales have been published.

In 1980, because Canada had adopted metrication, a decision was made to change the publication scale from the earlier 1 inch to 1 mi (1:63,360) to the more compatible scale of 1:50,000. Similarly, aeromagnetic maps that were formerly 1:63,360 scale are now being issued at 1:250,000 scale. Thus, the scale of the published aeromagnetic maps (fig. 11) will increase in three steps from 1:50,000 to 1:250,000 to 1:1,000,000 to 1:5,000,000, which are jumps of 5:1, 4:1, and 5:1, respectively. This appears to be the most logical sequence for a country the size of Canada, which has an areal extent of about 10 million square kilometers.

For many years, about 30,000 aeromagnetic maps were distributed per year, and these maps are the most popular single item distributed by the GSC in conjunction with the appropriate Provincial agencies. However, with the downturn in mineral exploration activity in the early 1980's, the number of aeromagnetic maps distributed has dropped to about 10,000 per year.

There has been a gradual upgrading in the survey specifications since the Federal/Provincial program began. For regional surveys, the fluxgate magnetometer has been replaced by proton precession magnetometers. In addition, digital recording is now mandatory and the profile and gridded digital data are now considered the prime end product of GSC-funded aeromagnetic surveys.

For aeromagnetic surveys that utilize proton precession or optical absorption magnetometers, an aeromagnetic calibration range has been set up in a low-gradient area at a crossroads near Bourget, Ontario, which is about 45 km east of Ottawa and easily recognizable from the air (Hood and Sawatzky, 1983). The values at the ground level at the crossroads have been tied to the Blackburn Magnetic Observatory using calibrated proton precession magnetometers. The values at 150-m and 300-m elevation above the crossroads have

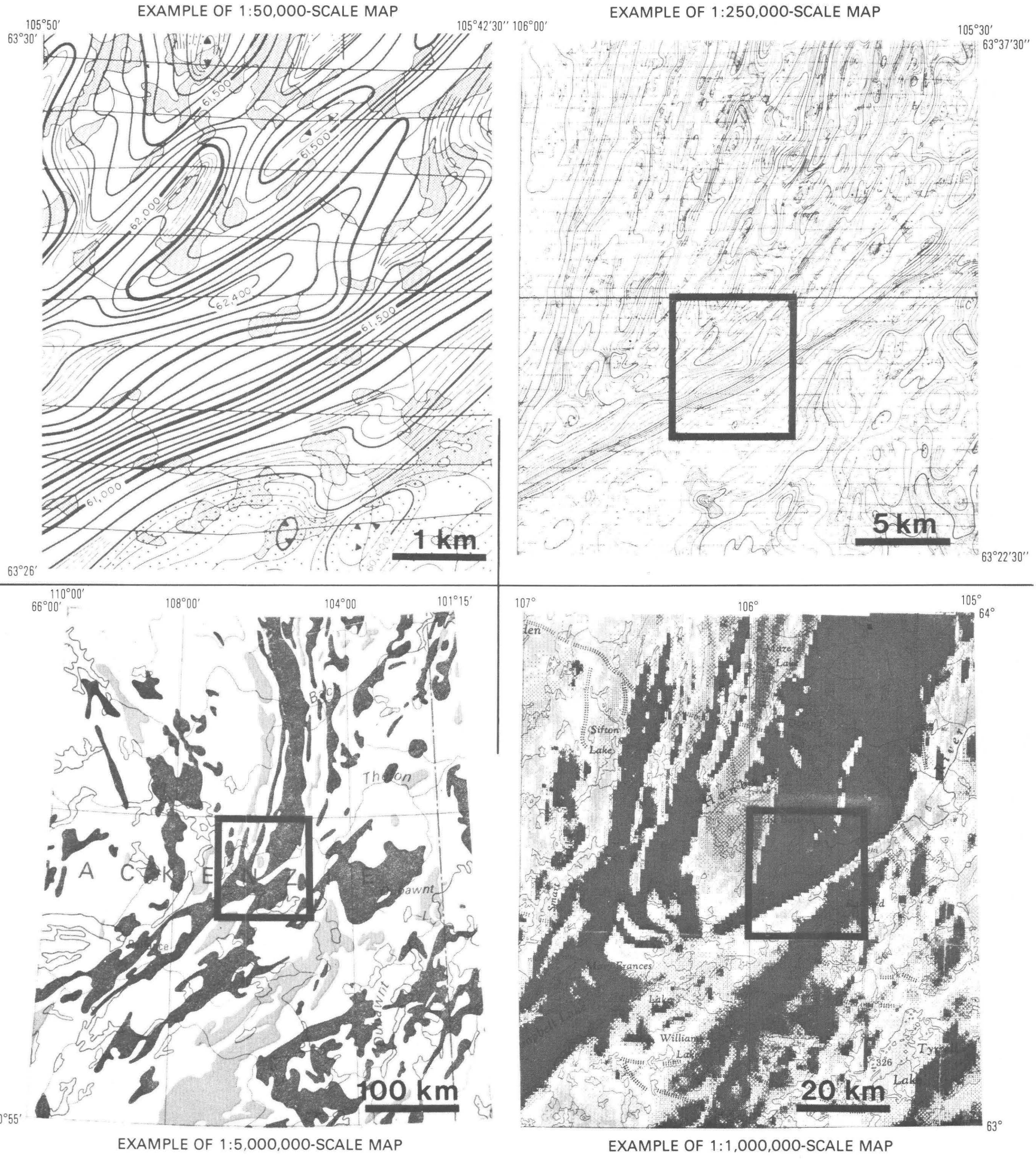

Figure 11. Various scales utilized in aeromagnetic maps published by the Geological Survey of Canada.

been measured by flying a survey aircraft at various heights across the crossroads to ascertain that the field increases by about 12 gammas per 300 m rise in height. Thus, the total-field values at the two levels above the Bourget crossroads have been tied, within a few gammas, to the continuously recording magnetometer at the Blackburn Magnetic Observatory. Because the diurnal variation at the Bourget crossroads can be expected to follow closely the diurnal variation at Blackburn, the value at Bourget can be calculated at any instant of time by subtracting a constant difference value from the Blackburn Magnetic Observatory value.

Aeromagnetic survey aircraft are normally flown along the four cardinal headings across the Bourget crossroads with their flight-path cameras operating, and the field values for each cardinal heading are ascertained at the crossroads. The difference value is subtracted from the Blackburn reading at the exact time that the survey aircraft crossed the Bourget crossroads to get the true reading. The heading errors for the survey aircraft are also calculated as part of the same calibration procedure. In general, the calibration errors should not exceed 10 gammas and the heading errors should be within 5 gammas of the Blackburn values in an acceptable aeromagnetic system.

Because most of the aeromagnetic survey data in Canada were obtained prior to the general adoption of digital recording techniques, a great deal of the original data were recorded in analog form. As a result, because it would have been very expensive to go back to the original chart records, the data on the resultant contour maps have been digitized to produce the digital data set from which 1:1,000,000-scale magnetic anomaly maps have been prepared. This procedure also avoids a releveling of the data. Several digitizing techniques have been experimented with, and the one that has been finally adopted is digitization of the location of the contour intercepts along the flight lines. Because the values along the flight lines have the greatest accuracy in comparison to the interpolated contours between the flight lines, this technique retains the accuracy of the original compilation prior to contouring. Moreover, there is close compatibility between the 0.8128-mm-square size of the 16-dot matrix pixel utilized on the final, digitally produced color map and the flight-line spacing which is 0.805 mm at the 1:1,000,000-scale.

An Applicon plotter has been utilized to print the final 1:1,000,000-scale magnetic anomaly map. The plotter utilizes three color-ink jets, one for each primary color (red, yellow, and blue), and these jets are controlled by a digital tape. A combination of ink blobs that correspond to the correct shade is fired at a rotating drum around which is wound a sheet of paper. The ink jet system moves progressively down the rotating paper which is consequently painted by the ink raster. It is possible by utilizing one ink jet at a time to produce three color separations for printing purposes. Unfortunately, stable-base plastic material cannot be utilized by the Applicon plotter because the ink is not absorbed and consequently smears. The three color separations therefore have to be photographed the same day they are produced to avoid the effects of differential expansion along the length and across the width of the paper map. The resultant end products are utilized together with a base map, which shows planimetry, in printing the final, colored, 1:1,000,000-scale magnetic anomaly map.

The color scheme used in the 1:1,000,000-scale magnetic anomaly maps is essentially the spectrum of white light. Thirty-nine shades, which range from red at the positive end to blue at the negative end, are employed. The zero value coincides with pure yellow. Twenty-six of the shades in the central part of the spectrum represent 25-gamma contour intervals with the contour interval of the remainder coarsening in discrete steps to cover the necessary range.

It was intended that the 1:1,000,000-scale magnetic anomaly maps would be utilized essentially as basic building blocks in compiling future editions of the 1:5,000,000-scale Magnetic Anomaly Map of Canada as one of a series of national geologic, tectonic, and gravity maps of the country at the same scale. In turn, the Magnetic Anomaly Map of Canada has been utilized for the Magnetic Anomaly Map of North America, compiled as part of the Decade of North American Geology to celebrate the centenary of the Geological Society of America in 1988. However, an additional end product of the 1:1,000,000-scale compilation has been a digital aeromagnetic data base for Canada which can be utilized for many purposes, such as the production of a variety of filtered maps that typically emphasize the high- or low-frequency content of the data. Also of much current interest to qualitative interpreters of aeromagnetic data are the previously described simulated shaded-relief maps which emphasize linear features in the magnetic anomaly maps that are not otherwise easily seen.

Aeromagnetic surveys are conducted overseas as part of Canadian aid programs of the Canadian International Development Agency, and the preparation of regional magnetic anomaly maps has usually been made part of the contract at the interpretation stage. It is abundantly clear that such magnetic anomaly maps should be made a standard end product of regional aeromagnetic surveys because of their several uses. The regional maps not only serve as indexes to the aeromagnetic survey coverage available on a national basis (as well as the gaps in the coverage) but also stimulate comparison of the regional magnetic features with those appearing on similar-scale geologic and geophysical maps and with Landsat imagery.

DEVELOPMENT OF AN INBOARD VERTICAL GRADIOMETER

In order to keep current with the continually advancing technology and to update contract specifications, the GSC has maintained its own expertise in aeromagnetic surveying over the years. In 1962, the

Figure 12. Beechcraft B80 Queenair aircraft of the Geological Survey of Canada equipped with twin-boom system for aeromagnetic gradiometer surveys.

GSC purchased a rubidium-vapor magnetometer from Varian, Inc., on behalf of the group at the National Aeronautical Establishment (NAE) in Ottawa, who installed it in their North Star aircraft which is used for military aeromagnetic research related to antisubmarine warfare. The GSC aeromagnetic survey group has had an assocation with NAE that continues to the present day. Initially, the optical absorption magnetometer was towed in a bird because of the magnetic interference of the aircraft. However the NAE group, who are specialists in the magnetic compensation of aircraft, developed an active compensation system that permitted the magnetometer sensor to be mounted inboard on the aircraft. The GSC instrumentation group, which was headed by Peter Sawatzky, worked closely with the NAE group during that period and took part, for example, in the 1965 aeromagnetic survey of the central portion of Hudson Bay. The same magnetometer was used to carry out an aeromagnetic reconnaissance of the Labrador Sea and later of Baffin Bay. The discovery of an extensive sedimentary section on the Labrador continental shelf (Hood and others, 1967; Hood and Bower, 1973) led to the oil companies embarking on an exploration program that subsequently resulted in the discovery of significant amounts of oil and gas.

In 1968, the GSC purchased a Queenair B80 aircraft (fig. 12) and proceeded to equip it with an inboard Varian rubidium-vapor magnetometer (using an NAE prototype single-cell orienting device). The new magnetic compensator system developed by NAE, which was being manufactured by Canadian Aviation Electronics of Montreal for military antisubmarine aircraft, was also utilized. Actually, provision for the recording of data from two sensors was made in designing the first Queenair data acquisition system. Data acquisition was by digital technique, which was rather new at that time, and was later incorporated as a requirement into the standard GSC aeromagnetic survey contracts after the technique was well proven in inhouse aeromagnetic surveys.

A number of high-sensitivity single-sensor surveys that were carried out in the period 1970–73 were contoured at 2-gamma and even 1-gamma intervals, which demonstrated that a light twin-engine aircraft could be well compensated magnetically. Then in 1973, as a result of theoretical studies in aeromagnetic gradiometry (Hood, 1965), the next, more difficult step was taken to build an inboard vertical gradiometer system with a 2-m sensor separation. The design was initially based on the requirement to delineate the vertical gradient at a height of 1,000 ft above a dipping contact that had an effective susceptibility contrast equivalent to a difference of 0.04 percent magnetite content across the contact (Hood, 1981). The contact case is the most frequently encountered geometric model for the Canadian Shield and is actually the worst case model in that the rate of fall-off of the total field with height is least.

The first gradiometer survey was carried out in the Spring of 1975 in the White Lake area close to Ottawa

(Hood and others, 1976a, b, 1979), and the results well demonstrated the improvement in resolution and other desirable properties of the gradiometer which may be summarized as follows:

(1) Resolution of anomalies that are produced by closely spaced geologic formations is superior;

(2) Anomalies produced by near-surface features are emphasized with respect to those produced by more deeply buried features;

(3) Direct delineation of vertical contacts by the zero-gradient contour value (vertical contact mapper) is achieved; and

(4) Regional gradient of the Earth's magnetic field and diurnal variation are automatically removed.

The foregoing advantages have been described in greater detail in Hood and others (1979) and Hood (1981). It follows therefore from the advantages listed that vertical-gradient aeromagnetic survey results are in fact a better aid to geologic mapping programs than the more conventional total-field results. Moreover, because many orebodies are located at or near contacts, the vertical-gradient technique should prove invaluable in tracing such contacts using airborne techniques.

It has been found that aeromagnetic gradiometer surveys are actually best flown at 500 ft (152 m) with a 1,000-ft (305 m) flight-line spacing to obtain the best definition of the vertical-gradient anomalies which fall off much more rapidly with height. At this height, it is also possible to delineate contacts that have only a 0.02 percent magnetite contrast. Thus the aeromagnetic gradiometer tool is intended for use in detailed geologic mapping and for mineral exploration programs, particularly those in drift-covered areas. Indeed, when the gradiometer results are color contoured using a device such as the Applicon color plotter, the result is in essence an objective, pseudogeologic map. A number of mining companies in central Canada have utilized this technique where the area is drift covered and outcrops are sparse.

A series of experimental surveys were then carried out to demonstrate the efficacy of the vertical-gradient technique in various geologic environments. The Radioactive Waste Disposal program was getting underway at the same time, and the aeromagnetic gradiometer soon proved its value in unravelling areas of complex geology at the various sites. Another particular highlight was the survey in the Wollaston Lake area on the east side of the Athabasca Sandstone. The gradiometer was able to delineate easily the metasedimentary units at the edges of the uranium orebodies. The high-sensitivity data could also be high-pass filtered to show the dominant glacial direction (because eskers are slightly magnetic). Use of glacial direction to trace the origin of radioactive boulder trains is a prime exploration technique in the area (Kornik, 1982).

With the decline of base-metal exploration in the past several years, the only significant activity has been in exploration for gold. In September 1979, the Association of Prospectors of Quebec asked for a test survey in the Abitibi mining camp. Because the Val D'Or 1:50,000-scale map contains many gold mines, it was chosen for the test survey which was carred out in June 1980. The resultant colored maps were published using the Applicon color plotter, and compilation techniques were developed inhouse. It was readily apparent that many of the diorite plugs that are associated with gold are magnetic and could readily be detected by the gradiometer (Hood and others, 1982). The release of the maps caused a flurry of exploration activity in the area and helped in at least one new discovery, the New Pascalis prospect.

By 1980 the time was ripe for a technology transfer to take place to the airborne geophysical survey industry, although the various airborne contractors were still somewhat reluctant to build a system without assurance of a market for the product. Fortunately, that year a vehicle for the technology transfer manifested itself through the Canada–Eastern Ontario Subsidiary Agreement, which was administered by the Ontario Geological Survey (OGS). R.W. Barlow of OGS and P.J. Hood were coleaders of the project, and Dr. N.R. Paterson of Paterson, Grant and Watson, Ltd., was retained by OGS as a consultant for the project. The specifications for the Commercial Aeromagnetic Gradiometer System (CAGS) were prepared by the GSC, and proposals were invited from industry.

Two companies responded, namely Kenting Earth Sciences, Ltd., of Ottawa and Questor Surveys, Ltd., of Toronto. After considerable deliberation, a contract was awarded to Kenting in the Spring of 1982. Under the terms of a Memorandum of Understanding between the various parties, the GSC undertook to provide Kenting with technical support on a day-to-day basis including the provision of technical drawings and compilation programs. Kenting spent about 15 months fabricating their improved system on a Navajo aircraft, and it was accepted for survey work in August 1983. The company did two test surveys as part of the OGS contract before the system was offered commercially. Subsequent work included GSC contracts in Nova Scotia, Quebec, Manitoba, and Saskatchewan, which were funded under various Federal/Provincial Mineral Development Agreements.

Thus, the history of development of the aeromagnetic gradiometer has extended over two decades. It could not have been accomplished without dedicated team work, and one essential ingredient was the possession of an inhouse survey platform, namely the Beechcraft Queenair aircraft. It is also abundantly clear that, in the development of an essentially new survey technique, it is not sufficient just to build the necessary black boxes, test them on a few survey lines, present the results at a scientific meeting, and wait for the commercial survey contractors to act. The contractors have to be convinced that they can make a profit on a continuing basis by offering such a service. Otherwise, they are unwilling to take the risk.

One of the important conclusions of the gradiometer program is that national aeromagnetic surveys should be carried out in two phases in order to provide adequate coverage for multipurpose usage. In the first phase, a regional aeromagnetic survey should be carried out at a sufficient height to permit a reasonably wide flight-line spacing so that costs are not excessive. In the second phase, the areas of complex geology and (or) interesting mineral possibilities should be reflown at a lower elevation and a closer flight-line spacing. Moreover vertical gradiometers should be utilized for the second survey phase because of their distinct advantages over total-field, single-sensor systems.

HELICOPTER–BORNE AEROMAGNETIC GRADIOMETER SURVEYS

There is a problem in carrying out aeromagnetic gradiometer surveys in areas of mountainous terrain. As previously described, the GSC has utilized the technique of flying at CBE to carry out regional total-field aeromagnetic surveys of mountainous areas, such as the Cordillera of British Columbia and the Torngat Mountains of Labrador. However, this procedure does not yield useful results when flying vertical-gradient surveys of rugged areas, because gradient surveys are much more sensitive to the separation between the sensors and the causative bodies of anomalies than is the case for total-field surveys. Gradiometer surveys must always be drape-flown. Accordingly, in 1983 the GSC began fostering the development of helicopter-borne aeromagnetic gradiometer survey systems through research and development contracts to the Canadian airborne geophysical industry (Hood and Teskey, 1986). The successful companies that initially received funding were Geotech, Ltd., of Markham, Ontario, and Geophysical Surveys, Inc., of Ste. Foy, Quebec. Geotech built a 3-m-separation system using Overhauser magnetometers developed under a previous GSC-sponsored contract by Gem Systems, Ltd., of Toronto. Two proton oscillators (GSM–11A) were installed in a mastlike structure above an electromagnetic (EM) bird with a 3-m separation. The noise envelope achieved was about 0.1 gamma for two readings per second for a single sensor and 0.033 gammas per meter for the gradient measurements.

The second helicopter-borne vertical gradiometer system was developed by Geophysical Surveys, Inc., and utilized two V–200 Scintrex split-beam cesium-vapor magnetometers with a separation of 2 m mounted on a towed bird, which permitted the vertical gradient to be measured twice a second with a sensitivity of 0.0005 gammas per meter. The total-field and vertical-gradient fourth-difference noise levels of the system are less than 0.02 gammas per meter and 0.025 gammas per meter, respectively.

Both systems were first field tested in the relatively flat Carleton Place area previously flown by the GSC fixed-wing system to ensure that repeatable results could be obtained. Then a survey of Mount Megantic, Quebec, which is about 700 m high, was carried out in March 1984 to ascertain whether the technique would produce useful results of areas of rugged terrain. The area had been previously surveyed in 1951–52 by a fixed-wing aeromagnetic survey flown by the GSC. In general, the experimental surveys demonstrated the excellent repeatability of total-field survey data, but in the fine detail there were many differences that are important to the mapping geologist. There is an even more striking comparison with the resultant vertical-gradient color interval map. This map showed that Mount Megantic consists of two concentric rings of magnetic rock that extend about 270° in azimuth, which have significant magnetization and a central nonmagnetic core. This is confirmed by a comparison with the geologic map which shows an outer ring of syenite, an inner ring of gabbro, and a central core of granite.

In 1984 a tender for the first contracted helicopter-borne vertical gradiometer work was issued for an area in the Gaspe Peninsula of southeastern Quebec, and the successful contractor was Geophysical Surveys, Inc. The published results of the survey demonstrated that the helicopter-borne gradiometer technique is a viable one for geologic mapping programs, and this is confirmed by the resultant contour maps. Moreover, the results show a significant improvement in resolution over the older, drape-flown survey.

Two other Canadian companies have developed helicopter-borne gradiometer systems. Aerodat, Ltd., of Mississauga, Ontario, has fabricated a vertical gradiometer that utilizes split-beam cesium-vapor magnetometers with a sensitivity of 0.0005 gamma which are manufactured by Scintrex, Ltd. Sander Geophysics, Ltd., of Kanata, Ontario, has completed the development of a helicopter-borne vertical gradiometer system that utilizes Overhauser magnetometers of their own design. The sensor separation is 3 m, and the 7-m-long bird structure is towed by an Aerospatiale AS 350D Astar helicopter at the end of a 30-m cable. They have carried out their first contract survey for the GSC in the Gaspe Peninsula of southeastern Quebec.

Helicopter-borne aeromagnetic gradiometer contracts have now been awarded to the forementioned companies to carry out surveys in four eastern provinces, namely Newfoundland, Nova Scotia, New Brunswick, and Quebec. It is clear that the helicopter-borne aeromagnetic gradiometer technique combined with very low frequency electromagnetic (VLF EM) techniques is an excellent geophysical tool to assist geologic mapping programs in areas of rugged terrain.

CONCLUSIONS

It is generally recognized that the aeromagnetic survey program of the GSC has been one of its most successful endeavours over the past 40 years. It has led directly or indirectly to the discovery of many ore deposits, and its overall cost has been recovered many times over the years both through the general economic benefits to the country that result from such discoveries and from the taxes that are subsequently paid to the provincial and federal governments. After many years of development, the aeromagnetic survey technique is still being improved in many new and novel ways and it remains the most utilized airborne survey technique in terms of the line kilometrage flown each year throughout the world. This continued popularity is due in part to a variety of reasons. Of all the airborne geophysical survey techniques, the aeromagnetic survey technique has by far the greatest depth penetration; this technique is able to detect features down to the Curie point geotherm, which is about 20 km beneath the Earth's surface. Moreover, the aeromagnetic survey technique is unaffected by the presence of surficial material such as overburden and weathered material or by the presence of lakes and swamps. Aeromagnetic surveys also provide a continuity of information at low cost that is impossible to achieve in ground geophysical or geological surveys. One of the outstanding advantages of aeromagnetic surveys becomes apparent when large areas are surveyed because large regional geologic features are commonly discovered. These regional features may not be recognizable on the ground because they are very large or perhaps obscured by sedimentary formations. Clearly, further significant developments in the aeromagnetic survey technique can be expected in the next decade, especially in the development of aeromagnetic gradiometer techniques and in the methods of presentation and interpretation of aeromagnetic data.

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Rock Magnetism, The Distribution of Magnetic Minerals in the Earth's Crust, and Aeromagnetic Anomalies

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Abstract

A review of current understanding of relations among rock magnetic properties and petrology of igneous, metamorphic, and sedimentary rocks, as well as of the distribution of magnetic minerals in the Earth's crust, shows that rock magnetic and petrologic studies can provide important constraints on the interpretation of aeromagnetic anomalies. The development of three-dimensional geologic maps based on aeromagnetic data requires an improved understanding of: (1) petrologic and petrochemical controls on magnetic properties of rocks in the lower oceanic and continental crust and of plutons in the middle and upper continental crust; (2) effects of lower and middle crustal temperatures and pressures on total magnetizations; (3) relations among metamorphic facies, premetamorphic lithostratigraphy, and magnetization; and (4) relations among types and origins of ore deposits, host-rock composition and mineralogy, and magnetic signatures that may be diagnostic for specific mineral and energy habitats. Magnetic contrasts in sedimentary rocks are controlled by depositional factors and by geochemical and consequent mineralogic alterations that either enhance or suppress magnetizations. Examples are drawn from the formation of uranium deposits in sandstones and from the effects of hydrocarbon seepage.

INTRODUCTION

The purpose of this report is to present a broad overview of the magnetic properties, petrologic controls, and magnetic mineral composition of crustal sources of magnetic anomalies. This overview is preceded by a brief review of the factors that control magnetic properties of minerals and rocks. We also attempt to identify avenues of rock magnetic and petrologic investigations that will provide important constraints on the interpretation of aeromagnetic data and thus contribute to the development of three-dimensional geologic models. The discussion is intended to serve as a general guide for interpreters of aeromagnetic data to current knowledge and some recognized problems of crustal magnetization.

Special attention is given to the causes of magnetic contrasts in sedimentary rocks. Recently improved techniques for the acquisition and analysis of aeromagnetic data, as well as newly developed models and guides for the exploration of energy and mineral resources, have expanded interest in aeromagnetic anomalies that arise from sedimentary rocks. The potential of aeromagnetic methods for detecting the magnetic-diagenetic effects of vertically directed alteration plumes, such as may be caused by hydrocarbon seepage (Donovan and others, 1979), is an outstanding example. The understanding of such features is currently very limited, but where such an understanding exists, it is based on detailed rock magnetic, mineralogical, and geochemical study.

ACKNOWLEDGMENTS

Technical reviews by Bill Hanna and Carol Finn greatly improved the manuscript.

MAGNETIC PROPERTIES OF ANOMALY SOURCES

The physical property that relates magnetic anomaly to its source is total magnetization. The magnitude and direction of total magnetization (J_t) are given by the vector sum of two components: remanent magnetization (J_r) and induced magnetization (J_i). J_t can be computed as:

$$J_t = J_r + J_i = J_r + kB,$$

where k is magnetic susceptibility (SI, dimensionless), and vector B is the magnetic induction of the Earth at the location of the body. The measurements of J_r and k of samples at ambient temperature and pressure are easily obtained using laboratory instruments. Another widely used quantity is the Koenigsberger ratio of remanent magnetization magnitude to induced magnetization magnitude.

The magnetic properties of rocks and minerals have been discussed in detail from an aeromagnetics perspective by Haggerty (1979), McIntyre (1980), Grant (1984/1985a, b), and Clark (1983). Clark (1983) and Carmichael (1982) present summaries of representative values of susceptibility, remanent magnetization, and Koeingsberger ratio corresponding to many magnetic minerals and some rock types.

The magnitude of J_i depends on the quantity, composition, and size of the magnetic-mineral grains, as well as on the magnitude of the magnetic induction (the Earth's field direction). The direction of J_i is usually parallel to the local magnetic induction, but it may differ if anisotropy of magnetic susceptibility is great. In general, k, and thus J_i, is relatively low for small magnetic grains and higher for larger grains.

The magnitude of J_r is also a function of quantity, composition, and sizes of the magnetic grains. In addition, naturally occurring J_r (natural remanent magnetization, NRM) is strongly influenced by the physico-chemical environment (which determines the type of remanence that is acquired) and the strength of the induction field at the time of acquisition. Other types of remanence include thermoremanent magnetization-(TRM), chemical remanent magnetization (CRM), isothermal remanent magnetization (IRM), and depositional (or detrital) remanent magnetization (DRM). The in-situ direction of J_r is usually parallel to the ambient magnetic induction (the Earth's field direction) during the acquisition of remanence, but it may be rotated due to later tectonism. In contrast to J_i, small magnetic grains produce relatively strong and stable J_r.

The types of remanent magnetizations that are acquired by different rock types are listed in table 1. Viscous remanent magnetization (VRM), in the direction of the present Earth's field, dominates the remanence of rocks in the middle and lower crust as well as that of coarse-grained plutonic rocks. The direction of NRM for other types of rocks must, in general, be determined experimentally. In some cases NRM magnitudes can be estimated for known or expected rock types (Clark, 1953). However, NRM directions are usually difficult to estimate because the NRM may be the result of both primary and secondary components, which may have been affected by tectonic rotations. An excellent review of paleomagnetic methods, including problems that involve multiple components of magnetizations and tectonic rotations is given by Hillhouse (in press). Not only is knowledge of the direction and magnitude of remanent magnetization commonly important in constraining the total magnetization vector, but knowledge of the type of remanence may be crucial to the correct geologic interpretation of magnetic anomalies. For example, the implications of anomalies over sedimentary rocks are very different if the magnetization is dominated by detrital remanent magnetization rather than by a chemical remanent magnetization related to the presence of hydrocarbons.

MAGNETIC MINERALS AS ANOMALY SOURCES

The most important magnetic minerals for aeromagnetic measurements are those of the magnetite-ulvöspinel (Mt-Usp_{ss}) solid-solution series, the titanomagnetites [$xFe_2TiO_4*(1-x)Fe_3O_4$ ($0 \leq x \leq 1$), fig 13]. A number of magnetic properties of titanomagnetites vary as a function of composition. For example, Curie temperatures decrease systematically from about 580 °C for ferrimagnetic magnetite to –153 °C for antiferromagnetic ulvöspinel (fig 13). A Curie temperature of 25 °C corresponds to titanomagnetite that has about 75 percent ulvöspinel in solid solution. Saturation magnetization, which is the maximum possible magnetization (92 A m^2/kg for Fe_3O_4), similarly decreases with increasing content of titanium. Although the Earth's magnetic field is too weak to saturate magnetically the common magnetic minerals, saturation magnetization is a useful indicator of the capacities of different magnetic minerals to become magnetized. The susceptibility of Mt-Usp_{ss} is effectively zero for Usp_{ss} contents greater than about 70 percent. For Mt-Usp_{ss} that is more enriched in Mt, the variation of susceptibility with composition depends on grain size. Discussions of relations among grain sizes, domain structures, and magnetic properties are given by Dunlop (1981) and Clark (1983).

Minerals of the ilmenite-hematite (Ilm-Ht_{ss}) solid-solution series [$xFeTiO_3*(1-x)Fe_2O_3$ ($0 \leq x \leq 1$), and referred to here as titanohematites], vary complexly in magnetic structure and properties as a function of composition. In the compositional range $0.5 \leq x \leq 0.8$, between weakly magnetic hematite (antiferromagnetic) and ilmenite (paramagnetic), the titanohematites are ferrimagnetic, have Curie temperatures in the range of 235 to –26 °C, and attain a saturation magnetization of as much as a third that of magnetite.

Table 1. Types of remanent magnetizations that may contribute to aeromagnetic anomalies

[T, temperature; T_c, Curie temperature. Based partly on table 4.1 in Tarling (1983)]

Remanent magnetization	Abbreviation	Rock types	Definition or characteristic
Natural	NRM	All	Summation of all components of remanence.
Thermal	TRM	Igneous, metamorphic	Acquired during cooling from the maximum T_c to room T (Total TRM).
Partial thermal	pTRM	Igneous, metamorphic.	The TRM acquired during cooling in a T interval having maximum $T<T_c$. The total TRM equals the sum of the pTRM's.
Partial thermochemical.	pTCRM	Igneous, metamorphic.	Remanence acquired by products of exsolution-oxidation during cooling.
Viscous	VRM	All	Secondary remanence related to thermal agitation of domain walls that causes decay of primary remanence and changes domain assemblage to lowest energy state.
Viscous partial thermal.	VpTRM	All	Distinguished from VRM on basis of higher temperature conditions below T_c.
Detrital, depositional.	DRM	Sedimentary	Primary remanence acquired by the physical rotation of detrital grains during deposition.
Postdepositional	PDRM	Sedimentary	Acquired during postdepositional rotation of interstitial grains. Some investigators include effects of early diagenetic chemical-magnetic alterations.
Chemical	CRM	All	Secondary remanence acquired during growth of magnetic minerals in presence of magnetic field. Includes growth by nucleation or replacement.

Titanomaghemites (maghemite) form by low-temperature oxidation of titanomagnetites (magnetite). Maghemites are nonstoichiometric spinels with variable amounts of cation site vacancies caused by either addition of oxygen or removal of metals (shaded pattern in fig. 13). The Curie temperature increases with progressive degree of oxidation, and the saturation magnetization decreases with increased oxidation of titanomagnetites that originally have less than 50 mol percent ulvöspinel. The saturation magnetization of the titanomaghemites is 85 A m²/kg for maghemite (γFe_2O_3). The oxidation of magnetite also commonly produces hematite (saturation magnetization is 0.5 A m²/kg). The factors that dictate the formation of either hematite or maghemite are not well understood but may be related to presence or absence of water; the presence of water favors maghemite.

Other magnetic minerals, which are not illustrated on figure 13, that are or may be responsible for magnetic anomalies include metallic iron, metal alloys of Fe-Ni-Co-Cu, and the magnetic sulfides, monoclinic pyrrhotite and greigite. In addition, as described later, nonmagnetic iron sulfide minerals, particularly pyrite, can play a significant role in changing magnetization in certain sedimentary rocks that have been altered at low and high temperatures.

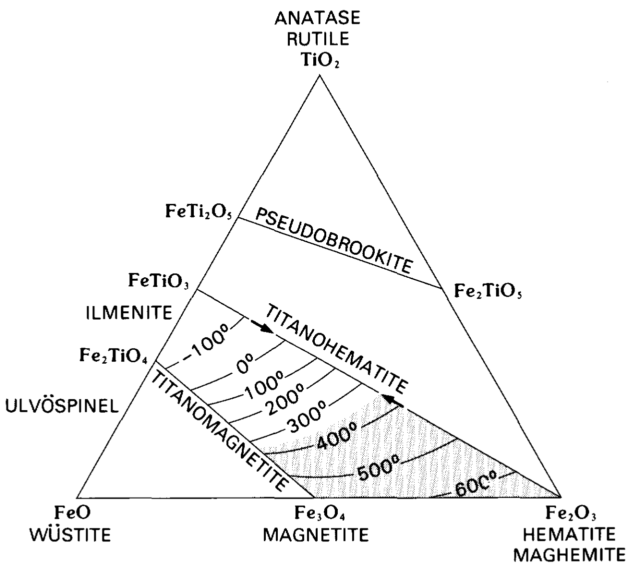

Figure 13. The FeO-Fe_2O_3-TiO_2 ternary system showing the titanomagnetite, titanohematite, and pseudobrookite solid-solution joins, as well as the Curie temperature contours (in degrees Celsius) between the titanomagnetite and titanohematite joins. In the compositional range (50–80 mol percent ilmenite) indicated between the arrows, the titanohematites are ferrimagnetic. The shaded area represents the field of titanomaghemite.

PETROLOGIC CONTROLS ON MAGNETIC PROPERTIES

The magnitudes of remanent and induced magnetization in rocks depend primarily on the abundance, composition, and grain size of magnetic minerals in the rocks, as well as on the nature of the remanence. In igneous rocks, these factors are controlled mainly by bulk chemistry, by initial temperatures of formation, and by cooling conditions, including especially cooling rate and oxygen fugacity (Haggerty, 1979). In metamorphic rocks, such factors are controlled similarly by rock and mineral chemistry and by the thermal history (McIntyre, 1980; Grant, 1984/1985a). In clastic sedimentary rocks the factors are controlled primarily by source area, depositional process, depositional environment, and diagenetic alteration. Although most chemical and biogenic sedimentary rocks have negligible magnetizations, chemical precipitation of abundant magnetite from waters, has occurred under appropriate conditions of pH, amount and valences of iron and sulfur, oxygen fugacity, and temperature.

The following sections focus on factors that determine the types and characteristics of magnetic minerals, as well as the growth or depletion of these minerals in rocks, and that thus control rock magnetic properties. Although the emphasis is not on links between rock magnetization and specific features [such as polarity (positive or negative), magnitude, and shape] of aeromagnetic anomalies, some general statements on these links can be made. In the simplest cases, for example, positive magnetic anomalies can result from strong induced magnetizations, from a dominant VRM, and (or) from stable remanence of normal polarity. Negative magnetic anomalies can be caused by rocks with dominant stable remanence of reversed polarity. However, the shape of the magnetic anomaly depends not only on the direction of total magnetization but also on the shape of the magnetic body and on the spatial relations among different bodies that differ in their magnetizations (either magnitude or direction, or both). An excellent overview of aeromagnetic methods (including data acquisition and processing, and techniques for interpretation) is given by Blakely and Connard (in press); reports by Hinze (1985) and Paterson and Reeves (1985) also cover this subject.

Igneous Rocks

In general, concentrations of Mt-Usp_{ss} grains tend to be higher in basic rocks (about 5–10 percent by volume) than in intermediate and acidic rocks (about 1–3 percent). The difference in magnetization between basic and acidic rocks is not as great as one might expect from differences in the Fe-Ti oxide contents. In basic rocks the titanomagnetites usually have high titanium content, weak magnetizations, and low Curie temperatures. Conversely, in intermediate and acidic rocks the titanomagnetites have low titanium content, strong magnetizations, and high Curie temperatures. In the latter, increasing SiO_2 content is associated with lower titanium content and higher oxidation states.

The aeromagnetic signatures of igneous rocks are strongly influenced by their cooling history, primarily because of the effects of cooling and oxygen fugacity on the solubility of the magnetic oxide solid solutions (Haggerty, 1979). The effects of mineral exsolution and of high- and low-temperature oxidation on mineral type, and consequently on magnetization, Curie temperature, and magnetic stability of the magnetite-ulvöspinel solid-solution series minerals are summarized in figure 14. Both exsolution and high-temperature oxidation favor the isolation of low-temperature titanomagnetite and therefore lead to increases in magnetization, Curie temperature, and magnetic stability. Advanced high-temperature oxidation of magnetite + ilmenite, however, creates weakly magnetic hematite (Curie temperature of 680 °C) and nonmagnetic titanium-rich phases. Low-temperature oxidation of magnetite-ulvospinel to titanomaghemite causes a decrease in magnetization, an increase in Curie temperature, and little change (perhaps a small increase) in magnetic stability. As with high-temperature oxidation, low-temperature oxidation of low-titanium magnetite to hematite greatly diminishes magnetizations.

Exsolution and oxidation also strongly influence rock magnetic properties by decreasing magnetic grain sizes. For example, the separation of original grains of Mt-Usp_{ss} by exsolution or by high-temperature oxidation into segmented particles of magnetite + ulvöspinel or of magnetite + ilmenite, respectively (fig. 14), creates

REACTIONS	SATURATION MAGNETIZATION	CURIE TEMPERATURE	MAGNETIC STABILITY
MINERAL EXSOLUTION Mt–Usp_{SS}→Usp+Mt	Increase	Increase	Increase
HIGH-TEMPERATURE OXIDATION Mt–Usp_{SS}→Mt+Ilm	Increase	Increase	Increase
ADVANCED OXIDATION Mt+Ilm→Ht+Pb+R	Decrease	Increase	Increase
LOW-TEMPERATURE OXIDATION Mt–Usp_{SS}→(Ti) Maghemite Mt→Ht	Decrease	Increase	Increase

Figure 14. Reactions that involve exsolution and oxidation and their effects on saturation magnetization, Curie temperature, and magnetic stability. Mt-Usp_{ss}, magnetite-ulvöspinel solid solution; Ilm, ilmenite; Ht, hematite; Pb, pseudobrookite; R, rutile.

smaller intergrowths of ferrimagnetic magnetite with antiferromagnetic or paramagnetic phases. In general, fine-grained titanomagnetites and magnetite have higher remanent and lower induced magnetizations than coarse-grained particles of identical composition. High Koenigsberger ratios ($Q > 1$, remanent magnetizations dominant) are thus characteristic of volcanic rocks, which typically have undergone substantial high-temperature oxidation and contain small magnetic particles, whereas low ratios ($Q < 1$, induced magnetizations dominant) are characteristic of many coarse-grained intrusive rocks.

Metamorphic Rocks

Magnetic minerals may be produced or destroyed during metamorphism. In metasedimentary rocks the production of magnetite depends mainly on two factors that are largely inherited from the original sediment: (1) the total iron content, and (2) the oxidation state of the iron (the relative amounts of Fe^{3+} and Fe^{2+}). These factors control the amounts and types of iron oxide minerals that may form by limiting potential production of iron oxide and by controlling the partitioning of iron between oxides and silicates (McIntyre, 1980; Grant, 1984/1985a). Regional metamorphism of sedimentary rocks under conditions of lower greenschist to granulite facies drive many reactions that are capable of producing secondary magnetite (Grant, 1984/1985a). In general, formation of magnetite is favored in iron-bearing rocks under low-grade conditions or under high-grade conditions that promote the dehydration and breakdown of hydrous minerals such as biotite and amphiboles. Extreme metamorphism, which involves differential melting, strongly reduces magnetizations, possibly because of recombination of iron and titanium oxides to $Mt\text{-}Usp_{ss}$, if titanium is available (McIntyre, 1980; Grant, 1984/1985a).

Other intrinsic properties that influence the production of magnetite in metamorphic rocks include the contents of silica, carbon, and aluminum. McIntyre (1980) made the following generalizations: (1) Magnetite formation is favored in rocks that are undersaturated in silica; in the iron-oxygen system, silica saturation expands the stability field of fayalite (iron silicate) at the expense of magnetite. (2) The presence of carbon may restrict the formation of magnetite. Gas phases CO and CO_2 produced from carbon can lower oxygen fugacities below the magnetite stability field at high metamorphic temperatures (more than 630 °C). (3) In micaceous rocks, excess aluminum favors muscovite over biotite, and as a result the silicate minerals do not compete effectively with the oxides for available iron. Therefore, high aluminium content favors the production of magnetite.

Strong magnetic contrasts may develop in rocks of similar composition that have undergone different metamorphic reactions due to different metamorphic conditions. Moreover, metaigneous rocks of similar bulk composition may have different magnetizations that reflect differences in the original magmatic conditions of oxygen fugacity and temperature.

Magnetizations of igneous rocks are usually diminished by metamorphism and metasomatism due to destruction of preexisting magnetic minerals (Haggerty, 1979; McIntosh, 1983). Magnetite, however, can be produced by alteration of olivine and orthopyroxene during serpentinization of mafic and ultramafic rocks. Evidence for both depletion of primary magnetite and creation of secondary magnetite by hydrothermal alteration in a plutonic terrane (Criss and Champion, 1984) will be further discussed.

Mineralization in Igneous and Metamorphic Rocks

In certain ore-forming environments magnetic contrasts are useful as pathfinders to mineral deposits (Grant, 1984/1985b; McIntyre, 1980; Clark, 1983; Wright, 1981). Destruction of primary magnetic minerals or addition of secondary magnetic minerals, either by conversion of preexisting nonmagnetic phases or by growth from ore-related fluids, can develop such magnetic contrasts. Ferrimagnetic magnetite and pyrrhotite, as well as antiferromagnetic hematite if present in sufficiently large quantity, may be sources of magnetic anomalies in mineralized rocks.

Sedimentary Rocks

The amount, type, and grain sizes of detrital magnetic minerals in epiclastic rocks depend on the nature of and proximity to the source areas, as well as on the depositional environment. Postdepositional diagenetic and authigenic alterations strongly influence the magnetic character of sedimentary rocks and can either enhance or diminish the original magnetization. In general, the degree of oxidation of detrital titanomagnetite, if initially present, to hematite and other ferric oxide minerals increases with age (Van Houten, 1968), but such a relation has not been quantified in terms of magnetization. Rocks that contain detrital and (or) secondary hematite from usual depositional and (or) diagenetic processes are abundant in the sedimentary column, but they have low total magnetizations and are of little interest in aeromagnetic studies. However, important changes in magnetization of sedimentary rocks may be produced by reducing conditions that are related to mineralization or to hydrocarbons. Under sulfidic reducing conditions the original magnetization may be either suppressed by the replacement of the detrital iron oxides by iron sulfides or enhanced by the production of magnetic sulfide minerals, such as pyrrhotite or greigite. The formation of diagenetic magnetite related to hydrocarbons has been proposed as another process by which the magnetization of sedimentary rocks may be increased under reducing conditions (Donovan and others, 1979; McCabe, 1986). Geochemically reducing fluids, especially those with organic acids, are also known to dissolve iron-titanium oxide minerals and thus to diminish magnetizations.

Sedimentary rocks of chemical or biogenic origins, such as evaporites and carbonates, usually have low to negligible magnetizations. In certain settings, such as salt domes, these rocks may be juxtaposed with more magnetic rocks and thereby indirectly associated with subtle but important negative magnetic anomalies. In some strata, magnetic minerals, principally magnetite, have precipitated chemically from sea water and may comprise or be closely associated with mineral deposits. For example, magnetite that formed in this manner produces high magnetizations in Lower Proterozoic banded iron-formations and in distal sediments related to volcanogenic base-metal massive sulfide deposits (McIntyre, 1980; Large, 1977).

CRUSTAL DISTRIBUTION OF SOME MAGNETIC MINERALS

A simplified summary of the distribution of magnetic minerals that may be important for magnetic surveys is presented in figure 15. This figure serves as an outline for the remainder of the paper. The shapes of the symbols denote either a primary (circle) or secondary (square) magnetic mineral. Depletion (destruction) of a mineral is indicated by a circle-slash (ø) symbol. The sizes of the symbols have not been quantitatively derived and are only crude indications of relative abundance of the different minerals. The symbol sizes have meaning only within a single column (crustal setting); a comparison of sizes between columns has no significance. The summary is not comprehensive and is intended simply as a general guide.

Oceanic Crust

The dominant magnetic mineral in the uppermost layer of newly formed oceanic crust, which is mostly composed of pillow lavas erupted from spreading centers, is titanomagnetite that has a nearly uniform content of ulvöspinel (Usp about 60 percent, which corresponds to a Curie temperature of about 175 °C) (Johnson, 1979). Hydrothermal alteration, however, readily converts the primary titanomagnetite to titanomaghemite, so that a CRM largely replaces the original TRM. The magnitude and direction of the CRM depend on those of the original TRM, the time and degree of alteration, and the polarity history during alteration. A model of such CRM acquisition (Raymond and LaBrecque 1987) helps explain a number of magnetic features of the oceanic crust, among them the decrease in amplitude of anomalies away from spreading ridges, the enhanced magnetization of the Cretaceous Quiet Zones, and amplitude and skewness discrepancies in intermediate- and short-wavelength magnetic anomalies. The alteration also results in increases in Curie temperature and in remanent stability. Nevertheless, the pattern of positive and negative anomalies, which reflect the normal/reversed polarity rock sequence, will be preserved if polarity intervals are randomly distributed during CRM acquisition (Raymond and LaBrecque, 1987).

Magnetite is rarely described as being present in samples of oceanic crust, and thus has been considered uncommon in these rocks. The paucity of reported magnetite occurrences, however, may stem partly from the lack of extensive deep sampling below the pillow-basalt layer. Magnetite (or titanomagnetite that has higher Curie temperatures and magnetizations than that produced near or on the sea floor) may form in the oceanic crust in at least two different ways. These magnetic minerals may form from Mt-Usp_{ss} by oxidation/exsolution during initial cooling of intrusions. This mechanism is represented by the circle for magnetite in figure 15. Magnetite may also be produced by later high-temperature alteration (for example, by hydrothermal reheating) of titanomagnetite under oxidizing conditions or by thermal breakdown of titanomaghemite, regardless of redox conditions. Kristjansson and Watkins (1977), in fact, suggested that the Curie temperature of magnetite (580 °C) determines the base of the magnetic oceanic crust. Other magnetic minerals, which may be responsible for deep-seated magnetic anomalies over oceanic crust but for which direct evidence is lacking, are alloys of Fe-Ni-Co-Cu and metallic iron that might result from the partial serpentinization of ultramafic bodies (Haggerty, 1978). Such magnetic phases have Curie temperatures in the range 620–1,100 °C and thus, if present, would greatly deepen the Curie isotherm.

The 0.5-km-thick layer of pillow basalts makes a substantial contribution to the observed marine magnetic anomalies, but it cannot solely account for the magnitude of observed anomalies. Recent reviews of the sources of the magnetization of the oceanic crust (Johnson, 1979; Lowrie, 1979) favor an additional contribution from a magnetic layer of intrusive rocks below the pillow basalts.

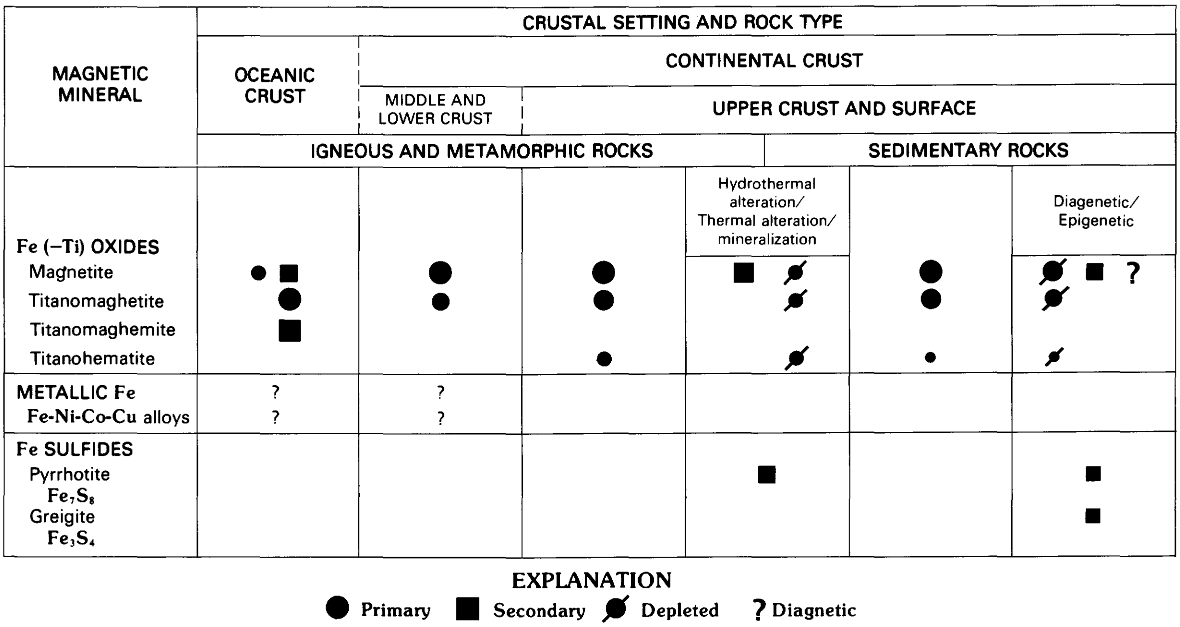

Figure 15. Summary of the crustal distribution of the aeromagnetically important minerals. As explained in the text, the minerals are divided according to primary (circle) and secondary (square) origin. The primary minerals are considered to be (l) minerals crystallized in magma, (2) deuteric alteration products in igneous rocks or metamorphic products in metamorphic rocks, or (3) detrital minerals in sedimentary rocks (including chemically precipitated magnetite, such as that deposited in banded iron-formations). The circle-slash symbol denotes settings or conditions under which minerals may be depleted. Diagenetic magnetite is represented by a bold query. Secondary minerals include those formed by replacement of earlier magnetic precursors (such as titanomaghemite from titanomagnetite in the oceanic crust) and those formed by nucleation or from a nonmagnetic precursor. For example, magnetite in the oceanic crust is considered to be both primary, formed during initial cooling by the exsolution of original $Mt\text{-}Usp_{88}$ (titanomagnetite), and secondary, formed by the hydrothermal alteration of either titanomagnetite or titanomaghemite. Under conditions of hydrothermal alteration, local thermal alteration (as in contact metamorphism), and mineralization in the continental crust (shown in the figure as hydrothermal alteration, thermal alteration, and mineralization, respectively), primary magnetite may be destroyed or new magnetite may be formed. Secondary magnetite may be destroyed later in these settings. The diagenetic and epigenetic alterations are represented in the column on the far right. The sizes of the symbols have not been derived quantitatively and are only crude indications of relative abundance of the different minerals. The symbol sizes have meaning only within a single column (crustal setting); a comparison of sizes between columns has no significance.

A recent iteration of this two-layer model consists of an upper, 0.5-km-thick layer with M = 5 A/m (where M is the magnetic dipole moment per unit volume, taking into account partial oxidation of original titanomagnetite) and a lower, 3.5-km-thick, dike and gabbro layer with M = 0.5 A/m (Banerjee, 1984). Magnetization in the lower layer may be carried by both primary titanomagnetite and magnetite of either deuteric or hydrothermal origin (Banerjee, 1984).

The magnetic properties of the first drill-core samples from beneath the pillow-basalt layer suggest a more complicated picture than that portrayed by two-layer models and provide direct evidence for a role for magnetite in oceanic-crust anomalies (Smith and Banerjee, 1986). The drill hole penetrated 1,076 m of crust in the Pacific Ocean about 200 km south of the Costa Rica Rift and intersected three distinct petrologic and magnetic layers. The upper layer of pillow basalts (about 0.5 km thick) has an average NRM moment of 5.5 A/m that resides in titanomaghemite. Below this layer is a mixed zone (270 m thick) of pillow lavas and dikes which have been hydrothermally altered to greenschist facies. The alteration produced some magnetite by the oxidation of primary titanomagnetite but more importantly promoted the replacement of titanomagnetite by silicate minerals. Consequently, this layer has a low NRM moment (average of 0.74 A/m) and contributes little to magnetic anomalies. The bottom 300 of the core consists of a sheeted dike complex, in which magnetite production has occurred as in the overlying layer but in which replacement by silicate minerals is minor. As a result NRM moment in the bottom layer is sufficiently large (average of 1.4 A/m) to contribute significantly to the anomalies.

Many factors cause vertical and lateral variations in the magnetization of the oceanic crust and thereby produce irregularities in magnetic anomaly patterns. These factors include the geometry, composition, and cooling history of intrusions below the upper extrusive rocks; the compositions and temperatures of hydrothermal fluids; the geometries of hydrothermal convection cells; and the positions of the cells with respect to the spreading ridge or to the accreting plate (Johnson, 1979; Smith and Banerjee, 1986; Cathles and Fehn, 1985). Better understanding of the influences of these factors on magnetic contrasts is important in mapping and interpreting the geology of the oceanic crust.

Lower Continental Crust

Long-wavelength magnetic anomalies sensed primarily from satellites are potentially useful for mapping large, deep crustal bodies that may reflect the tectonic and geochemical evolution of the continents (Mayhew and others, 1985; Mayhew and LaBrecque, 1987; Wasilewski and Mayhew, 1982; Wasilewski and others, 1979). These deep-seated anomalies require sources with large vertical (about 10–20 km) and lateral (about 100 km or more) dimensions and magnetizations of about 3–6 A/m, approximately 10–100 times greater than that of the average value of upper crustal rocks at the surface and even greater than those obtained from rare deep-crustal sections now at the surface (Shive and Fountain, 1988; Shive, 1989). Induced magnetization is an important (probably dominant) contributor to total magnetization; VRM may contribute to the magnetization of deep crustal sources.

Nearly pure magnetite is probably the major source of high magnetization in the lower crust. This conclusion comes from studies of xenoliths and uplifted sections of lower crustal rocks and from thermodynamic considerations (Wasilewski and Mayhew, 1982; Schlinger, 1985; Williams and others, 1985; Frost and Shive, 1986). The rock magnetic and compositional studies of lower crustal rocks are consistent with thermodynamic predictions of low titanium content in the magnetite; typical measured Curie temperatures range from about 550 to 580 °C. The few exceptions noted by Wasilewski and Mayhew (1982) are xenoliths from rift zones with Curie temperatures less than 300 °C and were interpreted by them to indicate the presence of deep crustal titanomagnetite in anhydrous, perhaps relatively reducing, zones in a steep geothermal gradient. Thus in most areas the Curie isotherm is controlled by nearly pure magnetite. At deeper crustal depths the isotherm is elevated from 580 to about 600 °C, because of the effect of pressure on Curie temperatures (Schult, 1970; Frost and Shive, 1986).

A discontinuity in magnetic mineralogy occurs at the mantle-crust boundary (Mohorovičić discontinuity, commonly called the "the Moho"); below the Moho nonmagnetic spinels dominate (Frost and Shive, 1986; Mayhew and others, 1985). Thus the Moho is considered to be the bottom of the magnetic crust, except in areas of high heat flow where elevated temperatures may raise the base of the magnetic crust far above the Moho (Mayhew and others, 1985). Nevertheless, certain satellite anomalies have dimensions and amplitudes that indicate very deep sources (Taylor and Frawley, 1987), possibly in the upper mantle (P. Taylor, oral commun., 1987); if this is the case, minerals other than magnetite apparently cause the magnetic contrasts. Haggerty (1978, 1979) and Haggerty and Toft (1985) have argued that metallic iron and iron alloys formed in altered serpentinites may account for deep-seated anomalies, but Frost and Shive (1986) dismissed a major contribution from these phases on thermodynamic, petrologic, and geologic grounds. The locations and causes of deep-seated magnetic anomalies are topics that deserve more study.

Other important uncertainties in the distribution of magnetization in the lower and middle crust include changes in the quantity of magnetite as a function of depth and the effects of temperature and pressure on magnitudes of susceptibility and VRM. Enhancement of susceptibility in magnetite with increasing temperature within about 150 °C of the Curie temperature (the Hopkinson effect) has been considered an important contributor to high magnetizations in the lower crust (Wasilewski and others, 1979). Recent experimental work by Schlinger (1985), however, suggests that this contribution may not be as large as previously thought. Another critical factor is the contribution of VRM to total remanence. Although the rate of VRM acquisition increases with increasing temperature (Dunlop, 1983; Shimazu, 1960), data are lacking on the variations in VRM magnitude as a function of temperature and pressure.

Upper Crust and Surface

Igneous and Metamorphic Rocks

At depths shallower than about 5 km in the continental crust, minerals of the magnetite-ulvöspinel series dominate magnetizations of most rocks that are the sources of aeromagnetic anomalies. In certain plutonic, volcanic, and uplifted high-grade metamorphic settings, however, ferrimagnetic titanohematite may also produce anomalies. Many rock types have broad and overlapping ranges of magnetic susceptibilities and magnitudes of NRM, and thus, correlations among aeromagnetic signatures and lithologies are commonly not possible (Clark, 1983). Nevertheless, examples of useful relations between the magnetizations and petrology exist.

An instructive example comes from an aeromagnetic and rock magnetic study of Precambrian igneous and metamorphic rocks of the Adirondack Mountains, New York, in which regional anomalies were closely correlated with mineralogy and lithology (Balsley and Buddington, 1958). Magnetic highs are caused by NRM in titanomagnetites, whereas magnetic lows from gneisses are produced by reversed remanent magnetizations in titanohematite. These reversed directions resulted from a self-reversing process (the acquisition of a remanent direction opposite to that of the applied field) that is peculiar to a narrow range of mineralogic compositions of ferrimagnetic titanohematite. Although potentially important in gneissic terranes, ferrimagnetic titanohematites are not the dominant magnetic species in most other rock types, based on abundant paleomagnetic and rock magnetic data acquired over the past 25 years. This conclusion differs from those of Grant (1984/1985a), who, from our perspective, overemphasized the importance of titanohematite solid-solution series minerals to the NRM of rocks and the role of self-reversed magnetizations in producing magnetic anomalies.

An example that illustrates the potential for identification of rock types by magnetic contrasts concerns granites of different origins. Petrochemical and isotopic distinction can be made between granites derived primarily from melting of igneous crust (I-type) and those from melting of sedimentary crust (S-type). Such a distinction, which reflects regional tectonic and magmatic evolution, may, in some settings, be discerned aeromagnetically. This is because magnetite tends to be sparse in granites derived from carbonaceous metasedimentary rocks (S-type) and abundant in granites generated by melting of rocks that have low contents of carbonaceous matter (I-type). Clark (1983) stated that similar magnetic distinctions exist for amphibolites derived from igneous or sedimentary rocks. In a study of granitoids of the Piedmont Province in the southern Appalachian Mountains, Wenner (1981) and Ellwood and Wenner (1981) found that plutons that have low initial ^{18}O content correspond to I-type granite and have relatively high magnetic susceptibilities (greater than 1.2 $\times 10^{-2}$ SI). In contrast, granites that have high initial ^{18}O content correspond to S-type granite and have susceptibilities less than about 1.2×10^{-2} SI. Such petrologic-magnetic relations are similar to those described by Ishihara (1977, 1981) for "magnetite-series" and "ilmenite-series" granites. The former contain more than 0.1 volume percent iron-titanium oxide (dominantly magnetite) and are considered important sources for magnetic anomalies, whereas the latter contain less than 0.1 percent iron-titanium oxides, mostly ilmenite, and hence usually have magnetizations (magnetic susceptibility less than about 0.3×10^{-2} SI) too low to produce important aeromagnetic anomalies.

Detailed oxygen-isotopic and magnetic susceptibility studies of aeromagnetic anomalies over the southern half of the Idaho batholith (Criss and Champion, 1984) demonstrate the usefulness of, and limits to, the interpretation of the extent and origin of magma types from magnetic data. Many unaltered samples exhibited relations between $\delta^{18}O$ values and magnetic susceptibility similar to those described for the Appalachian Piedmont granitoids (Ellwood and Wenner, 1981). However, because hydrothermal activity strongly modified the original $\delta^{18}O$ and susceptibility magnitudes in many exposed plutons, as discussed later, simple characterization of magma type by magnetic properties is not possible for most plutons (Criss and Champion, 1984). It is worth noting also that some plutons in the Idaho batholith defy the standard geochemical classification as I or S type, or as magnetite or ilmenite series, regardless of hydrothermal alteration.

Volcanic rocks exhibit many characteristics of their intrusive equivalents. However, combinations of exsolution and high-temperature oxidation commonly cause enormous variations in the magnetic properties of volcanic rocks, even within individual flows (Wilson and others, 1968; Haggerty, 1976). Moreover, in some extrusive rocks, notably welded ash-flow tuffs, emplacement and cooling phenomena, such as initial thickness and the effects of compaction, are capable of locally causing large, systematic changes in primary directions and magnitudes of NRM (Rosenbaum and Snyder, 1985; Rosenbaum, 1986; Rosenbaum and Spengler, 1986).

Remanence commonly dominates total magnetizations in volcanic rocks, mainly because of the typically small initial grain sizes and (or) the subdivision of magnetic phenocrysts into effectively smaller portions by exsolution and oxidation; such grains consequently produce relatively high TRM and low susceptibility. For example, an aeromagnetic low within the 23.1-Ma Lake City caldera, San Juan Mountains, Colorado, is produced by the reversely magnetized intracaldera ash-flow tuff (Grauch, 1987), the eruption of which caused the caldera collapse. Understanding of the magnetic sources was aided by modeling that used rock magnetic and paleomagnetic data from the caldera units (Grauch, 1987); the conclusions of this study also provide an instructive example of the interplay between remanent and induced magnetizations. Both types of magnetization exhibit large variations vertically and areally in the intracaldera tuff. The reversed NRM dominates magnetizations in parts of the intracaldera tuff to produce the observed low. Elsewhere, reversed remanent components are effectively cancelled by induced components to yield weak total magnetizations that have little aeromagnetic expression.

Recent contributions have shed light on petrologic controls of magnetite production in metamorphic rocks. Krutikhovskaya and others (1979) showed that premetamorphic compositions and the degree of metamorphism of rocks in the Ukrainian Shield are the main determinates of magnetite content. The quantities of magnetite and of iron + magnesium + manganese + titanium oxides, as well as the magnitudes of the rock magnetization, all increase with a decrease in SiO_2 content and with an increase in metamorphic grade. The results imply that metamorphic magnetite was derived from the breakdown of iron and magnesium silicate minerals (Grant, 1984/1985a).

Even in rocks that have similar original compositions, different metamorphic reactions and conditions may either produce or consume magnetite. For example, Robinson and others (1985) proposed that many of the magnetic anomalies associated with chemically similar metavolcanic rocks of the Carolina slate belt in North Carolina are caused by magnetic contrasts produced by different activities of water and oxygen during metamorphism. Apparently, iron was incorporated into magnetite during greenschist-facies metamorphism and into silicate minerals during amphibolite-facies metamorphism of equivalent rocks.

The control on magnetite content by metamorphic reactions is also demonstrated by a detailed study of a contact metamorphic aureole in pelitic rocks at the margins of an Upper Carboniferous granitoid pluton in South Carolina (Speer, 1981). Bulk rock compositions in the aureole hornfelses do not vary greatly. Controlled mainly by temperature but also by changes in fluid pressure and composition, many metamorphic reactions occurred over a short distance. These reactions produced magnetite in the outer and middle parts of the aureole but destroyed magnetite near the pluton under conditions of relatively high temperature and low oxygen fugacity. The metamorphic magnetite produced a ring-shaped magnetic high that is concentric with the contact between the pluton and the country rock.

Magnetite is not the only cause of annular magnetic anomalies around plutons. Pyrrhotite is also reported as the source of magnetic lows from contact metamorphic aureoles in Jurassic argillites around Late Cretaceous and early Tertiary plutons (mainly granodiorites) in the Alaska Range, south-central Alaska (Griscom, 1979; A. Griscom, oral commun., 1987). The magnetic lows are caused by reversed remanent magnetizations carried by the ferrimagnetic (monoclinic) pyrrhotite.

Metavolcanic rocks of virtually the same lithology may have different magnetization because of different original conditions in the source magmas. Urquhart and Strangway (1985) found distinct magnetization differences in a suite of metamorphosed iron-rich tholeiites, which had essentially the same major-element chemistry. They ascribed the differences to contrasts in the original temperature and oxygen fugacity conditions of the source magmas.

We next discuss some effects of hydrothermal fluids and of high-temperature, ore-related alteration on the original magnetizations of igneous, metamorphic, and sedimentary rocks. Although the magnetizations of some rocks exposed to such fluids and conditions may change little and remain dominated by the original magnetic particles, the chemical conditions involved in such alteration usually destroy or create magnetic phases (fig 15), and (or) may reset earlier remanence. The temperatures of such alterations are too low to allow the formation of $Mt\text{-}Usp_{ss}$ or $Ilm\text{-}Ht_{ss}$. Of the magnetic oxides, therefore, only magnetite is normally an aeromagnetically important secondary mineral in these settings. Many ores consist of, or are associated with, metal sulfide minerals, including magnetic pyrrhotite (Fe_7S_8). More common nonmagnetic sulfides, particularly pyrite (FeS_2), also play important roles in decreasing magnetization by replacing magnetic oxides or in indirectly enchancing magnetization by providing concentrations of iron that are easily converted to magnetite by oxidation at elevated temperature.

Hydrothermal Alteration

The geochemical and magnetic study of the Idaho batholith by Criss and Champion (1984) documented both enhancement and depletion of magnetization by hydrothermal activity (at temperatures between about 150 and 400 °C) related to the emplacement of Tertiary intrusions into Mesozoic plutons of the Idaho batholith. Rocks that underwent strong hydrothermal alteration in the interior of the batholith have lower magnetic susceptibilities than their unaltered equivalents, presumably because of oxidation of primary magnetite. Hanna (1969) reached a similar conclusion to explain low magnetizations of mineralized plutons of the Boulder batholith, Montana. In contrast, similar alteration, but probably involving less water and hence lower oxidation potential, increased magnetic susceptibility in parts of some leucocratic plutons in the Idaho batholith. This increase was ascribed to the growth of "hydrothermal" magnetite.

Little is known about the effects of hydrothermally driven metasomatism on the magnetizations of silicic volcanic rocks. It appears, nevertheless, that metasomatic conditions that involve oxygen-rich fluids destroy titanomagnetite. Metasomatic alteration, which resulted in enrichment of potassium, decreased magnetic susceptibility and remanent intensities of intracaldera welded tuffs relative to unaltered material of some ash-flow tuffs of the Mogollon-Datil volcanic field, New

Mexico (McIntosh, 1983). Oxidizing and perhaps slightly acidic conditions were thought to be responsible for the formation of hematite from magnetite and for the dissolution of magnetite. Preliminary study of the Carpenter Ridge Tuff (27.61 m.y.), the major host for precious- and base-metal vein deposits of the Creede mineral district in the Bachelor caldera of the central San Juan volcanic field, Colorado, shows that the potassium-metasomatized intracaldera facies (Bachelor Mountain Tuff) have much lower magnetization than that of non-metasomatized outflow facies (D. Sweetkind, written commun., 1989). Reduction of magnetization by potassium-metasomatism or other pervasive alteration may explain, at least in part, why some calderas, such as the Bachelor caldera, have indefinite aeromagnetic expression, whereas other calderas, which are filled with largely unaltered tuffs of nearly identical initial compositions, are the sources of large-amplitude magnetic anomalies (Williams and others, 1987)

Magnetization and Mineral Deposits

The practical value of magnetic exploration for mineral deposits has long been recognized (Grant, 1984/1985b; Clark, 1983; and Wright, 1981 for recent summaries) and is based on the experience that high or low magnetizations characterize some ore-forming environments. Magnetic contrasts may be related to formation or destruction of magnetic minerals in direct response to mineralization or related to a generally high or low magnetic-mineral content of a particular host rock or, on a larger scale, of a favorable rock assemblage. For example, certain types of mineral deposits were thought by Ishihara (1981) to be related to magnetite-series or to ilmenite-series magmatism with their respective high and low magnetizations. As a specific case, Hattori (1987) described an association between magnetite-bearing, anomaly-producing felsic intrusions and gold deposits in Archean rocks of the Superior Province of the Canadian shield. The association of magnetic intrusions and mineralization suggests either that ore constituents were derived from oxidized magmas or that the intrusions were emplaced in zones of deep flow of gold-bearing fluids. Other associations among magnetic patterns and mineral deposits can be attributed to tectonic setting, in particular to the extent of faulting and its controls on the chemistry and flow paths of altering fluids (McIntyre, 1980).

Effective use of magnetic patterns in mineral exploration depends on understanding relations among petrology and structure of the host terrane, mineralization, and magnetization. Many such relations are discussed in the review by Grant (1984/1985b). Yet much remains to be learned about links among ore petrology and geochemistry, the genesis of magnetic minerals, the structure of the host terrain, and magnetic anomalies, as well as about the applications of these links to effective magnetic exploration in frontier areas

Although a few mineral-deposit settings have a characteristic magnetic signature, most settings do not. This lack of uniformity has many causes, including: (1) variations in chemistry of mineralizing fluids; (2) differences in host-rock composition, structure, and crustal level; and (3) variations in the type and degree of post-ore alterations. We will not dwell at length on the associations among mineral deposits, magnetite, and magnetic signatures that are reported by other authors. However, we will examine some examples that provide typical reasons for different magnetic signatures that arise from similar mineral deposits. These examples are drawn from skarn and porphyry copper deposits and from the magnetite-pyrite association that is common to many types of deposits.

Skarn Deposits

Skarns are metal-bearing deposits associated with the hydrothermal replacement of carbonate rocks by a complex assemblage of Ca-Fe-Mg-Al silicate minerals. The classification, description, tectonic-magmatic settings, and origins of skarn deposits are presented in Einaudi and others (1981). Magnetite is common in many skarns and is the ore mineral in iron skarns. Magnetite enrichment is associated with many zinc-lead, molybdenum, magnesian tin-bearing skarn deposits and with some tungsten and calcic tin-bearing skarns. The magnetite content in skarns depends on many factors. For tungsten skarns, differences in magnetite content reflect different depths of emplacement of related intrusions and different oxidation states of the altered rocks (Einaudi and others, 1981). Tungsten skarns that were formed at great depth in a carbonaceous-rich, low-oxidation, and low-sulfidation environment contain abundant magnetite and only a small quantity of sulfide minerals, mainly pyrrhotite. In contrast, tungsten skarns that were formed at higher levels in carbonaceous-poor, intermediate-oxidation and intermediate-sulfidation environments may lack magnetite but tend to have relatively greater amounts of sulfide, principally pyrite. Copper skarn deposits are of special interest because of their common association with porphyry copper stocks (Einaudi and others, 1981; Einaudi, 1982a, 1982b; Titley, 1982; Beane, 1982; Titley and Beane, 1981; Beane and Titley, 1981). Magnetite is common in both calcic and magnesian copper skarns but is apparently more abundant in the magnesian skarns.

Porphyry Copper Deposits

The association of magnetite with many porphyry copper deposits makes these deposits attractive targets for magnetic exploration. Magnetic anomalies may arise from both the igneous intrusion and from associated peripheral skarns. Jerome (1966) presented a model of a copper porphyry that portrays secondary magnetite in skarn at the margins of a mineralized intrusion as the cause of ground magnetic and aeromagnetic highs that might define an annular anomaly around an orebody. Grant (1984/1985b) discussed porphyries (based largely on the work of Lowell and Guilbert, 1970) and concluded that recognition of favorable environments for porphyry copper deposits may be based on the magnetic identification of felsic-intermediate plutons of appropriate size (about 1–10 km in diameter) and on the possible existence of a "magnetite halo" within the pluton. The Ely, Nevada, area provides an example of positive aeromagnetic anomalies associated with a porphyry copper deposit. Magnetic anomalies reflect the high magnetizations both of the quartz-monzonite intrusion and of the magnetite-bearing skarn in nearby carbonate strata (Wright, 1981).

Other important magnetic characteristics of the porphyry copper environment have been discerned from a regional aeromagnetic map of Arizona which was designed to show large-wavelength anomalies from deeper and broader sources than those at the ore-deposit scale (Sumner, 1985). On this map most of the copper districts are associated with regional lows, with arcuate magnetic lows at the district level, or with a 400-km-long magnetic lineament that is interpreted to reflect a late Precambrian transform fault. Sumner (1985) suggested that the magnetic lows are caused by the destruction of presumable primary magnetite in hydrothermal fluids that circulated in deep fractures. Conversely, the regional magnetic data also revealed a relation between a few deposits and magnetic highs that may be at least partly explained by relatively mafic compositions of the mineralized intrusions.

Magnetite-Pyrite Association

The association between magnetite and nonmagnetic iron sulfide minerals is common to many types of mineral deposits. We discuss nonmagnetic iron sulfides (referred to here as pyrite, the most common variety) because they may play important but not fully recognized roles in the magnetic contrasts of some mineral deposits.

The relationship between magnetite and pyrite in some types of mineral deposits can be explained on the basis of thermodynamically controlled sequences of precipitation (McIntyre, 1980; Grant 1984/1985b; Beane, 1982). Nevertheless, other explanations for the magnetite-pyrite association should be considered, especially in view of the complex thermal, tectonic, and geochemical histories of many mineral districts. For example, pyrite can be converted to magnetite by the loss of sulfur at elevated temperatures. In addition, magnetization can be reduced by the replacement of primary or secondary magnetic iron oxide minerals by nonmagnetic sulfide minerals (Wright, 1981). Such distinctions, which can usually be made on petrographic criteria, are obviously important for genetic models that link mineral assemblages and paragenesis to magnetic anomalies.

The anomaly over the Calico Hills in southwestern Nevada is an example of magnetic high that is caused by the high-temperature conversion of pyrite to magnetite. The anomaly is centered over an area underlain by a thick Paleozoic section which is capped by a thin veneer of hydrothermally altered Tertiary ash-flow tuffs. Bath and Jahren (1984) attributed the anomaly to strongly magnetized, thermally altered Paleozoic strata. Measurement of magnetic properties of drill-core samples indicates that some of the Paleozoic sedimentary rocks are nonmagnetic, whereas others are strongly magnetic (Baldwin and Jahren, 1982); the strongly magnetic rocks have an average NRM of about 4 A/m. Petrographic observations clearly demonstrate that the magnetic rocks contain magnetite which formed by the oxidation of pyrite and the resultant loss of sulfur. The magnetite occurs as replacements of pyrite cubes and pyritohedrons, pyrite veinlets, pyrite that filled cell lumens in detrital plant fragments, and framboidal pyrite. In contrast, nonmagnetic rocks either contain pyrite in the above forms (and little or no magnetite) or show no evidence of having ever contained pyrite.

Sedimentary Rocks

The magnetizations of epiclastic sedimentary rock depend directly on the abundance of detrital magnetic minerals and on the geochemical history of the rocks that either preserved or destroyed detrital magnetic minerals or that created diagenetic-authigenic magnetic oxide or sulfide minerals. Postdepositional effects on rock magnetization are especially important because of their potential as indicators of mineral and hydrocarbon deposits. Although most sedimentary materials contain magnetizations that are useable for paleomagnetism, the relatively thin sedimentary crust is normally not an important contributor to aeromagnetic anomalies. Even the most magnetic of the epiclastic sedimentary rocks generate low-amplitude, high-wavelength anomalies. Because flat-lying or shallowly dipping strata, even if strongly and uniformly magnetic, do not generate strong magnetic contrasts except locally at their edges, most anomalies from sedimentary rocks are those associated with steeply dipping or faulted units or with alterations controlled by fluid migration paths that either are vertically directed or are limited in horizontal extent.

Ironically, the most magnetic rocks, on the average, are sedimentary—the Early Proterozoic quartzmagnetite banded iron-formations (Clark, 1983). These rocks, which contain iron ores, can be easily detected by aeromagnetic methods. Magnetite in these rocks was chemically precipitated from sea water that was rich in dissolved ferrous iron before the buildup of free oxygen in the oceans. The magnetics and economic importance of banded iron-formations are described by McIntyre (1980) and Grant (1984/1985b), and we will not discuss further chemically precipitated, primary magnetite.

Strongly magnetic detrital minerals in the sedimentary rocks are primarily magnetite and titanomagnetite derived from crystalline or other sedimentary source areas. Ferrimagnetic titanohematite is generally rare or absent, but it may be the dominant magnetic oxide in some sedimentary rocks (Reynolds, 1977; Reynolds, 1982; Butler, 1982). Concentrated detrital magnetic grains can, of course, be responsible for anomalies, as shown below; for the most part, however, ferrimagnetic oxides are destroyed under most conditions of oxidation and reduction in sediments and sedimentary rocks. The extent of the destruction depends primarily on the duration and nature of altering conditions (such as Eh, pH, temperature, bacterial activity, concentrations of Fe^{2+} and Fe^{3+}, types and abundances of sulfur species, and organic matter). Such destruction includes dissolution and the oxidative or reductive replacement of the detrital oxides by essentially nonmagnetic minerals, such as of magnetite by hematite or by iron sulfide, respectively. Uncommon, but important in certain sulfide reducing environments, is the authigenesis of ferrimagnetic sulfide minerals, monoclinic pyrrhotite (Fe_7S_8) and cubic greigite (Fe_3S_4). The postdepositional growth of magnetite is currently a topic of growing interest among aeromagnetists and paleomagnetists. Such growth may be via inorganic geochemical pathways (Murray, 1979) or may be the result of bacterial metabolism. Two different types of magnetite-producing bacteria have been identified. Magnetotactic bateria produce small quantities of intracellular magnetite (less than 0.2-μm diameter) and operate in the presence of oxygen in marine, brackish and fresh-water environments; thus they deposit magnetite in surficial sediment layers that contain dissolved oxygen (Blakemore, 1982; Kirschvink and Chang, 1984). In contrast, dissimilatory iron reduction by anaerobic bacteria appears to be capable of producing large amounts of fine-grained (less than 0.2-μm diameter) magnetite outside the microbial cell (Lovley and others, 1987). The only known strain of dissimilatory iron-reducing bacteria was isolated in 1986 from fresh-water anaerobic sediments of the Potomac River (Lovley and others, 1987; Lovley and Reynolds, 1987). Possible roles of anaerobic, magnetite-producing bacteria in generating magnetic anomalies in sedimentary rocks (especially in fault zones above hydrocarbon deposits) are topics immediately worthy of intensive research.

RESEARCH FRONTIERS: PROBLEMS INVOLVING SEDIMENTARY ROCKS

Alteration Associated with Sandstone Uranium Deposits

The following examples from uranium-bearing sandstones in the San Juan basin, New Mexico, and in the south Texas coastal plain illustrate the destruction of detrital magnetic grains. The two areas have either not been surveyed or not been assessed in sufficient detail to determine whether ore-related alteration has caused magnetic anomalies; moreover, rock magnetic studies are incomplete or lacking in these examples. However, on the basis of the originally high contents of detrital magnetic minerals and on the spatial distribution of zones that contain or lack the magnetic grains, it seems likely that current aeromagnetic techniques are capable of detecting the effects of near-surface, uranium-related alterations on sandstones that originally contained abundant detrital magnetic grains.

Most uranium deposits that occur in Phanerozoic sandstones are classed either as tabular or as roll-type deposits (Nash and others, 1981). The largest uranium reserves in the United States are found in the tabular ore deposits of the Upper Jurassic Morrison Formation on the Colorado Plateau. Many of these deposits differ in some important genetic aspects, but all share a common association with organic matter. The tabular orebodies in sandstones of the Westwater Canyon and Brushy Basin Members of the Morrison in the Grants uranium region in west-central New Mexico consist of uranium intermixed with epigenetically introduced organic matter that was expelled by compaction from overlying mud-flat facies of the Brushy Basin Member (Turner-Peterson and Fishman, 1986; Fishman and Turner-Peterson, in press). The organic matter, which was derived from detrital carbonaceous debris, was apparently transported as humic and perhaps as other organic acids in alkaline, mildly reducing fluids. Such acids leach iron from the Fe-Ti oxide minerals (Lynd, 1960; Schnitzer and Skinner, 1965; Baker, 1973; Adams and others, 1974; Schnitzer and Kodama, 1977).

Petrographic, geochemical, field and mine mapping, and laboratory and borehole magnetic susceptibility studies document important relations among the genesis of the uranium deposits (including the nature and timing of ore formation and paths of mineralizing fluids), the alteration of Fe-Ti oxides, and the magnetic properties (Adams and others, 1974; Adams and Saucier, 1981; Fishman and others, 1985; Fishman and Reynolds, 1986; Reynolds, Fishman, Scott, and Hudson, 1986; Fishman and Turner-Peterson, in press). The Fe-Ti oxide minerals (principally titaniferous magnetite and ilmenite) were abundant detrital components of the Morrison sandstones that are now exposed at the margins of the San Juan basin and are still well preserved in places, where they compose nearly 1 weight percent of the rock. In these sandstones, susceptibilities and remanent moments are typically greater than 5×10^{-4} SI (maximum 8×10^{-3} SI) and 10^{-4} A/m, respectively. In sandstone beds that encompass the uranium deposits (the altered zone), however, the detrital oxides are highly altered by iron dissolution and consist typically of relict titanium dioxide. The abundance of such relicts, as well as the spatial and paragenetic relations, indicate postdepositional alteration of detrital magnetic grains during ore formation, which was most likely caused by humic-rich solutions that originated in the Brushy Basin Member (Adams and others, 1974; Adams and Saucier, 1981; Fishman and others, 1985; Turner-Peterson and Fishman, 1986). In the altered zone, magnetic susceptibilities and remanent moments are uniformly less than 5×10^{-4} SI and 10^{-4} A/m, respectively. Based on borehole core studies, the altered zone is as much as 100 m thick and extends from the base of the Brushy Basin Member to below the ore lenses, which are typically only 2–10 m thick. Outcrop studies reveal that this pattern of alteration extends essentially uninterrupted many tens of kilometers along the southern and south-western margins of the basin. The studies also show that the degree of alteration of Fe-Ti oxide minerals decreases away from the Brushy Basin Member. Where the mud-flat facies of the Brushy Basin Member (the source of the humic acids) dies out to the north, the Westwater Canyon Member lacks uranium mineralization and contains abundant, unaltered Fe-Ti oxides through its entire stratigraphic extent (Fishman and Turner-Peterson, in press). Thus the presence of uranium deposits and the related destruction of detrital magnetic grains in the Westwater Canyon Member has been controlled largely by distribution of the mud-flat facies of the overlying Brushy Basin Member (Turner-Peterson and Fishman, 1986).

Roll-type uranium deposits form by invasion of geochemically reduced, iron disulfide (FeS_2) bearing sandstone by oxygenated, uranium-bearing ground waters, followed by the reduction-precipitation of the uranium. Encroachment of such waters into reduced strata creates a tongue-shaped zone of oxidized rock (the altered or oxidized tongue) and a redox (reduction-oxidation) boundary that separates the tongue from reduced ground. Uranium is concentrated in a crescentric envelope or roll on the reduced side of the redox boundary, with the convex side of the roll front pointing in the downdip direction into reduced rock.

Magnetic contrasts may develop in host beds of some roll-type deposits as a result of the replacement of detrital magnetic grains by iron sulfide minerals. In the south Texas coastal plain uranium deposits in the Miocene Catahoula Sandstone (for example, the Benavides deposit) and in the overlying Miocene Oakville Sandstone (for example, the Felder-Lamprecht deposit, Ray Point district), pre-ore sulfide (pyrite and marcasite) created a reduced geochemical and mineralogic zone that controlled the concentration of uranium. The FeS_2 minerals extensively replaced detrital magnetic grains (Reynolds and Goldhaber, 1978; Reynolds, 1982; Goldhaber and others, 1978, 1983). In the Benavides deposit, the sulfidization resulted from the invasion of the shallow (30–45 m deep) aquifers by sulfidic brines from deep sour-gas reservoirs along a normal growth fault that lies 1.5 km downdip from the roll front. The FeS_2 partly to completely replaced titaniferous magnetite grains as much as 2 km updip from the fault. Ferrimagnetic titanohematite, which was initially about half as abundant as magnetite, was more resistant to sulfidization, and consequently it is the dominant magnetic oxide in the reduced zone and in the altered tongue. More than 2 km updip from the fault, the sandstone was never sulfidized; in these beds the Fe-Ti oxide population has only been affected by partial hematite replacement of magnetite (Reynolds, 1982).

Although the magnetic susceptibility of disaggregated core samples was not measured, the abundances and distribution of the magnetic oxides were examined using separates of magnetic minerals. The magnetic fraction, as a percentage of the whole rock, ranges from nearly 1 weight percent in the oxidized beds farthest (2.5 km) updip from the fault to less than 0.1 weight percent in reduced rock closer to the fault. The magnetic fraction of the samples in between decreases systematically within this range with proximity to the fault. This pattern and petrographic-geochemical studies strongly suggest that the magnetic minerals were nearly uniformly distributed in the host beds by depositional processes and that the degree of replacement by sulfide minerals decreased systematically updip from the fault (Reynolds and Goldhaber, 1978; Goldhaber and others, 1978).

A similar pattern, but presumably a more subdued contrast, appears to be present in the Lamprecht-Felder deposit based on laboratory magnetic susceptibility measurements of core samples (from about 60–80-m depth) from the Lamprecht part of the deposit. Values of susceptibility are highest ($3–4 \times 10^{-4}$ SI) in the host beds that lie updip from the roll front and the sulfide-producing Oakville fault (1 and 1.5 km distant, respectively) and decrease systematically (to about

2×10^{-4} SI) in the roll front and closer to the fault (Scott and Daniels, 1976; Scott and others, 1983). Again, the increase in magnetization updip from the fault was likely caused by a decrease in intensity of sulfidization and the corresponding decrease in replacement of detrital magnetic grains.

Observations from the two roll-type uranium deposits suggest that the delineation of growth faults by their magnetic expressions may be a general guide for sulfidically reduced zones with potential for uranium mineralization elsewhere along the Texas coastal plain. Diminished magnetizations are predicted on the updip (northwest) sides of faults. Detailed aeromagnetic surveys directly over known faults, many of which tap the hydrocarbon-producing deep Edwards reef trend, would be desirable, because the faults themselves may have a distinctive signature. Such a possibility is based on observations that faults and fractures that tap hydrocarbon deposits elsewhere can be recognized as magnetic features on aeromagnetic maps. An example is the association between fractures and magnetic contrasts over oil fields in the Williston basin, Montana (R. Wold, oral commun., 1985). Geochemical and mineralogic causes that change magnetization along faults, especially those that may be associated with oil and gas fields, are topics of obvious importance to studies of aeromagnetism and rock magnetism.

In addition to the roll-type uranium deposits in sandstones that contain extrinsic (postdepositionally introduced) sulfide and that lack detrital organic matter, an equally important subclass of roll-type deposits is found in sandstones that contain detrital plant debris. Examples include the roll-type deposits in the Wyoming intermontane basins and in the Eocene Whitsett Formation of the south Texas coastal plain. In these "biogenic" deposits, the pre-ore sulfide is related to the metabolic activity of sulfate-reducing bacteria that feed on carbonaceous matter (Rackley, 1972; Granger and Warren, 1969; Reynolds and Goldhaber, 1983). In biogenic deposits that we have studied, magnetic oxides have been little affected by sulfidization; magnetite may be overgrown by pyrite, but replacement by pyrite is rare. These associations may be related to the typically low concentrations of sulfide in these ore-forming systems. Sulfide sulfur averages between 1 and 4 weight percent of the host rock in the Benavides, Lamprecht, and Felder deposits, but less than 1 percent in a deposit in the nearby Eocene Whitsett Formation. These observations would appear to contraindicate aeromagnetic exploration for roll-type deposits in areas that are remote from faults along which sulfidic brines have passed. Nevertheless, the fluvial sandstones in which most roll-type deposits occur may be aeromagnetic targets, based on the likelihood of greater concentrations of heavy minerals in these relatively coarse-grained, high-energy facies than in enclosing mudstone.

Alteration Associated with Hydrocarbon Seepage

Recently proposed models that link hydrocarbon seepage, authigenesis of magnetic minerals in near-surface strata, and high-frequency magnetic anomalies have encouraged magnetic exploration for oil and gas deposits (Donovan and others, 1979, 1984; Foote, 1984; Saunders and Terry, 1985; McCabe and Sassen, 1986). Interest in this approach stemmed mainly from an aeromagnetic survey of the Cement oil field, Oklahoma, in which total-field anomalies, which have short wavelengths and low amplitudes (less than 40 nT), were detected over an area of past oil seepage and current production (Donovan and others, 1979). Donovan and others (1979) reported as much as 1.2 weight percent magnetite in well cuttings from bleached Permian red beds over the producing reservoirs. They proposed that the magnetite formed by reduction of ferric oxide in the presence of upward migrating hydrocarbons and that the magnetite was the source of the anomalies.

Similarly, aeromagnetic surveys over vast regions of Alaska's North Slope have revealed several areas of anomalous magnetizations over known oil fields and over structures that appear favorable for hydrocarbon deposits based on other geologic and geophysical criteria (Donovan and others, 1984). These anomalies were likewise attributed to formation of magnetite or other magnetic minerals under reducing conditions that were related to hydrocarbon seepage.

Support for an association between magnetite and hydrocarbons comes from recent reports of magnetite with diagenetic morphologies in bitumen and other solid hydrocarbons from surface seeps (McCabe, 1986; McCabe and others, 1987; Elmore and others, 1987). In addition, magnetite in similar forms has been reported in Paleozoic carbonate rocks; in these occurrences diagenetic processes that are related to hydrocarbon migration have been the favored interpretation for the origin of the magnetite (McCabe and others, 1983; Elmore and others, 1986).

Our investigations of the magnetic anomaly-hydrocarbon seepage problem have involved rock magnetic, paleomagnetic, petrologic, and geochemical studies of samples from the Cement oil field, the Simpson oil field on the North Slope of Alaska, and the Jurassic Preuss Sandstone in the Wyoming-Idaho-Utah thrust belt. This work has not found a connection among magnetite, hydrocarbons, and aeromagnetic anomalies.

Instead, the work demonstrates an important association among magnetic iron sulfide minerals, leaked hydrocarbons, and bacterial activity at Cement, and suggests a similar association at the Simpson field (Reynolds and others, 1984; Reynolds, Fishman, Hudson, and others, 1986). Studies of the Preuss illustrate the case in which magnetic anomalies in an area of hydrocarbon potential have been caused by detrital magnetite and are unrelated to seepage (Hudson and others, 1985; Fishman and others, 1989; Reynolds, Fishman, Hudson, and others, 1986). Diagenetic magnetite is represented on figure 3 with a bold query, because, to our knowledge, there are as yet no confirmed cases in which secondary (authigenic) magnetite has produced aeromagnetic anomalies.

Cement Oil Field

Studies of well cuttings, including those examined by Donovan and others (1979), of shallow (surface to about 36 m deep) core and of surface outcrop and quarry exposures have not turned up any evidence for diagenetic magnetite at Cement. Magnetite is abundant in most well cutting samples, but it exhibits synthetic, metallographic textures and (or) contains inclusions of industrial steel (Reynolds, Fishman, Hudson, and others, 1986; Reynolds and others, 1988; Reynolds, Fishman and others, 1990). The magnetite is interpreted to be a contaminant related to drilling; magnetite is a common product of corrosion-oxidation of drill stems (Gray and others, 1980). Furthermore, we have found magnetite in the rusty scale of a used oil-field drill collar, and this magnetite exhibits many textural features similar to those of the Cement magnetites.

Many samples from the cuttings, cores, and surface, however, contain authigenic ferrimagnetic pyrrhotite, which is commonly intergrown with and (or) replaced by pyrite and marcasite. Two lines of evidence—the distribution of the pyrrhotite and the sulfur isotopic composition of the sulfide minerals—strongly suggest that the pyrrhotite is related to migrated hydrocarbons. Pyrrhotite is limited to strata above the oil-producing structures, where it appears to be concentrated in a shallow (200–500 m deep) zone that cuts across lithologic and formational boundaries. Away from the main field and the area of hydrocarbon alteration at the surface, well cuttings do not contain pyrrhotite. Variations in the sulfur isotopic compositions of the sulfide minerals and comparison with published isotopic values of crude oils at Cement (Lilburn and Al-Shaieb, 1984) suggest that the pyrrhotite and other sulfide minerals formed from at least two different sources of sulfide and by a combination of inorganic and organic mechanisms (Reynolds, Fishman, and others, 1990). Aqueous sulfide in hydrocarbon-related fluids that leaked upward from depth along numerous pre-Permian faults in the area was probably the dominant sulfide source for the sulfide minerals at depths greater than about 300 m. There the sulfide minerals apparently formed by the inorganic reaction of aqueous sulfide with available iron. Fault-derived sulfide also probably contributed to the iron sulfide minerals at shallower depths, but this contribution waned toward the surface. With decreasing depth, increasing amounts of sulfide produced by sulfate-reducing bacteria were also incorporated into the iron sulfide minerals. Because these Permian beds contain only small amounts of organic carbon (typically less than 0.1 percent) and lack detrital debris, the sulfate-reducing bacteria must have derived energy from some food source other than plant matter. Organic compounds in or derived from hydrocarbons were likely sources for bacterial consumption in the hydrocarbon seepage plume at Cement.

The contribution of pyrrhotite to the anomaly at Cement is difficult to determine with certainty (Reynolds, Webring, and others, 1990). The magnetic properties of the pyrrhotite-bearing samples (borehole cuttings) necessary for magnetic modelling either cannot be measured, such as NRM direction and magnitude, or cannot be determined with confidence (magnetic susceptibility) because of contamination by magnetite. Moreover, uncertainty regarding the nature of the Cement anomaly and the likely effects of cultural interference have clouded the interpretation picture (Donovan and others, 1986; Boardman, 1985; Foote, 1984). We may conclude, nevertheless, that pyrrhotite is related to hydrocarbon seepage and that is the only possible natural source for anomalous magnetization at Cement.

Simpson Oil Field

At the Simpson oil field, ferrimagnetic greigite (Fe_3S_4) is concentrated locally in Upper Cretaceous sandstone, siltstone, and mudstone. Detrital Fe-Ti oxide minerals occur with greigite in some samples from bore-hole cores but rarely compose the majority of magnetic grains. Among the detrital oxides, ferrimagnetic titano-hematite is more common than titanomagnetite; petrographic observations suggest that this is due to the preferential dissolution of magnetite after deposition. Intensities of NRM of the greigite-bearing samples range from 3×10^{-3} to 2×10^{-1} A/m, whereas those of the samples dominated by the magnetic oxides range from only 6×10^{-4} to 10^{-2} A/m. Magnetic susceptibilities (4×10^{-5} to 3×10^{-3} SI units) are unimportant contributors to the total magnetizations. The remanence that resides in greigite is therefore probably responsible for the anomalies over the Simpson field.

A connection between the greigite and hydrocarbon seepage, however, has not been unambiguously established. The greigite probably formed by processes that involve sulfate reduction by bacteria (Berner, 1981) that used either organic compounds derived from leaked hydrocarbons or detrital organic matter, or both, as food sources. Available evidence points to a combination of factors. The greigite that is found on the surfaces and within cell lumens of abundant detrital plant fragments in many samples from the Simpson field may have formed during early diagenesis in the absence of hydrocarbons. However, greigite is present in some beds that are devoid of plant matter and absent in others that contain such matter. Geochemical studies that involve detailed sulfur isotopic analysis of the organic sulfur and mineral sulfur species may help to resolve the problem.

Preuss Sandstone

The Preuss Sandstone in the Wyoming-Idaho-Utah thrust belt was chosen as one of several targets for testing possible connections between hydrocarbon seepage and magnetic anomalies for the following reasons. An aeromagnetic survey (U.S. Geological Survey, 1981) showed positive magnetic anomalies west of the Absaroka thrust fault in the central thrust belt on trend with hydrocarbon production to the south. A subsequent ground magnetometer survey (S. Oriel and D. Mabey, written commun., 1982) and a preliminary magnetic study (Fishman and others, 1989; Reynolds, Fishman, Hudson, and others, 1986) confirmed the Preuss as the source of the positive anomalies. The magnetic study also revealed that the Preuss possesses a stable remanent magnetization carried by magnetite.

Paleomagnetic analysis indicated that the stable magnetization in the Preuss was acquired after deposition and at least partly during folding (Hudson and others, 1985, 1989). These stable synfolding directions are interpreted to be a viscous partial thermoremanent magnetization (VpTRM), which was acquired at low temperatures (less than 150 °C) over several tens of millions of years as thrusting migrated from west to east. Similar synfolding behavior in some other sedimentary units (principally limestones) elsewhere has been attributed to diagenetic magnetite formed from hydrocarbon-bearing fluids that were mobilized during deformation. In some of these carbonate units, magnetite has been identified in magnetic extracts that include grains with secondary (authigenic or diagenetic) morphologies (McCabe and others, 1983; Elmore and others, 1986). In contrast to these rocks, the Preuss lacks diagenetic magnetite. Rather, the magnetization in the Preuss resides in large (10–80-μm diameter), detrital titaniferous magnetite (contains as much as 14 mol percent ulvöspinel) grains, which are commonly concentrated in heavy-mineral laminations (Hudson and others, 1985; Fishman and others, 1989). The abundance of the detrital magnetite, which can be estimated from magnetic susceptibility, decreases systematically from west (nearer the source area for the magnetite) to east across the depositional basin. The gradient in the susceptibility values has been accentuated by thrusting and folding, which shortened the area by about 50 percent.

Thus, no evidence was found in the Preuss to link the magnetic anomalies with diagenetic magnetite formed under the influence of hydrocarbon-bearing fluids. Instead, the location of the magnetic anomalies is related to the distribution of abundant detrital magnetite. The distribution was controlled by the original depositional setting, by later thrusting and folding, and by the preservation of the titaniferous magnetite by calcite and by a favorable ground-water chemistry.

These results confirm that investigations of sources of magnetic anomalies over oil fields should encompass a wide variety of stratigraphic, geochemical, and structural settings to cover the wide range of diagenetic conditions that may affect magnetization in strata above oil deposits. Even the results of the limited and largely preliminary studies described above indicate that different styles of diagenesis can accompany hydrocarbon seepage and that aeromagnetic data should be cautiously interpreted in the absence of rock magnetic studies.

CONCLUSIONS

Magnetite (Curie temperature about 580 °C) is the dominant source of magnetic anomalies in continental crust. Magnetite is thought by most investigators to be the main source of anomalies from metamorphic rocks within the lower continental crust and thus to control the Curie isotherm in this part of the Earth. The proposed existence of metallic iron and iron alloys in the lower crust and possibly the upper mantle has fostered controversy that will certainly generate more study of this topic. Magnetite also carries the induced and remanent magnetizations in metamorphic rocks and in many acidic plutonic rocks at shallower depths. Titaniferous magnetite, which has lower Curie temperatures, is abundant primarily in basic igneous rocks at mid-crustal and shallower depths. Magnetic titanohematite may dominate the magnetizations of some acidic plutonic, gneissic, and dacitic volcanic rocks, but it is not an important source of anomalies in other settings.

In contrast, titanomagnetite (Curie temperature about 175 °C) and its alteration product, titanomaghemite, dominate magnetizations in upper layers of the oceanic crust, and these minerals probably are the major source of linear magnetic anomalies from the sea floor. At depth, however, magnetite may form by deuteric and hydrothermal alteration of the oceanic crust. Thus the depth to the Curie isotherm of the oceanic crust is controlled by the intrusive, cooling, hydrothermal history of the crust.

Magnetic contrasts in sedimentary rocks are caused by differences in the abundances of detrital magnetic minerals or by diagenetic and epigenetic destruction or addition of magnetic minerals. The types and abundances of detrital magnetic minerals in epiclastic sedimentary rocks reflect the relative and absolute abundances of these minerals in the source areas. Thus the magnetizations of epiclastic sedimentary rocks reside mainly in magnetite and titanomagnetite. Although titanohematite is more resistant to oxidation and reduction in the sedimentary environment than are the Mt-Usp minerals, it is insufficiently common to contribute significantly to magnetic signals. Even where titanohematite is abundant, the distinction between the detrital Mt-Usp and Ilm-Ht magnetic grains is not important for aeromagnetic interpretations.

Destruction of detrital magnetic minerals by postdepositional alteration may produce magnetic contrasts that are diagnostic for structural features such as faults or for facies changes. Such destruction arises from oxidative replacement of magnetite by hematite or from dissolution of magnetite or its replacement by sulfide minerals. Anomalies related to such magnetic contrasts may be useful exploration guides for stratabound mineral deposits.

Magnetic anomalies in areas of oil and gas potential are of current interest as possible indicators of secondary magnetic minerals that are related to hydrocarbon seepage. In such settings rock magnetic, mineralogic and geochemical studies can contribute to making crucial distinctions between primary and secondary magnetic minerals and between primary (DRM) and secondary (CRM, or other) remanence. In addition, the identification of the type of any secondary magnetic mineral (for example, iron oxide or iron sulfide) is important in developing geochemical models for seepage-related magnetizations that can be used for predicting its occurrence elsewhere.

Finally, we emphasize again the importance of alteration on the magnetization of rocks and hence on their aeromagnetic signatures. This conclusion has been stated recently by Mayhew and LaBrecque (1987), and it bears repeating. On a global scale, the types and degrees of metamorphism and hydrothermal activity in both continental and oceanic crust exert fundamental, widespread controls on crustal magnetic properties. On regional and local scales, rock alterations can cause magnetic contrasts that may be diagnostic for certain mineral and energy habitats.

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ABSTRACTS AND SHORT PAPERS

Worldwide Aeromagnetic Coverage: The Need for Data Bases and Map Inventory

By William J. Hinze[2]

As we enter into a new era of technological development in the acquisition, reduction, processing, and interpretation of aeromagnetic data, we look forward to increasing utilization of magnetics in contributing to the solution of a broad spectrum of earth-science-related scientific and societal problems. However, to realize the full potential of the magnetic method we must strive to make all nonproprietary magnetic anomaly data, particularly digital data, readily available to the geoscience community for individualized processing and interpretation.

A three-pronged program is recommended to achieve this goal: (1) Establish a data management system for all new surveys which includes provisions for placing the digital data into a central repository, (2) continue to update the national magnetic anomaly data base with new digital data observations and digitization of existing high-quality magnetic observations, and (3) prepare a computer-compatible inventory of available magnetic anomaly data bases and maps. In the United States an aeromagnetic data management system and a national magnetic anomaly data base have been initiated, but not on a formal basis. Problems remain with respect to standardized formats, quality control and assessment, reduction procedures, the role of data centers, and the lack of a central repository. The geophysical community, through the International Lithospheric Commission, is currently organizing an effort to achieve the third goal, which is to prepare a global inventory of available magnetic anomaly data bases and maps.

The need for an aeromagnetic data inventory is widely recognized and has been recommended for the United States by several working groups. The effort to initiate this inventory on an international level recognizes (1) the increasing importance of obtaining not only geologic, but also geophysical data, on a global basis as a necessary step to solving fundamental geologic problems; (2) the significant amount of aeromagnetic data that are becoming available in digital data bases and maps; and (3) the problems inherent in merging available international data bases and maps into a single computer-based, annotated inventory. Such an inventory would be available on tapes or disks and also in published catalogs which would be updated periodically. Many issues related to the inventory remain to be finalized. Recommendations regarding formats, annotation, types of data to be inventoried, and other details are solicited as well as suggestions of sources who could prepare an inventory of data from regional areas.

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Explanation for Shaded-Relief Aeromagnetic Map of Central Minnesota

By Val W. Chandler[3]

Figure 16 is a shaded-relief presentation of about 311,000 line kilometers of high-resolution aeromagnetic data from northeastern and central Minnesota. These data were collected as part of a state-wide survey that is being conducted by the Minnesota Geological Survey with funding from the Legislative Commission on Minnesota Resources. The data were collected using a 400-m flight-line spacing and an average terrain clearance of 150 m. Along-line sampling is doppler-scaled to intervals of 40–75 m. The aeromagnetic data are crucial to bedrock geologic studies and mineral exploration because of the widespread cover of Pleistocene glacial materials.

The shaded-relief aeromagnetic image (fig. 16) reveals many structural and lithologic details in the Precambrian bedrock. A generalized geologic map (fig. 17) of the surveyed area is provided for comparison. The northern part of the image in figure 16 corresponds to a 2,750-Ma greenstone-granite terrane of the Superior Province; prominent features include the broad fold patterns of migmatitic rocks north of lat 48° N., high-amplitude and sinuous magnetic highs over iron-formation, irregularly banded anomaly patterns over granitic batholiths, and sharp northwest-trending linear anomalies from a 2,120-Ma swarm of diabase dikes. A sharp lineament that extends northeast from near lat 45°30′ N., long 96°30′ W., corresponds to the Great Lakes tectonic zone, which is the boundary between the greenstone-granite terrane to the north and a high-grade gneiss terrane to the south. Parts of the gneiss terrane are older than 3,500 Ma, and the highly complex "birds eye" pattern in the southwestern part of the image is typical of rocks that have a high metamorphic grade. The east-central and southeastern part of the image corresponds to the Early Proterozoic Penokean orogen. The anomaly features associated with this orogen include, from north to south, (1) a broad area of subdued magnetic signature, which corresponds to a thick sequence of graywacke and slate in the Animikie basin and associated outliers; (2) northeast- to east-trending anomaly patterns, which delineate the Penokean fold and thrust belt; and (3) the somewhat irregular anomaly expression of a magnetic terrane. The extreme eastern and northeastern part of the image corresponds to 1,100-Ma rocks associated with the Midcontinent rift system; major anomaly features include the extremely complex signature of the mafic Duluth Complex (Middle Proterozoic) in the extreme northeastern part of the image, the strongly banded anomaly pattern over deformed lavas of the St. Croix horst in the extreme southeastern part of the image, and a series of northeast-striking linear anomalies over a dike swarm in the east-central part of the image.

[3]Minnesota Geological Survey, St. Paul, MN 55114–1057

This 1:2,500,000 scale, shaded relief map is one of the products of the detailed aeromagnetic survey, funded by the Legislative Commission on Minnesota Resources, that began in 1979 and is continuing. The program is supervised by Val W. Chandler.

The apparent relief is generated by computer and shows magnetic variations in the largely buried Precambrian bedrock. It is based on artificial illumination from the northwest at an inclination of 45°. This image, created at the Minnesota Planning Information Center under the supervision of John Hoshal, represents data acquired along 400-meter (1/4 mile) line spacing at a terrain clearance of 150 meters (500 feet).

Products of the survey include digital tapes, 1:24,000-scale contour maps, and 1:250,000-scale color and contour maps. Inquiries should be addressed to the Minnesota Geological Survey, 2642 University Ave., St. Paul, Minnesota 55114.

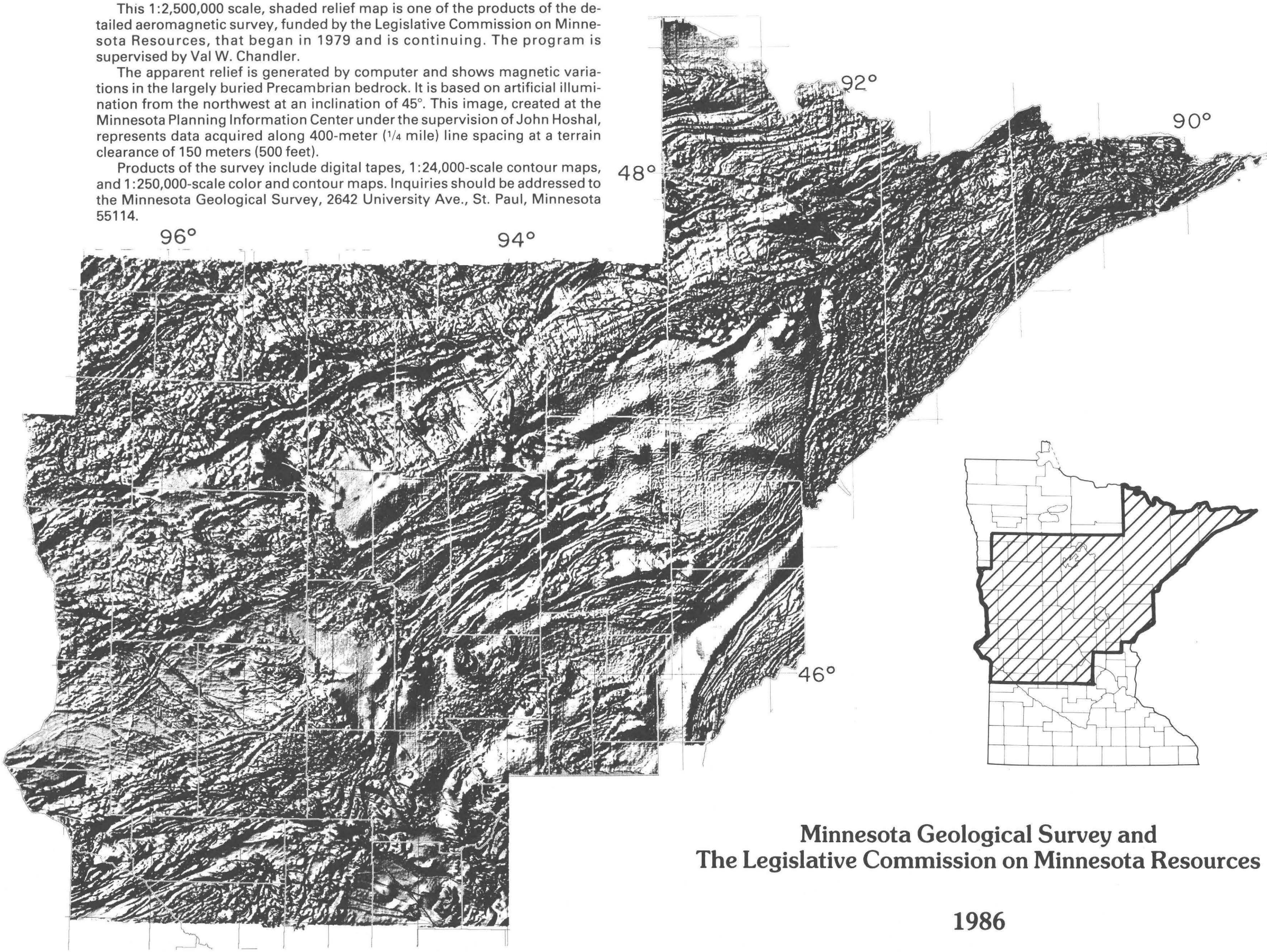


Figure 16. Shaded-relief aeromagnetic map of central Minnesota. Map was published by Minnesota Geological Survey and the Legislative Commission on Minnesota Resources in 1986.

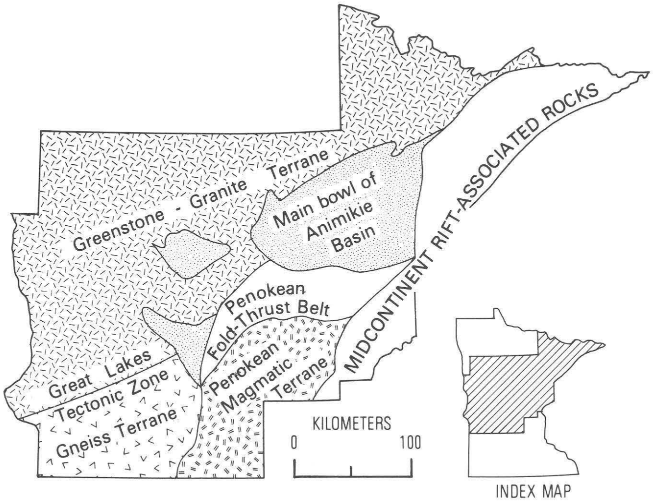


Figure 17. Generalized geologic map of central Minnesota.

A State's Perspective on a National Aeromagnetic Program

By Don R. Mabey[4]

The combined technical staffs of all the State geological surveys is approximately equal to that of the Geologic Division of the U.S. Geological Survey (USGS). The programs of the State surveys vary considerably, but in the public land states of the western United States they are similar to those of the Geologic Division. A few States have effective aeromagnetic programs that are largely independent of the USGS, but most do not have resources to develop such programs. Cooperative programs between the States and the USGS to obtain, publish, and interpret aeromagnetic data have been an important part of the USGS aeromagnetic program and could be an important part of any new National Aeromagnetic Program. In developing a cooperative program, the states can contribute: (1) political support, (2) funding support, (3) facilities for making products available and archiving data, and (4) material for studies of rock properties. The USGS is generally better able to: (1) manage data acquisition, (2) develop interpretation methods, (3) apply some interpretation methods, (4) conduct research on rock properties, and (5) provide leadership in the effective use of magnetic data. Both the State surveys and the USGS would have extensive uses for the data. These uses include hazards studies and general geologic studies as well as the economic geologic applications that are most commonly emphasized. Because of the diverse interests and resources of the State surveys, cooperative programs must be developed individually with each State. Nevertheless some method for providing coordinated State input to the development of the National program so that it serves both State and Federal needs is desirable.

[4]Utah Geological and Mineral Survey, Salt Lake City, UT 84108.

Some Notes on the Production of Aeromagnetic Surveys

By Mike S. Reford[5]

Aeromagnetic surveys usually involve two stages, each executed by a different group. Typically, the flying and compilation are accomplished by a contractor. The results then go elsewhere for analysis, which consists of a preliminary review of contour maps, followed by, perhaps months later, additional processing and interpretation. These notes concern the interface between the two groups.

Obviously, the client wants the best possible survey for the lowest possible cost. Previous speakers have noted that good survey aircraft are not equipped overnight and that good survey pilots are not easy to find. A low price will be a false economy if the contractor is incapable of meeting the desired specifications. This brings up the question of how the client checks the survey results to ensure that the specifications have been met. There is no substitute for experience. Here I wish to praise the work of the inspectors of the Geological Survey of Canada, who check the results of the aeromagnetic contractors. But the prime responsibility for survey quality must remain with the contractor.

The two following examples illustrate this responsibility by detailing the surprises that we have encountered at Geoterrex. Figure 18 shows anomaly data that were contoured at a 5-gamma interval. In the middle of the figure is a linear low axis. The axis is disturbed by lines 15 and 17, which have values that are too high by 10–15 gammas. These lines were flown consecutively. Just before they were flown, the magnetometer measurements suddenly dropped by about 7,000 gammas. After the drop, the record appeared normal. The operator concluded that a digital bit had been lost in the recordings, which could therefore be corrected by adding a constant. This correction was made, but the resultant contours shown in figure 18 still appeared to be incorrect. Also, the levelling adjustments for lines 15 and 17 were much stronger than usual. Further checking convinced us that a bit had indeed been lost, but in a multiplying rather than an adding sense. The data were corrected by multiplying the total-field values by 1.16, and this gave a smooth axis. It is interesting to note that the uncorrected data gave surprisingly good results close to the two control lines on either side of the diagram and that the error would have almost vanished if the control line spacing were halved.

The second example shows an unexpected problem with flight-path recording during our first survey with the Global Positioning System (GPS) in 1985. The positioning system was supplied and operated by a subcontractor. It allowed LORAN C to supplement or replace the GPS data when satellites went below the horizon. Because this positioning system was new and relatively untried, we decided to have an inertial navigation system (INS) as a supplement. The INS was also important as a safety factor to guide the aircraft back to base if the GPS/LORAN system failed. The survey extended almost 1,200 kms offshore and was largely flown at night due to satellite configurations. Figure 19 shows a comparison of the simultaneous INS and GPS positions. The GPS shows oscillations that sometimes exceeded ± 100 m from the mean. These departures, which correlated with small altitude changes of the aircraft, were finally explained as errors that resulted from an assumption of constant aircraft altitude in the position calculation program. This assumption was necessary due to time constraints and only created this problem in a very specific satellite configuration. The result of using these position errors is shown in figure 20, where International Geomagnetic Reference Field (IGRF) removal transforms the magnetic profile from trace 1 to trace 2, thereby introducing false anomalies, especially on the left end. The profiles using INS and final flight paths, traces 3 and 4, do not show these false anomalies. Note that without the INS path recordings, these position errors might never have been detected.

Both these problems—the lost bit and the position program error—illustrate "black box" effects. We know what the "black box" is meant to produce. Too often we may assume that the expected outcome is produced when this may not be the case. The contrac-

[5]Geoterrex Limited, Ottawa, Ontario, Canada.

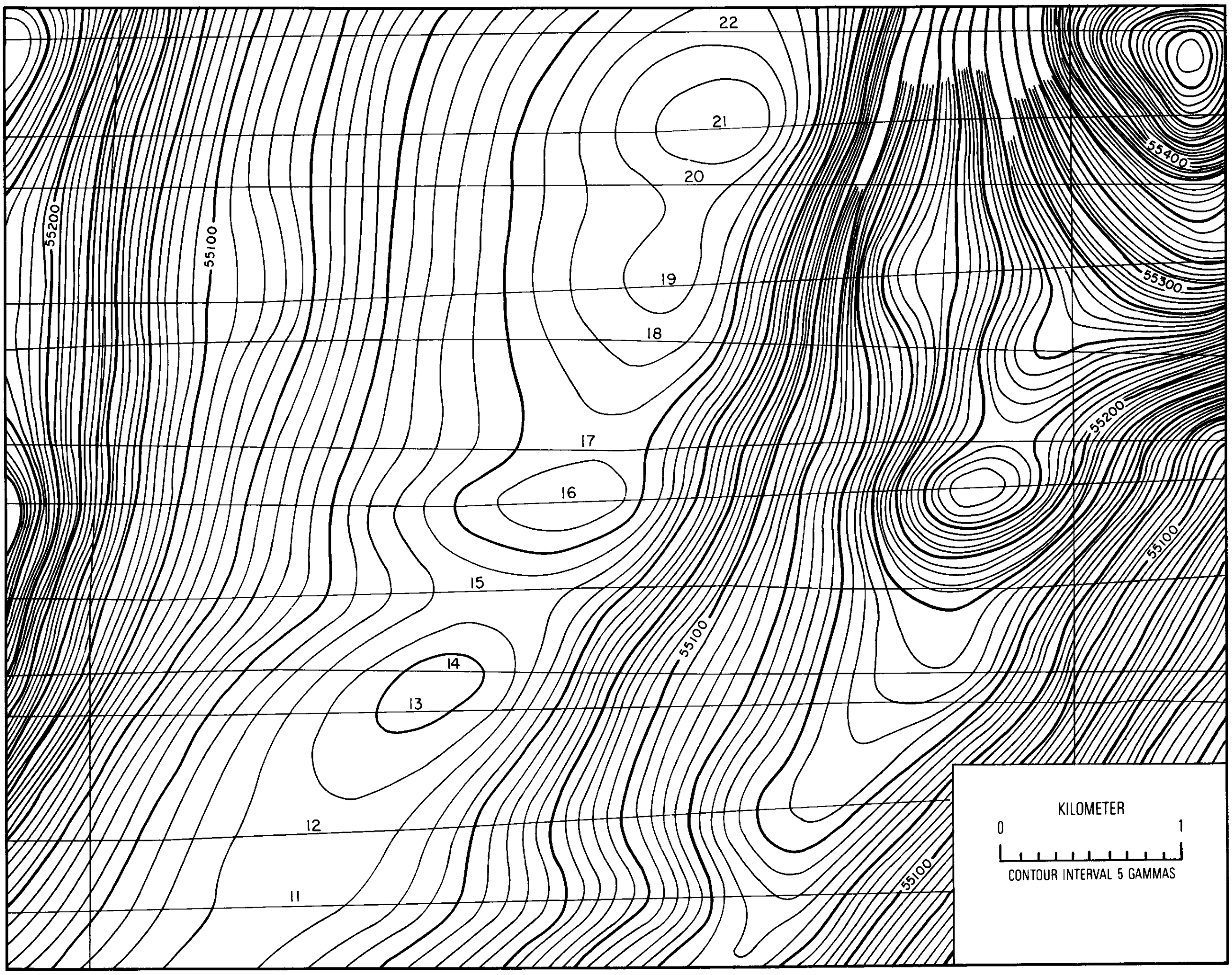


Figure 18. Aeromagnetic anomaly map showing a linear magnetic low axially disturbed along flight paths 15 and 17. Contour interval, 5 gammas (nanoteslas).

tor, the interpreter, and the client must be judiciously skeptical.

The other points I wish to note concern the final products of the survey. Contour maps used to be the final product. Now they serve more for preliminary checks and interpretation and also as an ideal index for further interpretation. As an index, it is most important that they be complete and show flight path and fiducials for each line. The real final products now are the digital data files, which are created in at least two data sets: Line-by-line and grid values. The line-by-line files should contain all the fundamental data from the survey, including both the original magnetic data and the data which has been compiled and contoured. The original magnetic data should be subject only to editing of bad values; the compiled data could be subject to various corrections and filters. Both sets might be used for additional processing, but it seems more likely that the grid values will be used to generate additional map products. To meet this purpose, the grid values should fulfill several requirements.

(1) Grid values should fit the line-by-line values. Isidore Zietz of the U.S. Geological Survey used to complain that the digital contours did not correspond with the line data. This complaint was rectified with some gridding-contouring routines.

(2) Grid values should fit the contours. Any fixing of glitches or other problems in the contours should involve revisions of the grid values. If the fixing is done instead by a draftsman, the problem will reappear as a nasty surprise in subsequent processing.

(3) Grid values should fit a satisfactory set of contours that reflect the actual geologic trends in the survey area.

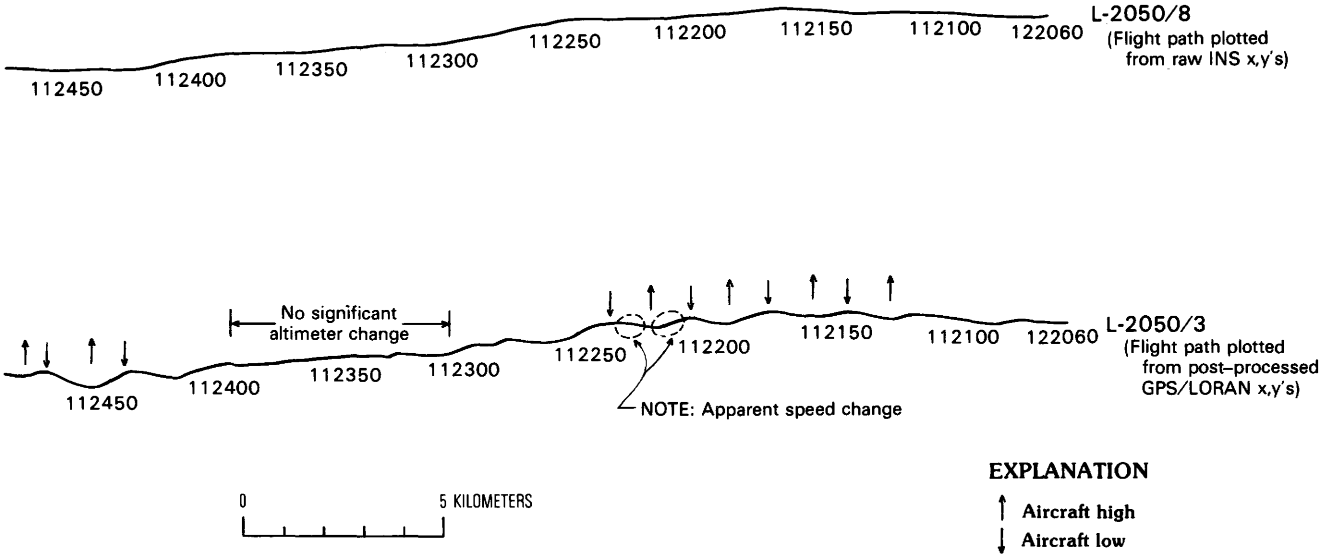


Figure 19. Contrasting plots of a single flight path showing artificial deviations in aircraft X and Y coordinates caused by changes in aircraft altitude. Upper plot shows flight path derived from raw Inertial Navigation System (INS) data. Lower plot shows same flight path derived from combined Global Positioning System and long-range radio (LORAN) navigation data; deviations along this path correlate with aircraft altitudinal changes.

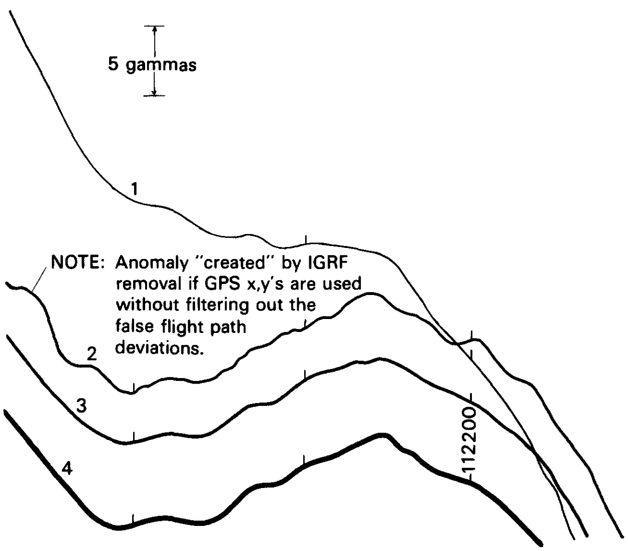


Figure 20. Contrasting plots of total-field magnetic anomalies associated with the flight path shown in figure 19. Trace 1 shows anomalies derived by fourth-difference editing and low-pass filtering. Trace 2 shows data of trace 1 with International Geomagnetic Reference Field (IGRF) removed based on post-processed Global Positioning System X and Y coordinates. Trace 3 shows data of trace 1 with IGRF removed based on inertial navigation system X and Y coordinates. Trace 4 shows data of trace 1 with IGRF removed based on final flight path.

Figures 21 and 22 show unsatisfactory contours. Figure 21 shows contours from two adjacent surveys. North of lat 24° S. the contours were hand-drawn, whereas south of lat 24° S. they were machine-drawn, using one of the older computer programs. The machine contours do not show the continuity of the several sets of dykes, especially those crossed by the flight lines at shallow angles. Further processing of these grid values would perpetuate the incorrect blobby pattern. Figure 22 shows a more recent case. On the left the contours show northwest-southeast-trending features, one of which consists of short east-west-trending segments. This actually reflects a pair of dykes, and the gridding algorithm has simply joined the wrong peaks together. By gridding in a northwesterly direction, this problem has been solved, as shown on the right. The new local grid values were then used to interpolate values onto the original grid locations, and these interpreted values were fitted into the complete grid archive.

These two examples demonstrate the need for treating computer products with a suspicious mind. Just as with the black boxes, we know what the programs are supposed to do, but they do not always perform as expected.

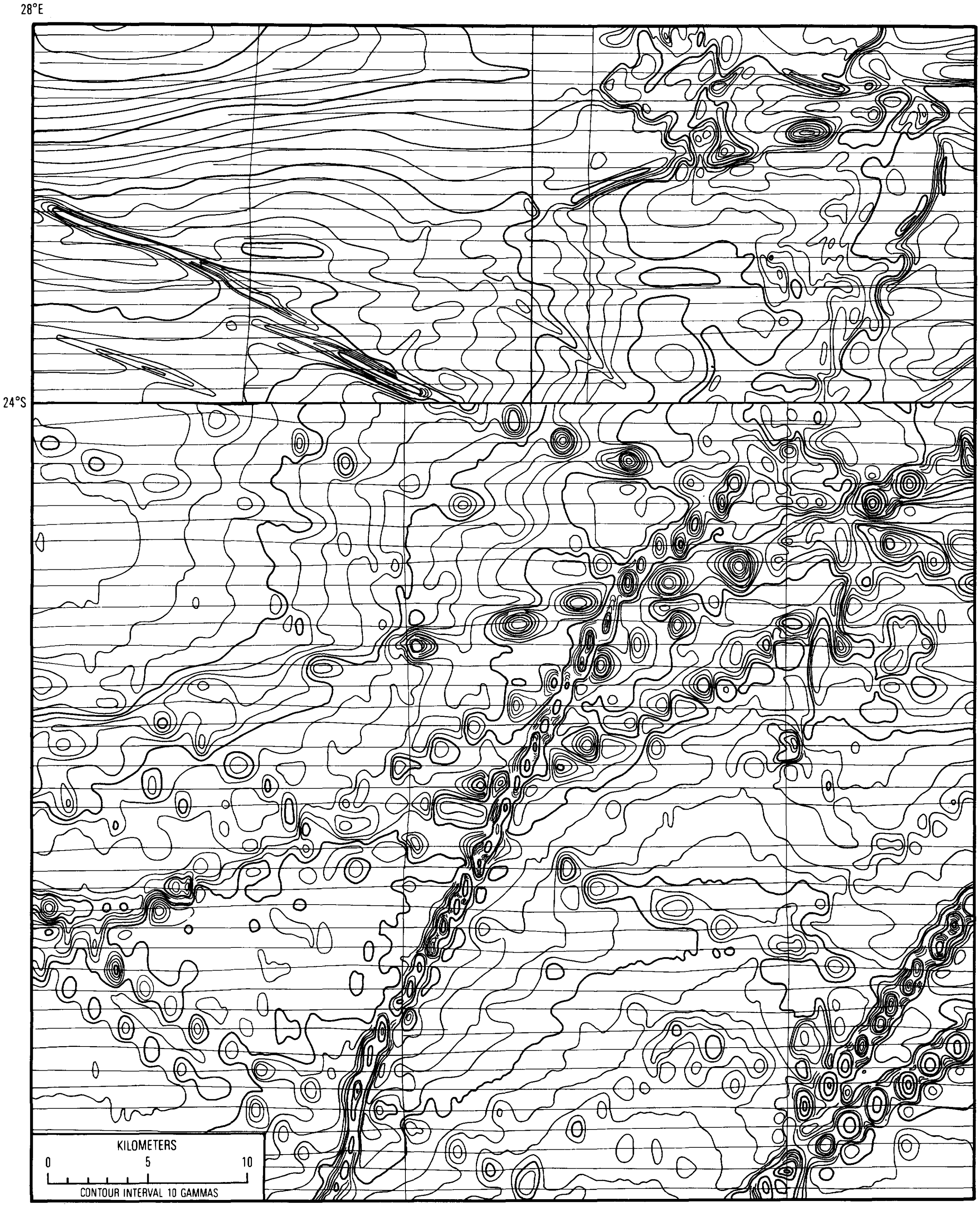
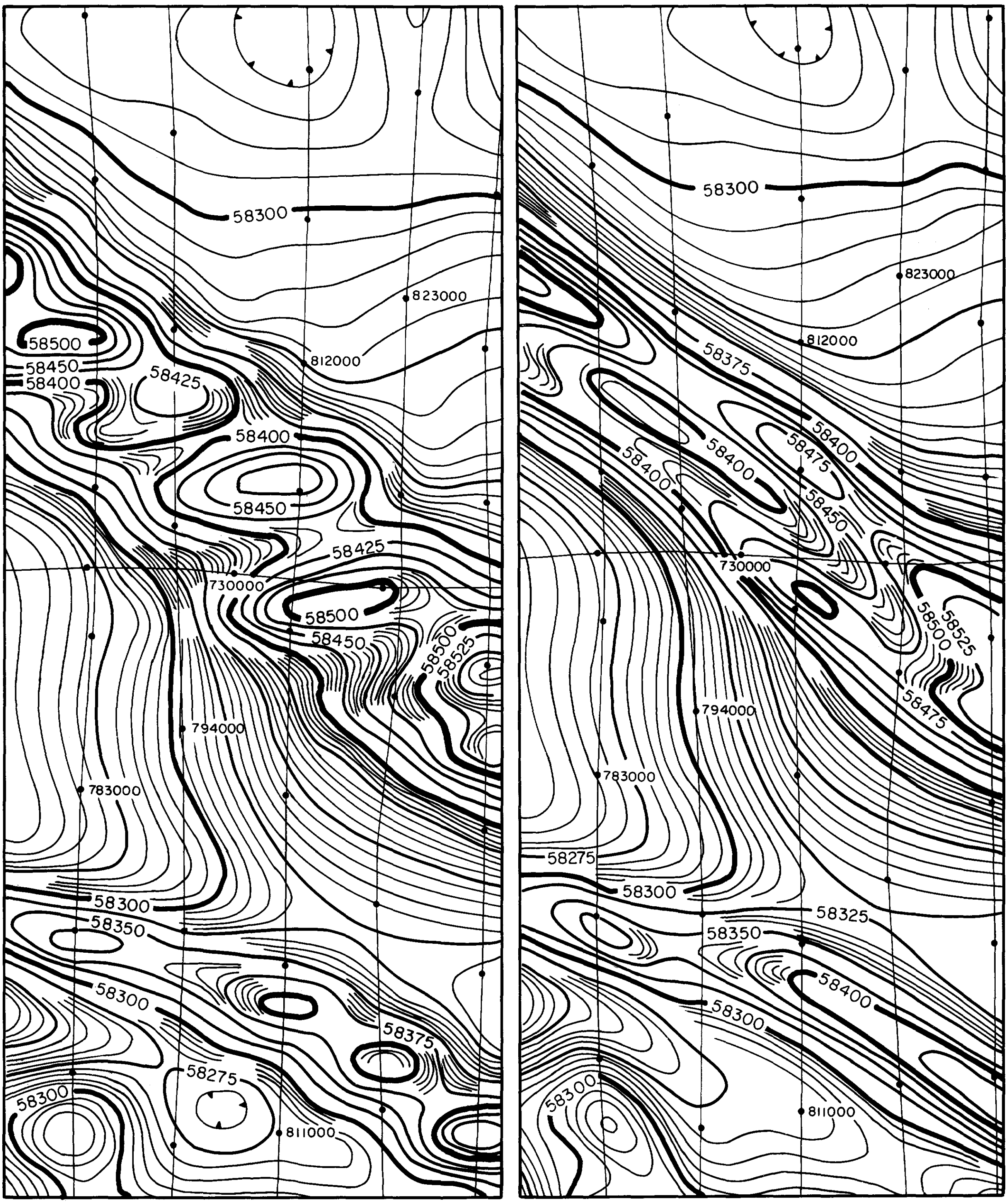


Figure 21. Aeromagnetic anomaly mosaic of two surveys. In the northern one-third of the area shown, contours are hand-drawn; in the southern two-thirds of the area shown, contours are machine-drawn. Machine-drawn contours fail to show the continuity of some dykes.



ORIGINAL CONTOURS TREND–ENHANCED CONTOURS

Figure 22. Contrasting aeromagnetic anomaly maps of a single area derived by gridding in different directions. On the left, the north-south gridding algorithm has joined some peaks together incorrectly, thus obscuring the locations of dykes. On the right, this problem has been solved by gridding in a northwesterly direction.

Aeromagnetic Surveys

By John M. Schmunk[6]

Airborne magnetic surveying has improved dramatically during the past 15 years. Microelectronics, optically pumped sensors, and satellite navigation are only part of the reason for that improvement. The technical advancement has been so rapid that awareness of this advancement and technical specifications that acknowledge this advancement are far from universal. This report recommends methods and specifications that are appropriate for taking fuller advantage of these latest advances in technology than has been achieved in the past.

For 40 years some members of the geophysical profession have devoted their energies to the measurement of the Earth's magnetic field. During that time the instrumentation and the procedures have been improved to such a degree that it is now possible to measure accurately, from an aircraft, anomalies that have amplitudes of 1 gamma (nanotesla) or less. In a static configuration such as that of a ground-based diurnal station, this resolution of measurement is increased by a factor of ten.

We at Airmag Surveys, Inc., originally began our aeromagnetic work with an analog system that expressed the magnetic value as an ink line at a sensitivity of 60 gammas per inch. Standard airborne production systems now measure fields to a resolution of 0.001 gamma and digitally record them to 0.01 gamma. Surprisingly, this high-sensitivity capability is seldom specified as a technical requirement, except by a few private companies. In contrast, most other airborne data acquisition programs incorporate rigorous procedures for evaluation and acceptance of equipment or results, such as the U.S. Geological Survey requirement for periodic calibrations of photogrammetric aerial cameras. Our prime objective should be to make the most accurate measurement possible within the physical and societal constraints that exist at the time of measurement. The specifications, in effect, will define the constraints.

The resolution and quality of aeromagnetic data are determined primarily by the following components: (1) Sensor, (2) platform, (3) measurement and recording system, (4) navigation and positioning system, (5) operational procedures, (6) diurnal measurements, and (7) flight crew. Each of these components can be evaluated and judged with respect to their applicability for accomplishing the objectives of a given survey. Standard procedures exist, which if applied, will facilitate this evaluation. These procedures are a compendium of those that our airborne operators believe to be the most effective quality control procedures in use today throughout North America.

SENSOR

Three prime sensors are in common use today: (1) The fluxgate sensor, the voltage output of which is used to determine the Earth's magnetic field strength; (2) the proton precession sensor, the frequency output of which is used to determine the Earth's magnetic field strength; and (3) the optically pumped alkali-vapor sensor, the electron precession frequency output of which is used to determine the magnetic field strength.

The fluxgate sensor is unique in that it can be configured to measure the components of the field as well as the total-field vector. The proton sensor has the advantages of low cost and ease of operation and maintenance. The cesium optically pumped sensor is preferred over the others for many reasons, among which are its high sensitivity (by a factor of 80 to 1), small size, continuity of measurement, low maneuver noise, good acceptance angle, high signal-to-noise ratio, low thermal noise, high gradient tolerance, and compatibility with electromagnetic (EM) systems.

PLATFORM

The choice of the platform, if made incorrectly, can obviate the benefits derived by using a high-sensitivity sensor. Some aircraft are so magnetically contaminated

[6]Airmag Surveys, Inc., Philadelphia, PA 19114.

that only a low-sensitivity, highly filtered sensor can be used. A modern airplane contains electromagnets, permanent magnets, induced magnets, and eddy currents which produce magnetic fields, and by regulation, an airplane must constantly communicate by emitting a variety of electromagnetic fields. Airplanes are mechanically flexible machines by design, especially along their wing axes. This flexing of aircraft components adds to the complexity of magnetic fields associated with devices attached to moving parts, such as rudder posts, control cables, and control surfaces. Despite this complexity, however, aircraft symmetry in some cases permits the use of certain models to simulate the complex fields that are generated. Even so, use of these models does not guarantee that all aircraft can be used for high-sensitivity magnetic surveys.

An aircraft should not be used for magnetic surveying unless its magnetic signature has been measured and recorded and found to be acceptable. First, measurements should be made on the ground while pulling the aircraft along cardinal headings. Once it is decided that the magnetic signature is of such a character that a successful compensation seems probable, then a test with a temporary installation can be made by flying certain patterns, such as a cloverleaf, followed by a figure of merit. A clover-leaf pattern will identify the two horizontal vectors of both the permanent and the induced fields as measured at the point where the sensor is mounted. The cloverleaf roll maneuver will provide a close approximation of the vertical vectors of the permanent and induced fields at the sensor position. The values of these six vectors will indicate whether or not the aircraft can be compensated and used as a magnetic survey aircraft.

After this procedure, the aircraft should be grounded and the demagnetization process started. Nonmagnetic materials should be substituted for magnetic materials where permissible, and landing gear, struts, engines, mounts, and other parts that might have been magnetized should be removed, checked, and demagnetized if necessary. Even a tiny staple near the sensor, a speaker in the cabin, or a fuel boost pump near a wingtip tank can generate signals that seriously interfere with the measurements. All aircraft, as they come from the factory, make use of the frame and skin as the ground return for the electrical equipment. These direct currents generate powerful magnetic fields that vary, depending upon what loads are in use, and should be eliminated. Certain navigation aids, such as rotary beacons, that generate magnetic fields should be identified and replaced. The H-type antennae should be moved or removed if necessary.

The optimum sensor position is invariably in a stinger attached to the empennage of the plane. This position places the sensor along the axis of rotation that is most symmetrical to the normal fields of the aircraft, the roll axis. It also permits the sensor to be placed at the greatest distance from the most intense aircraft fields.

The electromagnetic fields and the component motion fields can be measured and corrected on the ground. After this has been done, there theoretically remain only the permanent and induced fields. These can be measured by flying cardinal headings over an area of flat magnetic gradient and eliminated.

MEASUREMENT AND RECORDING SYSTEM

A great variety of options exists with respect to the measurement and recording phase of aeromagnetic surveying. Once the nature of the signals to be measured is defined, the instruments and recording system that are most suitable for that measurement can be selected. For example, the aircraft operated by our company in the Gulf of Mexico has three voltages, two frequencies, and three digital outputs available from the sensors that must be recorded. We prefer to use a high-quality system produced commercially by a company that provides strong technical support worldwide.

NAVIGATION AND POSITIONING SYSTEM

All electronic systems are subject to equipment failure. Because it is not always obvious that a failure has occurred, an error of position can be generated. The most striking example of this is the recent deterioration of the time standard in one of the satellites. A more mundane example is when the Doppler reading reverts to a frequency mode, which causes the sampling to be time-based instead of distance-based.

For all high-sensitivity surveys, the pragmatic positioning preference is continuous-strip photography or high-resolution video combined with the best electronic positioning system available for the survey area. This hard-copy concept provides a continuous permanent record with no ambiguities of position. It's a "show me" philosophy that has evolved as a result of equipment malfunctions experienced during the last 40 years.

At times we have experienced gross errors in position that were computed by every one of the electronic navigation systems in use today. Without photographic backup it would have been impossible to determine when the malfunction occurred. The photographic location is more accurate than lower order navigation systems such as Doppler, inertial, or very low frequency (VLF). The photographic location can be as accurate as the Range/Range systems depending upon the angle of fix and the altimetric information.

Global Positioning System (GPS) is the preferred electronic system. It is international and passive and has the most consistent accuracy. However, it is not yet available on a 24-hour basis. LORAN is the next best choice over areas where maps do not exist, such as the Gulf of Mexico. LORAN has a high degree of repeatability but must be calibrated for absolute position by correlating it to known positions within the area or to GPS. Range/Range positioning systems are accurate, but they are the most cumbersome type of system to use. Inertial, Doppler, and VLF are secondary systems and should be used only if no other options exist.

PROCEDURES

The procedures that are followed for the day-to-day operation have evolved over the years and have a purpose of eliminating any ambiguity with respect to the meaning of the data that are collected. Analog and digital annotation of the information must be clearly expressed so that it can be easily understood by the user of the data.

Superimposed on the day-to-day procedures is the need to be constantly aware of anything that might change the magnetic characteristics of the aircraft. Replacement parts or components must be carefully checked for magnetic characteristics before being installed.

As the plane moves in latitude, the induced signature of the plane will change. A heavy landing can change the permanent field. It is standard procedure to periodically fly the cloverleaf at a project site to confirm that the compensation is still effective. It is also standard procedure to monitor carefully the condition of the complete system by periodically flying a test profile while the project is in process. A system that is operating correctly will consistently repeat 1-gamma natural anomalies.

The series of test runs will be an important part of the data set. A test line should be included with the production for the day the line was flown and also should be part of the set of test profiles that accompany the final delivery products.

DIURNAL MEASUREMENTS

For ease of operations, it is wise to use exactly the same configuration for the ground station as that installed on the aircraft. The site location must be free of culturally induced magnetic noise.

CREW

Regardless of the extent and correctness of the effort and investment in the previously described factors, it is absolutely necessary to have an experienced, dedicated crew. It is our experience that only a select number of pilots prove to be effective survey pilots and that even fewer pilots prove to be effective magnetometer survey pilots, regardless of whether electronic navigation is used.

SUMMARY

From the preceding discussion it can be seen that our profession has reached a stage where we can consistently fly high-sensitivity, high-resolution aeromagnetic surveys. This stage has been reached because of desire, equipment, experience, and quality control. The hardware is available. A computed parameter known as the "fourth difference" monitors the instrument noise. The clover leaf and the figure of merit monitor the system noise. The repeated flights of the test line during the project monitor the quality of the data.

For the moment, this standardization to high sensitivity appears sufficient. Very soon, however, the next step must be taken; that is, three-dimensional measurements must be made. The magnetic field is a vector, which can be specified by its declination and inclination angles. With three-dimensional measurements, the location of the cause of the anomaly may be estimated more accurately. Experimental flights that measure the declination and inclination have been made since the 1970's. On the basis of these experiments, it is clear that aeromagnetic surveying is ready to become three-dimensional.

It's a great opportunity.

[EDITOR'S NOTE: Following the workshop, author Schmunk forwarded written and illustrative material to workshop participants, regarding some measurement precisions achieved (a numerical typographical error was discovered by participant Gerald G. Connard and afterward acknowledged by Schmunk) on ten successive repeat flights during a project. Schmunk also emphasized the importance of measuring the Earth's natural magnetic field before cultural development, including the anticipated increased usage of high-temperature superconductors which generate strong magnetic fields, adds further to the abundance of artificial magnetic contamination. We thank Schmunk for these additional contributions.]

A View from Afar: Comparison of Satellite and Aeromagnetic Anomalies

By Patrick T. Taylor[7]

Aeromagnetic measurements are useful in the study of the Earth's magnetic anomaly field from satellite altitude in three respects: (1) To simulate the results expected at higher altitude by upward continuing large data sets, (2) to verify that the satellite field is truly recording the crustal anomaly field (this was especially important when Magsat data were relatively new), and (3) to aid in the geologic interpretation of satellite data. The first two are particularly important.

In order to use aeromagnetic data to verify that Magsat anomalies are recording a true crustal field signature, we need large digital data sets. These data must already be in digital form because the cost of digitizing large anomaly field maps is prohibitive. If not already in a gridded format these data must be put on some form of grid. The upward-continued data set is qualitatively compared using standard algorithms with the satellite data for verification. However, we have found that long-wavelength magnetic anomalies can represent a problem. These long-wavelength anomalies, which are apparent in the satellite data, may not be revealed in the composite aeromagnetic maps. This problem could be due to the difficulty in combining diverse field surveys into one map, especially if the composite data were acquired over several years. Secular variation is believed to be the cause of this problem. Long-wavelength anomalies, however, may be erroneously introduced into the composite aeromagnetic anomaly map by an incorrect representation of the zero field level. This bias will be upward continued as a large magnetic anomaly.

A proposed NASA mission, the Geopotential Research Mission (GRM), is being designed to operate at an altitude of 160 km, which is an altitude where magnetic field measurements have not previously been made. In order to evaluate geologically the results from this proposed mission, we must use aeromagnetic data to simulate the anomaly field at 160 km. This process of upward continuation is the same as anomaly verification except that these data are continued to GRM, rather than to Magsat altitude. An alternate method of producing a synthetic or theoretical anomaly field at any altitude is to produce this field from idealized geometric bodies. This procedure permits a quantitative comparison with fields from various satellite altitudes.

Aeromagnetic and satellite magnetic data may be used together to make geological interpretations. Outstanding problems in the interpretation of satellite data are: (1) Determination of crustal or subcrustal depth to the source(s) of long-wavelength anomalies, (2) the lack of an observed anomaly signature over the continental-oceanic transition zone, and (3) development of techniques for removing external fields from the anomaly data.

Both Magsat and GRM were designed to record the components of the vector magnetic field as well as the magnitude of the scalar field. Little, if any, use of these components has been made in the study of geological problems. Techniques developed from ground-based or aeromagnetic data could be applied to these satellite results. In addition, the magnetic components are useful in selecting quiet data, particularly in the disturbed polar regions.

[7]National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771.

Dynamic Global Positioning System Navigation in an Airborne Geophysical Program

By George E. Williams and William F. Hanna

Navigation requirements for future aerogeophysical surveys depend upon both the degree to which the geophysical sensors are sensitive to position and the degree to which a given airborne measurement must be correlated to a point on the Earth's surface (land, ice, or water) for the problem at hand. It is well known that some of the most difficult problems of current airborne surveying involve flight-path recovery, especially over regions that lack readily identifiable cultural features or highly distinctive topographic features. To compound the problem, future airborne surveying is likely to incorporate an increasingly larger number of diverse sensors which have greater sensitivity for measuring quantities that vary with position and which will be conducted along lines spaced at increasingly tighter intervals.

Airborne navigation that meets most of the anticipated requirements for dynamic positioning can be achieved by use of the Global Positioning System (GPS), which is a constellation of Earth-orbiting satellites operated by the U.S. Department of Defense. To quote from a report of the Special Interagency Task Group on Airborne Geoscience (1989, p. 57), "The advent of navigation by the Global Positioning System has reduced positional errors—usually the dominant source of errors on aeromagnetic maps—by factors as great as 10. Thus, new navigational technology has rendered most existing aeromagnetic maps obsolete." Although the second statement of this quotation should not be construed to mean that existing aeromagnetic anomaly maps will become useless, it nevertheless serves as a reminder that limitations of navigation severely degrade the accuracy of many older maps.

At present, GPS consists of seven Block I satellites of a prototype constellation; they have been joined by the first of the Block II satellites of the operational constellation, the latter having been launched in February 1989. The operational constellation, which is scheduled to be in place by late 1992, consists of 21 satellites (and three in-orbit spares), four of which are in each of six orbital planes, which permits at least four satellites to be in view from anywhere on Earth 24 hours per day. Each satellite completes its nearly circular orbit in 12 hours at about 22,000 km above the Earth's surface. These satellites transmit signals on two L-band frequencies. The signals are modulated with a binary code that contains precise timing information and predicted orbital parameters which define the satellite's position in an Earth-centered reference frame. More precise orbital parameters are available within about 2 weeks after epoch from the National Geodetic Survey.

In principle, when at least four satellites are in view simultaneously (assuming favorable geometry), a four-channel GPS receiver may determine by pseudoranging its three-dimensional point position to an accuracy of about 15 m, using the Precise Positioning Source (PPS) signals, or about 50–100 m, using the Standard Positioning Source (SPS) signals. By using two receivers in a differential mode, the position of one receiver relative to the other may be determined to an accuracy of less than 5 m, using the SPS. This improved accuracy results from cancellation of common-mode errors tied to satellite position and clock offsets by differencing the received transmissions. This use of the SPS in a differential mode is considered important because the PPS may not be readily available for future real-time civilian use, depending upon National security policy, which has yet to be established. New Block II satellites will transmit the SPS in the clear, but the U.S. Department of Defense has reserved the right to encrypt the PPS. A bureaucratic procedure is being implemented to enable government agencies to obtain equipment capable of tracking the PPS and thereby utilizing the full accuracy of the GPS.

Dynamic positioning using GPS incorporates the differential mode of operation in one of two highly contrasting ways: (1) Differential pseudoranging, in which the position of a mobile receiver is continuously determined relative to a stationary reference receiver to an accuracy of about 5–10 m; and (2) kinematic GPS positioning, in which two receivers measure the change in phase of the carrier waves between succeeding measurement epochs to find the corresponding change in position of the mobile receiver relative to the stationary receiver to an extraordinary accuracy of less than 10 cm. Although less accurate, differential pseudoranging is more reliable than the kinematic technique, in that momentary loss of signal associated with atmospheric disturbances or aircraft maneuvering (aircraft wing briefly passes between receiver and satellite, thereby blocking receipt of signal) results only in a very small loss of positioning data. In contrast, the much more accurate kinematic technique is susceptible to "cycle slips" which can render all succeeding data useless for position determination. However, despite this shortcoming, the kinematic technique is expected to be sufficiently reliable for some applications by virtue of the current generation of receivers which track more than the minimum of four satellites, improved software for processing data, and utilization of careful operational procedures.

In order to alleviate the "cycle slip" problem of kinematic surveying and to provide maximum reliability, GPS systems will be integrated with inertial navigation systems (INS). A relatively simple commercial-quality INS could assist a phase-tracking mobile GPS receiver to patch "cycle slips."

Although current technologies already provide capabilities for GPS-based navigation, improved technologies are under development or are being tested. Examples of these developments include improvement of software for speeding up the editing and processing of navigation data; integration of INS or altimetry data with GPS navigation data; optimization of autopilot design and control for the GPS navigation application; reduction of systematic errors in phase measurements, multipath problems (multiple signals are transmitted by reflection to the GPS receiver), and imaging problems (distortion of the antenna's phase response); mitigation of the effects of ionospheric disturbances and magnetic storms which tend to increase the phase measurement noise and cause frequent losses of lock in polar regions; and improvement of knowledge about various sources that contribute to the error budget. Attention should also be focused on ensuring that data sets acquired using GPS be as compatible as possible with existing data sets acquired using older navigation technologies.

Modern GPS systems may be used in small, as well as large, aircraft because they weigh no more than 7 kg, consume only 8–15 watts, and can function all day from a small 12-volt battery. GPS data can be conveniently recorded and stored in flight using conventional laptop computers that have, for example, two flexible disk drives. Fortunately, aircraft speed does not adversely affect positioning accuracy. In principle, the precision of the carrier phase measurement made by a receiver degrades when the receiver is in motion because it is necessary to increase the tracking-loop bandwidth to ensure that the receiver maintains lock on the satellites. In practice, however, this precision degradation is negligibly small compared to other sources of error or noise for speeds of as much as 200 knots.

The U.S. Geological Survey (USGS) currently owns and operates two TI4100 four-channel dual-frequency receivers and three Wild/Magnavox 101 receivers; one of the latter has been converted from single-frequency to dual-frequency capability. In addition, the USGS has purchased nine 8- to 12-channel receivers that are capable of utilizing data simultaneously acquired from as many as eight satellites. As these systems are implemented, the USGS will have the necessary hardware and software for making kinematic surveys on a production basis. These systems are expected to be available for some applications testing. The USGS is also supporting the concept of integrating a phase-tracking GPS receiver with a commercial-quality, off-the-shelf INS to provide a robust, reliable kinematic GPS system for map accuracy testing. This system would also provide information on sensor orientation and would offer added security for aerial surveys of large and remote areas, such as Greenland, where resurveying lines of lost data would not be economically feasible.

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Some Historical Notes on Early Magnetic Surveying In the U.S. Geological Survey

By William F. Hanna

INTRODUCTION

The world's first full-scale airborne geophysical survey was conducted in 1945 by the U.S. Geological Survey (USGS) and the U.S. Navy over the Petroleum Reserve No. 4 in Alaska. In 1947 the USGS introduced the airborne magnetometer to Canada where it was inspected by officials of the Canadian Department of Mines and Resources and the Canadian National Research Council (Morley, 1969). As a consequence of that visit, the National Research Council purchased three U.S. Navy airborne magnetometers, which were converted for survey application and subsequently used for 15 years by the Geological Survey of Canada (GSC). As expressed by Peter Hood in his keynote report contained in this Workshop Proceedings Volume, the GSC has successfully conducted during a period of more than 40 years a program of aerogeophysical surveying unsurpassed in its combination of line miles flown and quality of data by any organization in the world. The GSC program should serve in many respects as a model to be emulated by the United States and other nations.

EARLY DISCOVERIES IN MAGNETISM

The history of magnetic prospecting is directly tied to the development of the science of terrestrial magnetism. Eight pre-17th-century discoveries in magnetism are especially noteworthy: (1) Mutual attraction of lodestones (natural magnets composed of iron oxides) at various distances from one another, in the 6th century B.C. by Thales of Miletus, as later reported by Aristotle and other Greek philosophers; (2) ability of lodestone to magnetize iron over a period of time, as reported by the Roman philosopher Lucretius Carus in the 1st century B.C.; (3) bipolar nature of lodestones, about the 1st century A.D., as reported by the Roman savant Pliny the Elder (Gainus Plinius Secundus) in his voluminous "Natural History;" (4) directive property of lodestone or magnetized iron (and therefore the directional property of the Earth's magnetic field), about A.D. 83 in China, which marked the birth of geomagnetism; (5) magnetic-needle compass and declination of the compass needle, reported by Shen Kua in China in 1088; (6) spatial variation of magnetic declination witnessed by Christoforo Colon (Christopher Columbus) in 1492; (7) magnetic inclination, known earlier to the Chinese but carefully observed by Georg Hartmann of Nuremberg in 1544 and measured by Robert Norman of London, prior to his publication of 1581; and (8) representation of the Earth as a great magnet, and the dependency of magnetism on temperature, both observed by William Gilbert in his monumental "De Magnete" of 1600, the world's first treatise on physical science based on the experimental method. These historical events, and others, are chronicled in Benjamin (1898), Crichton Mitchell (1932, 1937, 1939), Stoner, (1934), Adams (1938), Johnston and others (1939), Heiland (1939b), Chapman and Bartels (1940), Carlsborg (1963), Needham (1962), Hine, (1968), McConnell (1980), and Malin (1987).

In his "De Re Metallica" of 1556, translated in 1912 by Herbert and Lovit Hoover prior to Herbert's term as U.S. President, Georgius Agricola was the earliest to describe the use of the magnet compass in mine surveying (Dibner, 1958; Adams, 1938). However, this use of the compass was restricted to geographic surveying and did not extend to prospecting for magnetic ores. The first document referring to magnetic prospecting is found in correspondence from the State Chancellor in Sweden, Axel Oxenstjerna, dated around 1630 (Lundberg, 1929). The instrument used was the sundial compass, or mariner's declination compass. By 1640 Daniel Tilas had successfully used it to locate Swedish magnetic iron ores by reading anomalies of the declination relative to the normal value. As early as the 18th century this magnetic method of prospecting came from Sweden to the United States where a great many orebodies were discovered by this technique in New Jersey and New York. The sundial compass was succeeded by the invention of the miner's compass around the end of the 18th century, whereby anomalies in inclination of the magnetic field were observed. By the middle of the 19th century, the mathematical formulation of fields associated with magnetized bodies made obvious the need to measure the intensity of anomalous fields. Instruments for measuring magnetic intensity were developed by Thalen and Tiberg in the early 1880's (Lundberg, 1929). At this point we turn our attention to early magnetic observations made by geologist explorers in government-sponsored surveys, neglecting the post-16th-century geomagnetic discoveries made by the mathematical genius, Carl Friedrich Gauss of Germany, and other European scientists, as well as lesser known discoveries made by Benjamin Franklin in the United States (Pomerantz, 1986).

EARLY GOVERNMENT MAGNETIC OBSERVATIONS

Although Federal government agencies, such as the U.S. Army, sponsored several areally extensive expeditions during the first half of the 19th century (Nolan and Rabbitt, 1982), only the Long Expedition of 1819 to the Rocky Mountains included carefully recorded magnetic measurements using a compass and dip circle (Good, 1985; Goetzmann, 1959). The only significant State-sponsored surveys to include magnetic measurements during this period were conducted by John Locke (1844) in Ohio and by Ebenezer Emmons and Albert Hopkins in New York (Silliman, 1839). Emmons and Hopkins recognized that magnetism "might furnish a valuable criterion by which to judge of the proximity of iron, of the direction of the bed or vein, and perhaps its extent" (Good, 1985, p. 521).

The first Federal agency responsibility in geomagnetism was assumed by the U.S. Coast Survey, founded in 1807 as the "Survey of the Coast" and renamed the "U.S. Coast and Geodetic Survey" (USCGS) by Congressional correspondence in 1878. Geomagnetic work heightened in 1843 when Alexander Dallas Bache became Superintendent of the Coast Survey (American Philosophical Society, 1941). Bache had set up the first American magnetic observatory in the garden of his house in Philadelphia in 1830, and as a check on the magnetic influence of geographic longitude, had set up another observatory at Girard College in 1840 (Faul and Faul, 1983). He had also aligned his magnetic observatory in Philadelphia with a British plan promoted by Sir Edward Sabine (Good, 1985; Bloxham and Barraclough, 1985) who, like Alexander von Humboldt of Germany (Malin, 1987; Wiederkehr, 1985), had been convinced by his fellow scientist Gauss of the scientific value of worldwide magnetic coverage (Green, 1984). According to Faul and Faul (1983, p. 191), Bache "directed the Survey until his health failed 21 years later, and in that time it became the greatest scientific agency in Washington." The geomagnetic program of Bache continued at a steady pace until H.S. Prichett became superintendent in the late nineties, after having worked at several American observatories. Prichette turned the USCGS even more toward terrestrial magnetism, having set a goal of making one magnetic observation at every county seat in the United States (Manning, 1988). The continuation of geomagnetic work by the USCGS's Division of Terrestrial Magnetism, organized in 1899, into the 20th century is summarized in Wraight and Roberts (1957). The relationship to the USCGS of military agencies, which were also in need of magnetic measurements, such as the U.S. Army Corps of Engineers and U.S. Navy Naval Hydrographic Office, is addressed in Lasby (1966) and in the references of Manning (1988). In 1973 virtually all of the geomagnetic observatory program of the USCGS was transferred to the USGS, although essential geodetic and data-archiving components remain within the National Oceanic and Atmospheric Administration.

EARLY MAGNETIC OBSERVATIONS BY THE USGS AND RELATED AGENCIES

Returning to consideration of the latter half of the 19th century, we note that Clarence King, 2 years before he was to become the first Director of the USGS, published his report of the geological exploration of the fortieth parallel in 1877. In this report, S.F. Emmons noted that at Anita Peak of the Elkhead Mountains, "The rock of the peak has a strong influence upon the magnetic needle, which, at the summit, points east instead of north" (Hague and Emmons, 1877, p. 179). The black basalt to which Emmons referred undoubtedly had been remagnetized by lightning, a magnetic phenomenon that had been observed 80 years previously by von Humboldt (1797) on mountain peaks in Europe. After becoming Director of the USGS in 1879, King immediately acknowledged the value of making magnetic measurements when he stated in his first annual report "In this department the work should not stop with an exhibition of ores already discovered or outcropping upon the surface, but the iron areas should be constantly enlarged by the careful working out of the subterranean bodies by magnetometrical and stratigraphical methods known to geology" (King, 1880, p. 77). This was the only reference to what is now considered to be geophysical work.

Geophysical work described in the second and fourth USGS annual reports by new Director J.W. Powell (1882, 1884) was limited to the research of Carl Barus who invented the nonpolarizing electrode in 1880 and successfully used it in measurements of ground potential to map a hidden extension of the Comstock lode (Sweet, 1972, p. 248). Barus and his USGS colleague George F. Becker (Rabbitt, 1980) are generally credited with establishing that the best method of electrical prospecting for ore deposits is to determine the positions of the equipotential surface traces on the Earth's surface; the superiority of this technique was independently confirmed in 1912 and 1913 in studies by Frenchman Marcel Schlumberger and the Geological Survey of Sweden (Bergsbyran, 1922). With regard to the magnetic technique, we note that Becker and Barus later made magnetic studies of iron and steel in efforts to distinguish the physical properties of these metals. More notably, Becker published in 1909 a USGS bulletin on the relations between local magnetic disturbances and the genesis of petroleum (Becker, 1909). G.F. Becker was called "the father of geophysics in the Geological Survey" in a 1953 address given by USGS Director W.E. Wrather (King, 1953, p. 5).

Also before the turn of the century, USGS geologists who were mapping in Michigan's iron districts observed the magnetic attractions of magnetite and other iron ores as well as host magnetite-rich gabbro; their observations were similar to those made in other States, such as New Jersey (Smock, 1875; Farrington, 1852), Ohio (Locke, 1840), Wisconsin (Wright, 1880; Irving, 1880), and California and Arizona (Hanks 1890). According to J.R. Henderson (1953, p. 22), Thomas Alva Edison made systematic dip-needle surveys in the 1890's over New Jersey iron ore deposits. Maps showing some results of these measurements are in Bayley (1910). The Michigan work of Irving and Van Hise (1892), Van Hise and Bayley (1897), and Smyth (1899), published as USGS monographs, indicates that they recognized the difficulty of distinguishing some magnetic rocks from others, the value of plotting observations before returning from the field, and the economy of making magnetic measurements before money is spent in underground work. Smyth (1899) was the first to derive mathematically the anomalous effects of these iron ore-bodies.

In the early 20th century, the USGS spawned from its organization two important units which later conducted much work involving magnetic techniques. First, in 1907, the USGS physical laboratory was, in effect, reestablished in a recently created Geophysical Laboratory of the Carnegie Institution of Washington (Nolan and Rabbitt, 1982); the Department of Terrestrial Magnetism of the Carnegie Institution had been established in 1902 (Good, 1985). Second, in 1910, a large staff of USGS mining technologists was split off to form the U.S. Bureau of Mines (USBM) (Rabbitt and Rabbitt, 1954). From 1910 to 1927 very little magnetic exploration work was conducted in either the USGS or the USBM; most activity in magnetism was restricted to continuing work at the Carnegie Institution and at the USCGS. The Carnegie Institution during this period used for ocean surveys a specially commissioned non-magnetic sailing ship, the *Carnegie*, made of wood with bronze fittings (Malin, 1987). This ship was destroyed by fire in 1929 while refueling in harbor. Also during this period, magnetic investigations of Broderick (1918) on the Duluth gabbro incorporated the previously noted mathematical work of Smyth (1899) as well as some experimental corroborations of Hotchkiss (1915). The latter experimentalist, W.O. Hotchkiss, designed the famous "Hotchkiss superdip" needle-suspension magnetometer (Hotchkiss, 1923; Stearn, 1932), which together with Adolf Schmidt's field balances (Heiland, 1926, 1929b), constituted the ground magnetic instruments of choice in the USBM and the USGS through the 1950's (Dougherty and Fitzhugh, 1946; Hawkes and Balsley, 1946; James, 1948). Also within the 1910–1927 quiet period, F.L. Ransome, Chief of the USGS Metals Section and president of the Washington Academy of Sciences (Rabbitt, 1986), openly complained, "Research in geophysics was at one time a recognized function of the United States Geological Survey, but since the founding of the Geophysical Laboratory of the Carnegie Institution of Washington this field has been left almost entirely to that splendid organization, which is unhampered by some of the unfortunate restrictions of a Government bureau. Under these particular and unusual conditions this course may have been wise, although it does not negat[iv]e this conclusion that, in general, investigation[s] in geophysics are logically and properly a function of a national geological survey" (Ransome, 1921, p. 276–277).

In 1927 exploration geophysics in the USBM was stimulated by the arrival of A.S. Eve and D.A. Keys from McGill University in Montreal, who almost concurrently published as a USBM Technical Paper a 26-page account on geophysical methods of prospecting (Eve and Keys, 1927). The following year a Section of Geophysics was established in the USBM. Until then and shortly thereafter, the few references on geophysical prospecting best known to USBM personnel were journal articles of Stearn (1929) and Slichter (1929); a manual of M.C. Alexanian (Ayvazoglou, 1931); and textbooks of Eugene Haanel (1904), Richard Ambronn (1928), C.A. Heiland (1929a), and Alfred Nippoldt (1930), the latter translated in-house by Wladimir Ayvazoglou. Ayvazoglou and colleague V.L. Skitsky regularly published "Geophysical Abstracts" for the USBM, a function that was later coordinated in the USGS by current historian Mary C. Rabbitt, who at about that time also served as Assistant Chief of the Branch of Geophysics (Kronstedt, 1957). The 1927 work of Eve and Keys was expanded into a 296-page book in 1933 (Eve and Keys, 1933), which much later evolved into the 860-page book of Telford and others (1976); the last included Keys as a coauthor. The USCGS classical text on geomagnetism (Bauer, 1902) and its many successor versions were also considered essential background material for USBM personnel.

Meanwhile, during the period 1925–1928, large oil companies began to use magnetometers extensively; use of this equipment by these companies significantly declined in the 1930's (Sweet, 1972). Costs of magnetic surveying, according to a 1930 survey of oil companies by the Colorado School of Mines (Wantland, 1930), averaged $1 per station in California and Texas, $2–3 per station in the wetlands of Louisana, and as much as $11 per station in inaccessible parts of western Canada. According to Sweet (1972, p. 243–244), "Even though the earth magnetometer was abandoned by most of the major oil companies when the Depression hit, small oil companies and individuals continued its use, mostly because of the low economic cost of such surveys. In the year 1935 there was a single magnetometer working in each of the following states, Michigan, Utah, Mississippi, Alabama and Florida. Three magnetic parties were active in Colorado, four in the Permian Basin and three in South Texas. To many, South Texas was judged to be the most promising area, because oil fields do occur in connection with basaltic plugs." Although data were generally proprietary, significant journal articles were published, typical among which were those of Barrett (1931) on magnetic disturbances caused by buried casing; Jenny (1931) on magnetic vector studies of geologic structure in oil States; Van Weelden (1933) on magnetic anomalies in oilfields; Dick (1936) on the value of resurveying areas using newer magnetometer technology; and Evjen (1936) on the place of the vertical gradient of gravity, which is also applicable to magnetics. Applications of magnetic prospecting to oil-bearing terranes were summarized shortly thereafter by Jenny (1938) and Heiland (1939a) in the same comprehensive way that traditional applications to metal mining were presented by Marquardt (1939). Gulf Research and Development Company was one large company that continued its use of the magnetometer in the 1930's, which led later to Gulf's development of an airborne magnetometer. Airborne magnetic observations, according to Dobrin (1960), had already been made by Hans Lundberg from a captive balloon above Sweden's Kiruna orebody in 1921 (Eve, 1932) and by A.A. Logachev from an aircraft above Russia's Kursk orebody in 1936 (Logachev, 1946). One of the largest and richest ore deposits associated with the Kiruna feature had been discovered in 1918 by a prospector's wife who noticed while picking berries that her miner's compass, which she always carried with her, was pointing vertically (Lundberg, 1929). C.A. Heiland had also reported on the advantages of geophysical mapping from the air in 1935 (Heiland, 1935). At the USBM during this period, important in-house publications by Stratton and Joyce (1932) and Joyce (1937) focused on magnetic studies of iron deposits and on prospecting with the magnetometer.

In 1936 the Geophysics Section of the USBM was transferred to the USGS, in conformance with a recommendation made by the Science Advisory Board in 1934. This recommendation stated that the geophysics program, which had been developed in the USBM, "has to do with the finding of ore, which is a function of the Survey, and not with extraction and technology of ores, which are primary functions of the Bureau of Mines" (Rabbitt, 1986, p. 343). Near the end of the period 1936–1942, prior to the retransfer of the geophysics program from the USGS to the USBM, the Gulf Research and Development Company made significant progress toward furthering the development of saturation type magnetometers, also called fluxgate or fluxvalve magnetometers, which are devoid of movable parts subject to gravitational and vehicular accelerations. Also about this time a set of scales for evaluating components of magnetic attraction was published by the Geophysics Section of the USGS (U.S. Geological Survey, 1940) and comprehensive textbooks on exploration geophysics, including significant sections on magnetic techniques, were published by Heiland (1940), Jakosky (1940), and Nettleton (1940).

BIRTH OF THE AIRBORNE MAGNETOMETER

At Gulf Research and Development Company, Victor V. Vacquier is credited with developing, by 1940, the first magnetometer element suitable for airborne geophysical prospecting (Muffly, 1946). However, according to Sweet (1972), two persons were largely responsible for development of this airborne magnetometer: J.D.C. Hare, a physicist who held a patent on seismic sources and later patents on radiation detectors and downhole apparatuses; and Vacquier, an electrical engineer trained also in physics, who worked at Gulf from 1930 to 1941, when he went to Columbia University to work in the Division of War Research. Sweet (1972, p. 244) stated, "Dr. J.D.C. Hare invented the three element magnetometer and Victor Vacquier signed Hare's patent application thereto," and referred to this magnetometer, initially used in a gyrostabilized mode for submarine detection, as "the Hare element and the associated Vacquier electrical circuits." An added source of possible confusion is that Vacquier, prior to World War II, built an absolute magnetometer of new design for the determination of declination, vertical intensity, and horizontal intensity—not incorporating fluxgate technology—at the request of the USCGS (Vacquier, 1945). In 1939 Vacquier obtained a patent for an "apparatus for and method of measuring the terrestrial field" (Jakosky, 1950, p. 245). Supporting the account of Gary Muffly (1946), who was development engineer at Gulf, R.D. Wyckoff (1948), chief of the Geophysical Research and Development Division at Gulf, also credited Vacquier only as the one who developed the magnetometer element and also as one who did pioneering work on the first types of orienting apparatuses for the instrument. Wyckoff (1948, p. 183–184) stated, "V. Vacquier investigated the properties of iron-cored devices which had long been used in certain applications where great sensitivity was not required. *** By 1941, however, he had succeeded in developing an element of the flux-gate type having a very high sensitivity and a physical form amenable to the airborne application." Abstracts of Vacquier's 1946 patents for an "apparatus for responding to magnetic fields" (Skitsky, 1947, p. 50–51), for which 15 claims were allowed, clearly reflect his achievements on iron-cored devices and associated electronic circuits, fundamental to the Magnetic Airborne Detector (MAD) used for submarine detection during World War II. Although Sweet (1972, p. 244) stated that the need for an airborne magnetometer had come originally from the Army because of its interest in exploding enemy land mines, Balsley (1946b, p. 4) indicated that the original U.S. Navy magnetometer was developed from an idea submitted to the Navy in World War I by the Department of Terrestrial Magnetism, which proposed the magnetic detection of submarines by aircraft.

According to Knoerr (1946), airborne magnetometers were developed jointly by:

(1) The Gulf Research and Development Company, initially as part of their research and development program and later under contract to the National Defense Research Council (NDRC). See, for example, Gulf Research and Development Company (1943) for a summary of MAD magnetometers as well as a vertically stabilized instrument built to specifications of the Sperry Gyroscope Company, and Muffly (1946) and Wyckoff (1948) for the history of magnetometer development at Gulf.

(2) The Columbia University Division of War Research, through its Airborne Instruments Laboratory, also under contract to the NDRC. See, for example, Columbia University Airborne Instruments Laboratory (1943, 1944) for descriptions of mechanical and electronic systems used to stabilize MAD's, and Vacquier and Tolles (1943) and Tolles and Vacquier (1944) for methods of magnetically compensating an aircraft for wingtip installation of a MAD.

(3) The U.S. Naval Ordnance Laboratory and the Bell Telephone Laboratories, under the sponsorship of the U.S. Navy's Bureau of Ordnance and Aeronautics. See, for example, U.S. Naval Ordnance Laboratory (1941a, b) for descriptions of diverse fluxgate magnetometers and the General Electric Company's magnetometer for measuring a ship's magnetic field, Bell Telephone Laboratories (1943) for a description of a MAD orienting system, and Jensen (1945) for a comprehensive analysis of the AN/ASQ–3A model.

The USGS first became involved with the airborne magnetometer in late 1942 when Herbert E. Hawkes was consulted about interpreting the effects of rock masses on the magnetic detector developed by the Naval Ordnance Laboratory and Bell Telephone Laboratories. Hawkes recognized that the instrument had great potential in the Government's exhaustive search for strategic minerals (Knoerr, 1946). In late 1943 James R. Balsley, Jr., of the USGS initiated discussions with the U.S. Naval Ordnance Laboratory on modifying the magnetometer for use in mapping extensive areas. The equipment was made available to the USGS through the U.S. Navy's Bureau of Aeronautics, and a project was established in the U.S. Naval Ordnance Laboratory and Bell Telephone Laboratories for instrument modification according to requirements of the USGS geophysicists. The modified magnetometer was installed in a single-engine biplane furnished by Aero Service Corporation who also supplied a pilot experienced in low-altitude flying. In April 1944 a test flight was made successfully along three traverses at different altitudes along a line near Boyertown, Pennsylvania, which had been previously surveyed by the USGS using a ground-based magnetometer. These flights, which came within a few miles of finding a major magnetite deposit (the Grace Mine) later discovered by Aero Service (John R. Henderson, written commun., 1975), were followed by other single-engine test flights over wood and swamp land near Iron River, Michigan, and over the iron-bearing area of the Adirondacks. The obvious need to use a twin-engine aircraft for more extensive flights came to the attention of the Director of the Naval Petroleum Reserves, who identified a twin-engine U.S. Navy plane for aeromagnetic use. This more powerful aircraft was used cooperatively by the USGS and the U.S. Navy to survey a 10,000-mi^2 area in Naval Petroleum Reserve No. 4 in northernmost Alaska. Subsequent surveys over oil-producing structures of the Big Horn basin in Wyoming and over the Gulf of Mexico offshore from Texas and Louisana were completed by the USGS prior to an explosion of publications in 1946 which publicly announced the arrival of the aeromagnetic technique, when National security classification restrictions were lifted (Balsley, 1946a, b, c; Muffly, 1946; Heiland, 1946; Jensen, 1946; Jensen and Balsley, 1946; Mining and Metallurgy, 1946; Mining Congress Journal, 1946a, b; Skillings' Mining Review, 1946; Oil News, 1946; Knoerr, 1946). By 1950 the airborne magnetometer was recognized by the Department of Interior to be one of the greatest advances in techniques used in geological exploration (Horowitz, 1950).

It is ironic that the geophysical group that had promoted for many years the use of the ground magnetic technique in Federal programs was transferred in 1942 from the USGS to the USBM for wartime purposes at the time when Hawkes and Balsley at the USGS introduced the aeromagnetic technique in the Federal sector. Thus, when the geophysical group at the USBM was once again transferred to the USGS in 1946 with the strong encouragement of former oil geologist and then USGS Director W.E. Wrather, a substantial aeromagnetic program was already in place, spearheaded by Balsley. Hawkes remained interested in the interpretation of total-field magnetic data, whereas Balsley focused more on magnetic properties of rocks and their relationship to negative aeromagnetic anomalies. Balsley's continued interest in remanent magnetization led to the USGS program of paleomagnetic research headed by Richard R. Doell and Allan Cox (D.R. Mabey, written commun., 1976), which provided the first magnetic-reversal time scale widely used for estimating rates of seafloor spreading (Frankel, 1979; Glen, 1982; Opdyke, 1985; Morley 1986).

Hawkes in 1946 hired Roland G. Henderson and Isidore Zietz from the USGS Topographic Branch, who, under the supervision of Irwin Roman, initially made tabular computations for facilitating the use of complex formulas. Roman had previously helped to develop a magnetic gradiometer (Roman and Sermon, 1934) and had studied the resolving power of magnetic observations (Roman, 1946). As they became familiar with the theoretical work of Vestine and Davids (1945), Henderson and Zietz (1948, 1949a, b) soon began publishing on forward computations of magnetic models, second vertical derivatives, and analytical continuation, which catalyzed the release of many years' worth of mathematical geophysical analysis by scientists of the Gulf Research and Development Company [compare, for example, earlier articles of Vacquier and Affleck (1941) and Nettleton (1942) with later articles of Peters (1949), Elkins (1951), and Dean (1958)]. Some of these Gulf scientists had benefited at least indirectly from the influence of geophysicist John Bardeen, later a two-time Nobel Prize winner in physics, who worked at Gulf from 1930–1933, prior to his employment by the U.S. Naval Ordnance Laboratory and Bell Telephone Laboratories during the period of these laboratories' cooperation with the USGS. Theoretical papers also were published by scientists of other oil companies, such as the Shell Petroleum Corporation and the Carter Oil Company (Skeels, 1947; Skeels and Watson, 1949) at about this time. Henderson and Zietz later joined colleagues Victor Vacquier and Nelson Steenland in producing a landmark textbook on the interpretation of aeromagnetic anomalies (Vacquier and others, 1951).

Among the hundreds of aeromagnetic surveys conducted since the birth of the technique (Balsley, 1952), one of the best known was also one of the earliest, having been flown in 1947 by the USGS in cooperation with the Geological Survey of Missouri (Leney, 1964). This survey delineated the Pea Ridge anomaly over a major iron orebody, which was located by the St. Joseph Lead Company in Missouri. This type of orebody, first mined in Missouri about 1815, was last discovered using conventional geologic methods in 1845. Thus, more than a century elapsed before the fateful 1947 survey which revealed the presence of the hidden magnetite and hematite orebody. At that time four types of airborne magnetometer were in general use: The MAD operated by the USGS; the MAD modified by the Gulf Research and Development Company; a wingtip-installed sensor developed by C.A. Heiland for the Heiland Research Corporation; and a helicopter-borne magnetometer constructed by Hans Lundberg (Lundberg, 1947). By 1965, more than one hundred major mineral discoveries had been made entirely or in part by these and other airborne magnetometers (Pemberton, 1966).

According to the late William J. Dempsey of the USGS (written commun., 1979), who served for many years as Chief of the Airborne Surveys Section (Kronstedt, 1957), early low-level surveys were exciting. On occasion, watered gasoline obtained at small airports caused partial engine failure. A few magnetometer "birds," which were towed on long cables and which had to be manually lowered and raised, were lost in flight; however, the only complaint came from an Indiana farmer who discovered such a "bomb" dropped in his pig-pen. Complaints about the low altitude of the flying came from a mink rancher in New York and a turkey herder in Minnesota. On one flight, the USGS successfully located a bargeload of steel which sank in a Chesapeake Bay storm. A survey of Paricutin Volcano while still in eruption resulted in a pronounced etching of the once clear and shiny plastic nose of the aircraft. Much later, in a survey of the Island of Hawaii, a USGS aircraft was hit twice by rifle fire that was presumably directed from areas of significant marijuana growth.

EPILOGUE

During the nearly 45 years that have elapsed since the introduction of the airborne magnetometer as a geophysical instrument, many millions of line miles have been flown by governmental agencies, companies, and academic institutions throughout the world using flux-gate, proton-precession, and optically pumped airborne magnetometers in scalar, vector, and gradient modes aboard a multitude of fixed- and rotary-wing aircraft. During this period, the USGS has actively promoted a variety of budget initiatives in support of a national aeromagnetic program. Although these initiatives have not yet led to the unified program that is desired, they have nevertheless facilitated the funding of some surveys of limited areas. These regional surveys have been largely conducted under contract to private industry, funded either as parts of Congressionally mandated programs or as cooperative efforts involving various combinations of Federal, State, County, and Municipal governmental agencies; National laboratories; academic institutions; and private industry. Data from all available nonproprietary surveys have been utilized recently for compiling magnetic anomaly maps of the United States and North America (U.S. Geological Survey and Society of Exploration Geophysicists, 1982, 1984; Committee for the North American Magnetic Anomaly Map, 1987). Index maps showing most nonproprietary aeromagnetic coverage of the United States as of 1986 are presented in Hill (1986a, b, c, d, e, f, g). Although these index maps serve as a reminder of the successful application of the aeromagnetic technique over diverse terranes during the past 45 years, they also reveal the unfortunate lack of a single, coordinated national program for acquiring high-quality aeromagnetic data.

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DISCUSSION GROUP REPORTS

Alaska as a Frontier for Aeromagnetic Interpretation

By John W. Cady

INTRODUCTION

Alaska is a frontier geological province—a collage of many different terranes, kinds of geology, and types of potential mineral deposits. It has great potential for future mineral development, but at present the economy constrains development. The primary goal of geophysical investigations should be to understand better the regional geology, crustal structure, and tectonic framework of Alaska and the surrounding shelf areas. A properly designed aeromagnetic map of Alaska would provide information on horizontal variations in lithology and structure, with resolution that is adequate for geologic mapping at scales of 1:63,360 and 1:50,000, as well as a synoptic view suitable for a statewide geological synthesis.

The Alaska aeromagnetic map would serve as an ideal complement to the Trans-Alaska Lithospheric Investigation (TALI), which was designed to reveal vertical crustal structure along a transect across the State. Together with an improved gravity data set, the aeromagnetic data would permit the crustal structure determined from seismic and magnetotelluric investigations to be extrapolated throughout much of the State. The gravity and magnetic data together would be of great help in planning more expensive seismic and magnetotelluric investigations.

COVERED AREAS HIDE THE KEYS TO ALASKA TECTONICS

Large areas of Alaska are covered by Quaternary and Tertiary deposits that prevent bedrock mapping (fig. 23). The largest of these areas are, from north to south, Yukon Flats (YF), Nowitna lowland (NL), Tanana-Kuskokwim lowland (TKL), Yukon-Kuskokwim delta (YKD), Copper River lowland (CRL), Cook Inlet–Susitna lowland (CISL), and Nushagak–Bristol Bay lowland (NBBL). Other lowland areas where pre-Tertiary rocks crop out, but bedrock mapping is made difficult by poor exposure, include the Arctic Coastal Plain (ACP) and a number of lowlands of the Yukon-Koyukuk province (Selawik-Kobuk lowland, SKL; Kanuti Flats, KaF; Koyukuk Flats, KoF).

Airborne geophysical techniques are especially cost effective in Alaska because access to the ground is so much more difficult than in the conterminous United States. Even where the rocks are well exposed, logistical difficulties greatly increase the cost of doing geologic field work because helicopters are required virtually everywhere.

Figure 24 is a topographic map in color-shaded relief of a 3° swath across nothern Alaska that contains abundant lowlands. The map was made from elevations digitized at 1-minute intervals on 1:250,000-scale topographic maps. Highlands, shown in red through yellow, and lowlands, shown in shades of blue, are labeled in figure 25. The most prominent lowland is the Yukon Flats, in which one quadrangle (Yukon Flats, lat 65°–66° N., long 144°–147° W.) is nearly devoid of outcrops. The area west of the Ruby geanticline and south of the Brooks Range (fig. 25) is the Yukon-Koyukuk province, which contains several lowlands (Selawik and Kobuk lowlands and Koyukuk and Kanuti Flats) separated by bedrock hills.

A detailed study has been made of the part of the area of figure 24 west of long 149° W., that is, of the northern Yukon-Koyukuk province and its border lands (Cady, in press). Excerpts from that study are presented below to show the types of results that can be obtained from the combined interpretation of digital topographic, gravity, and aeromagnetic data. In the remaining area of figure 25 east of long 149° W., aeromagnetic data of adequate quality (2 km or narrower flight-line spacing) are available east to long 147° W. at all latitudes within the swath, as well as for Circle quadrangle (lat 65°–66° N., long 144°–147° W.). Four 1° × 3° quadrangles remain to be flown to complete the high-quality aeromagnetic data in order to make a study of Yukon Flats and vicinity comparable to the study described below for the the northern Yukon-Koyukuk province. Such a study would be especially valuable in unraveling the tectonics of northeastern Alaska, because numerous terrane

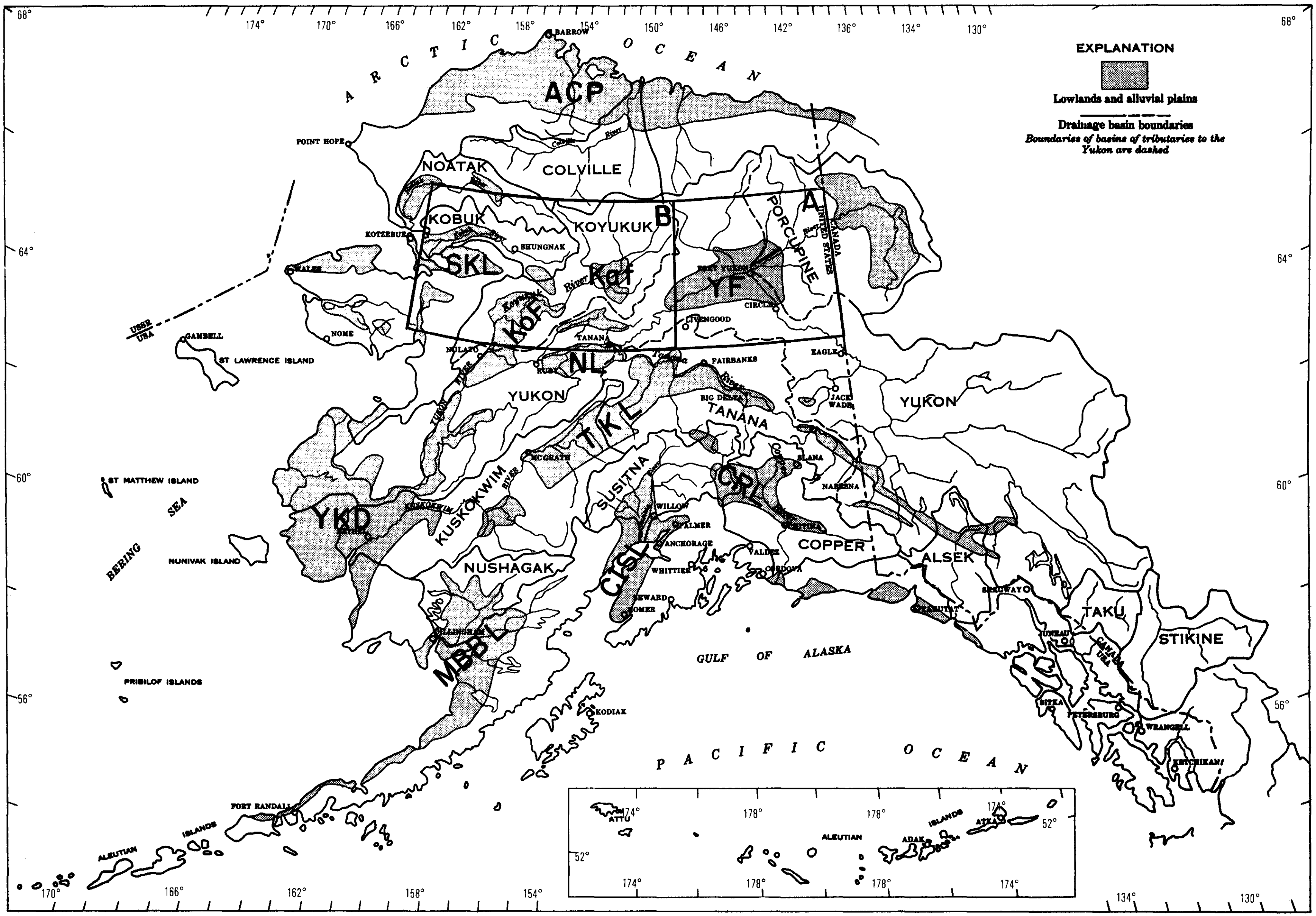


Figure 23. Drainage basins of major rivers of Alaska (modified from Wahrhaftig, 1965). ACP, Arctic Coastal Plain; YF, Yukon Flats; SKL, Selawik-Kobuk lowland; KaF, Kanuti Flats; KoF, Koyukuk Flats; NL, Nowitna lowland; TKL, Tanana-Kuskokwim lowland; YKD, Yukon-Kuskokwim delta; CRL, Copper River lowland; CISL, Cook Inlet–Susitna lowland; NBBL, Nushagak–Bristol Bay lowland. A, northeast corner of outline of figure 24. B, northeast corner of outline of figures 26–30.

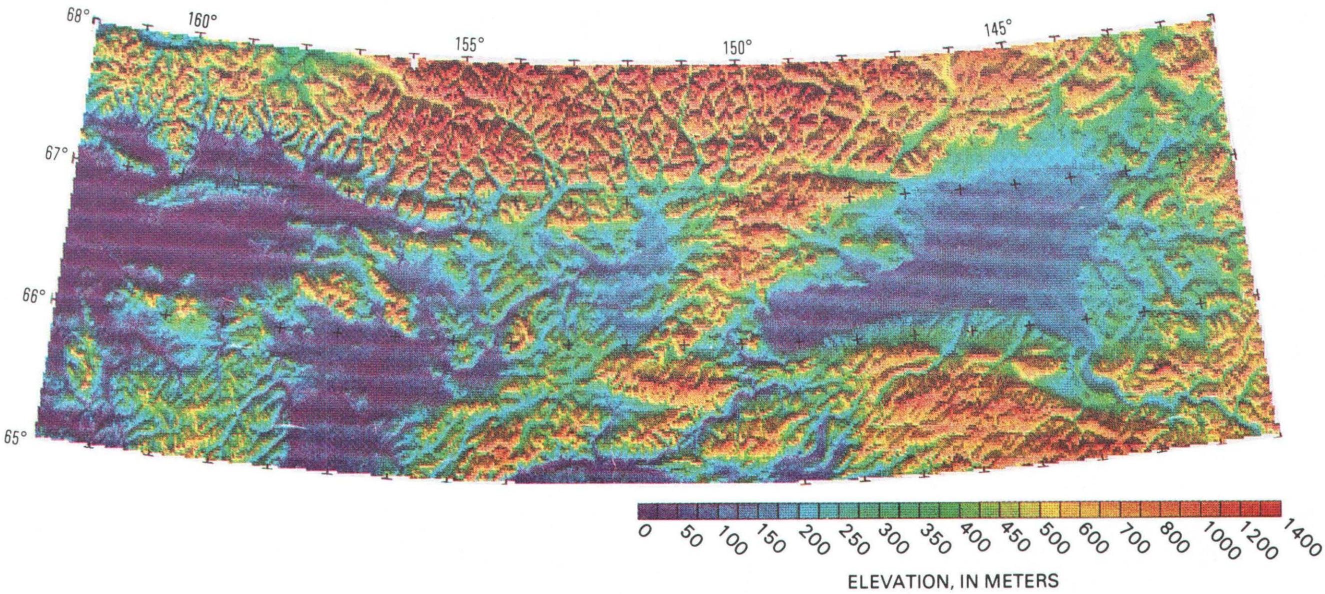


Figure 24. Color-shaded-relief topographic map of Yukon Flats and vicinity; illuminated from the south. The color scale is nonlinear; it tends to emphasize elevation changes near the bottom of the scale and de-emphasize changes near the top of the scale. Location of this swatch is shown on figure 24.

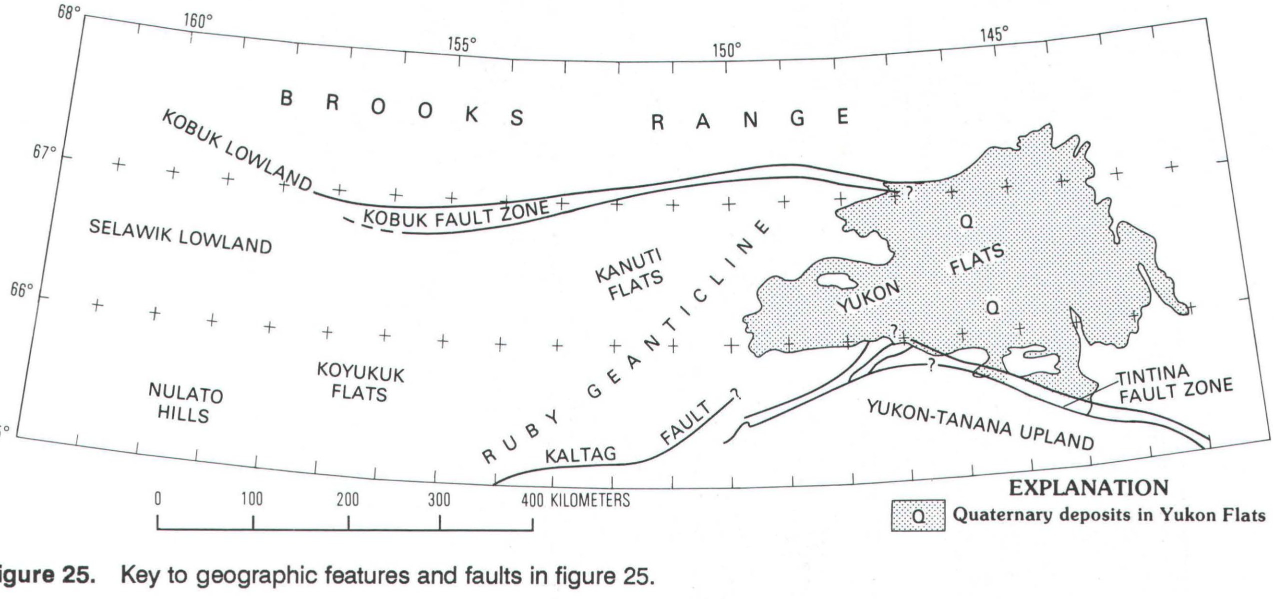


Figure 25. Key to geographic features and faults in figure 25.

boundaries disappear beneath Quaternary cover in Yukon Flats (Jones and others, 1984), and the Tintina, Kaltag, and Kobuk faults (fig. 25) either skirt Yukon Flats or disappear beneath it.

EXCERPTS FROM A STUDY OF THE NORTHERN YUKON–KOYUKUK PROVINCE

Figure 26 is an aeromagnetic map, presented in color-shaded relief, of the western two-thirds of figure 24. The aeromagnetic map is a digital composite of many different aeromagnetic surveys. The data are variable in quality, as shown in figure 27 and table 2. The worst quality data (10-km or wider flight-line spacing) are in the southwest, where anomalies are blurred and ill-defined. These data are not useful for geologic mapping at a scale larger than 1:2,500,000. Nevertheless, because of its large size, the Koyukuk volcanic arc, which is 9° wide and 2° high, stands out boldly in the southwestern quarter of the map.

The remainder of the map was flown with north-south flight lines that were between 1.2 and 2 km apart and were draped nominally 305 m above the ground. Such data represent the standard aeromagnetic data set

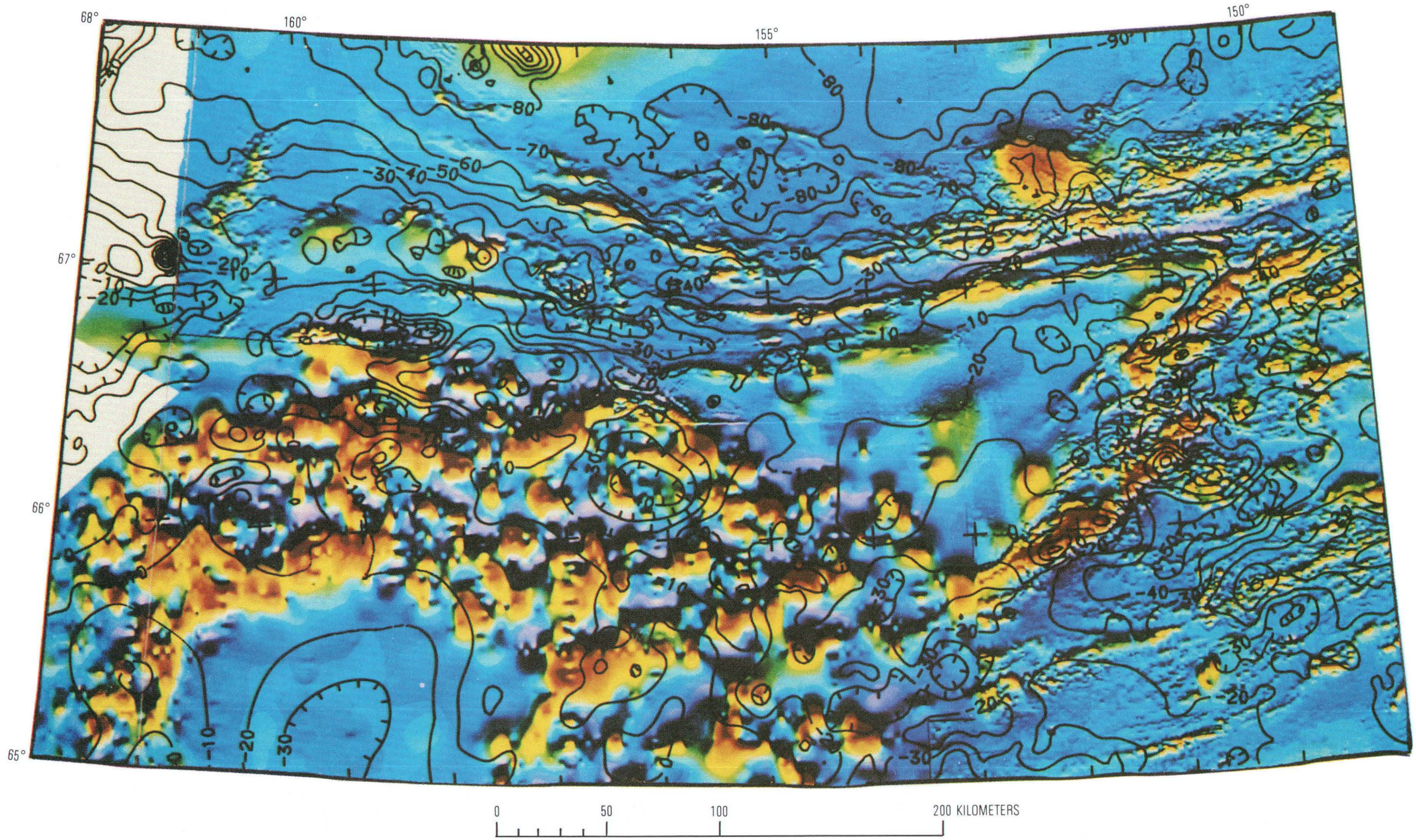


Figure 26. Color-shaded-relief map of the residual total-field magnetic anomaly in the area west of Yukon Flats, illuminated from the south. The nonlinear color scale (color-bar unavailable) shows highs in red and lows in blue and emphasizes magnetic variations in the midrange (yellow and green). Total range about 2,500 nanoteslas. To aid in comparing the magnetic map with the gravity map (fig. 27) simplified black contours of the complete Bouguer gravity anomaly are superimposed upon the colored magnetic map (contour interval 10 milligals).

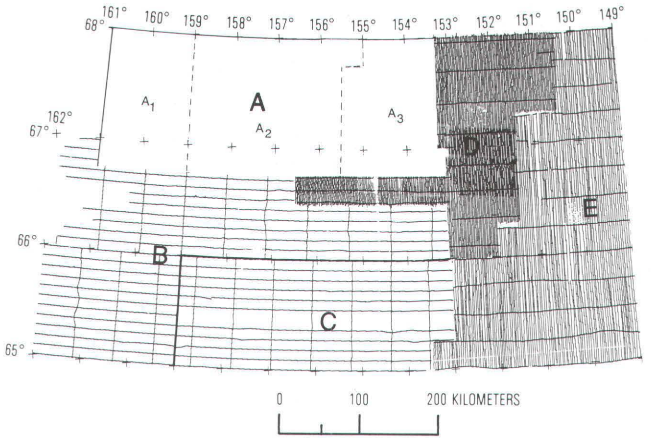


Figure 27. Map showing flight lines that were used to obtain aeromagnetic data. See table 2 for details. Flight lines are not shown in area A because the data were digitized by hand from a contour map and flight lines were not available in digital form.

that is available in those parts of Alaska that have been flown by "modern" surveys. In many places, the maps were made by analogue methods and were digitized by hand.

Figure 28 is an index map for identification of features shown in figures 26, 29, and 30. For a more complete discussion of geographic features and geophysical domains shown on the index map, refer to Cady (in press).

Figure 29 is a complete Bouguer gravity anomaly map of the same area as figure 26. The station spacing is variable; generally it is inferior (wider) to the line spacing of the high-quality aeromagnetic data of figure 26 and in some places it is equal to or worse than the line spacing of the low-quality aeromagnetic data. Major gravity lows occur over the low-density and (or) thick crust of the Brooks Range. Weaker gravity lows suggest that the Ruby geanticline is only a sliver of continental crust.

The Koyukuk geophysical domain (compare figs. 26, 28, and 29) is characterized by a distinctive horseshoe of magnetic and gravity highs that have been interpreted to delineate a Jurassic(?) and Early Cretaceous intra-oceanic magmatic arc. Geophysical data suggest a division of the Angayucham terrane of Jones and others (1984) into the Angayucham domain along the north margin and the Kanuti domain along the southeast margin of the Yukon-Koyukuk province. Both the Angayucham and Kanuti domains contain dense, magnetic oceanic crustal rocks that dip inward beneath the Yukon-Koyukuk province. The contacts between the Kanuti, Angayucham, and Koyukuk domains are buried by sediments of the Kobuk-Koyukuk basin. The gravity and magnetic maps show an undulating basement surface, which is of varied composition and is cut by faults of the Kobuk fault zone.

Figure 30 is a lithologic map derived from a combined interpretation of the magnetic, gravity, and topographic maps. It is presented as an example of the kind of map that can be made from geophysical data in a mostly covered area. In areas of near-total cover, such as Yukon Flats, such a map could be made by using geophysical data to extrapolate from observable bedrock geology on the margins of the basin. Carefully sited basement drill holes would be required within the basin to test the geophysical hypotheses.

Table 2. Aeromagnetic survey parameters keyed to map area shown in figure 29

Map area	Date flown[1]	Contractor	Flight-line spacing and direction	Flight elevation above ground	Regional removed (date of update)	Constant added (in nanoteslas)
A	A1: 1973	Geometrics	1.6 km N–S	305 m	1965 IGRF[2] (1973–74)	50160
	A2: 1974–75		1.6 km N–S	305 m	1965 IGRF (1974)	
	A3: 1975		1.2–1.6 km N–S	305 m	1965 IGRF (1974–75)	
B	1975	Texas Instruments.	10 km E–W, 40 km N–S	122 m	1975 IGRF (1 Jan. 1976)[3]	50140
C	1976	Texas Instruments.	10 km E–W, 40 km N–S	122 m	1975 IGRF (1 Jan. 1976)[3]	50140
D	1978	Geometrics	1.2 km N–S	305 m	1975 IGRF (1978)	50190
E	1972	Aero Service	2 km N–S	305 m	1965 IGRF (1972)	0

[1]For complete references to magnetic surveys, see Cady (in press).
[2]IGRF, International Geomagnetic Reference Field.
[3]Due to apparent errors in IGRF removal in area C by the contractor, areas B and C were difficult to merge. In order to facilitate merger, the IGRF of 1 January 1976, about midway between the survey dates, was removed from the raw Earth's magnetic field in areas B and C.

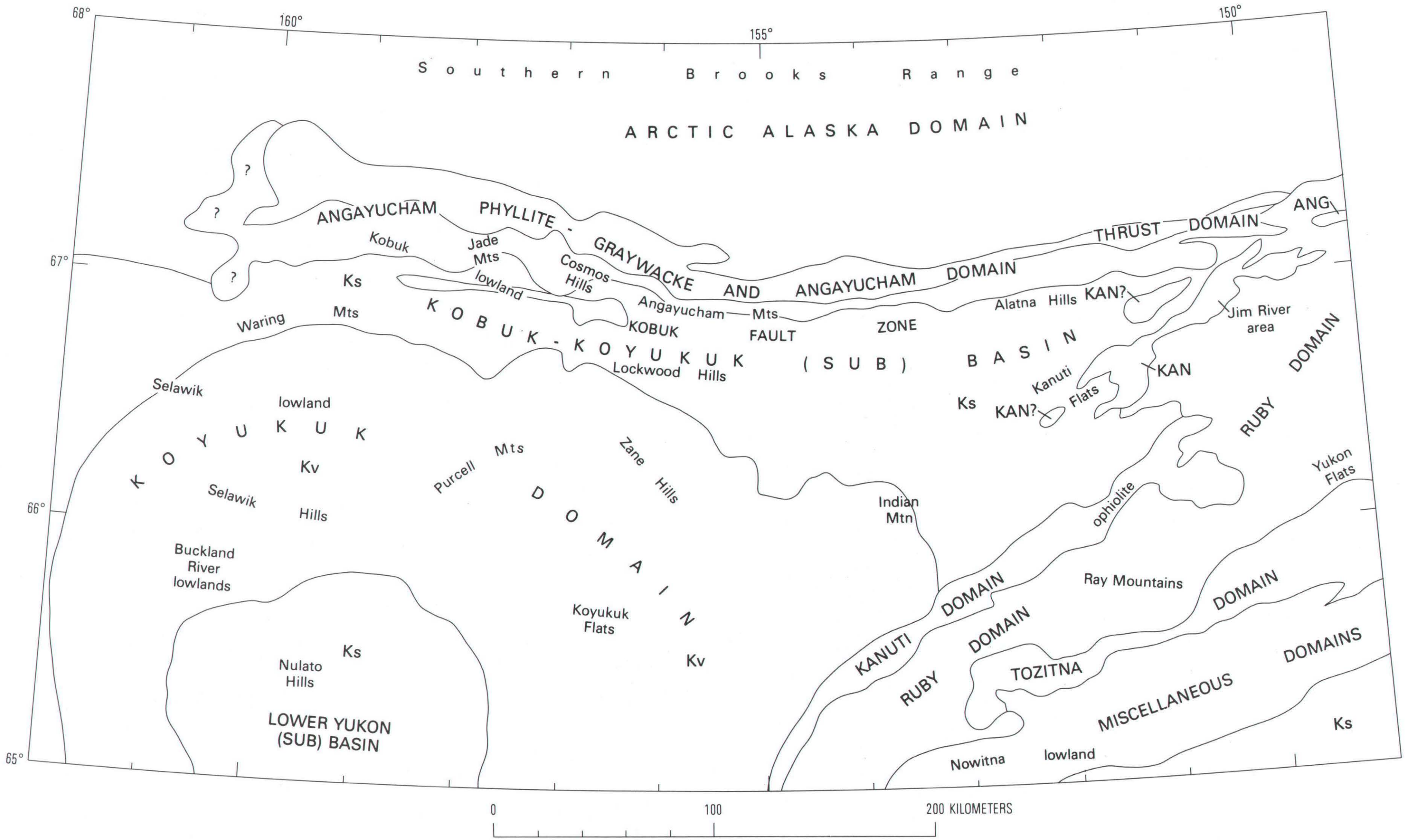


Figure 28. Index map of study area showing selected geographic features (upper and lower case letters), geophysical domains after Cady (in press) (ANG, Angayucham domain; KAN, Kanuti domain), Cretaceous overlap assemblages (Ks, with names in upper case letters), and Cretaceous arc volcanic rocks (Kv). Geographic features are named following Wahrhaftig (1965) except that the Kobuk and Selawik lowlands are separated.

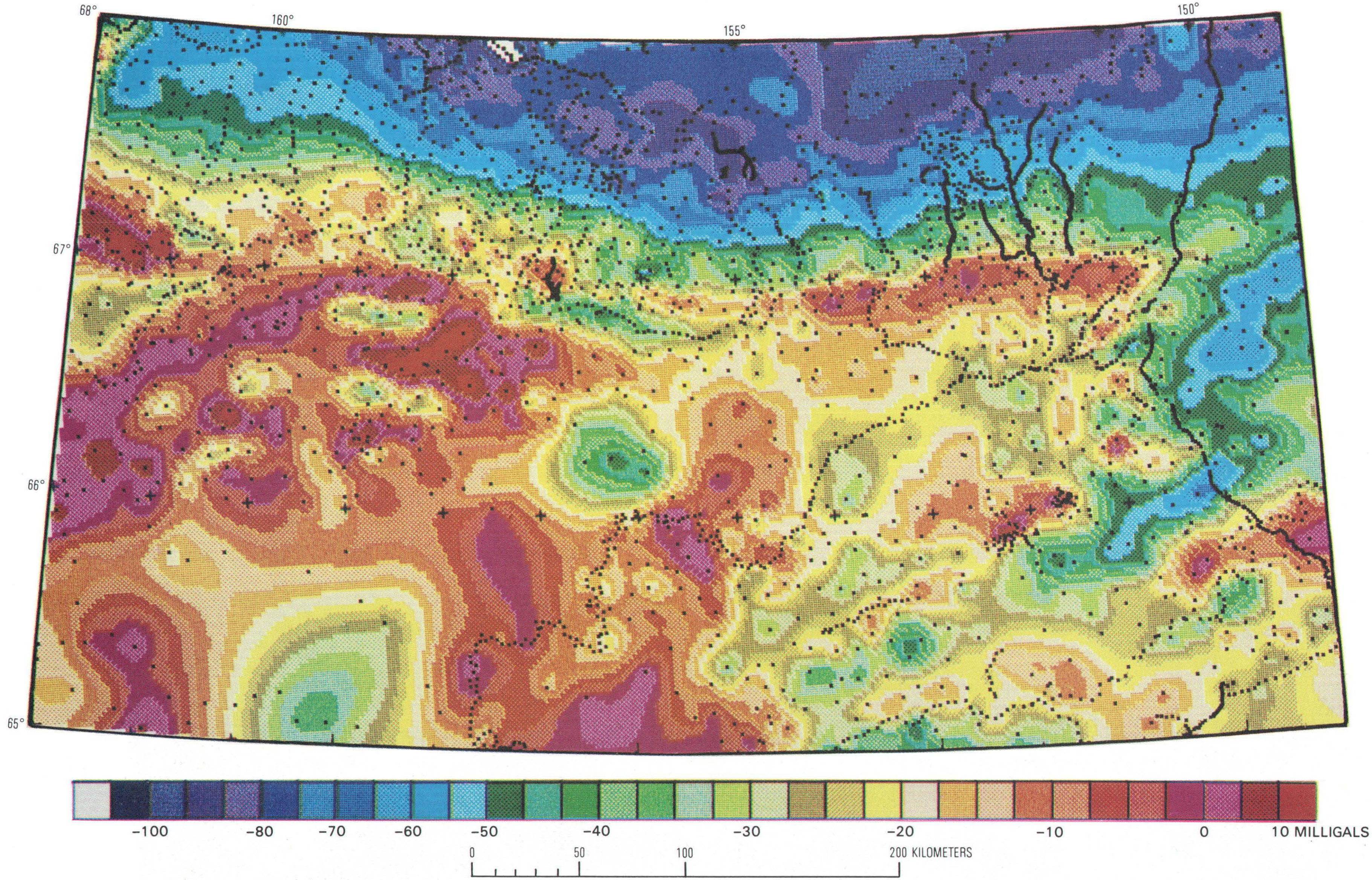
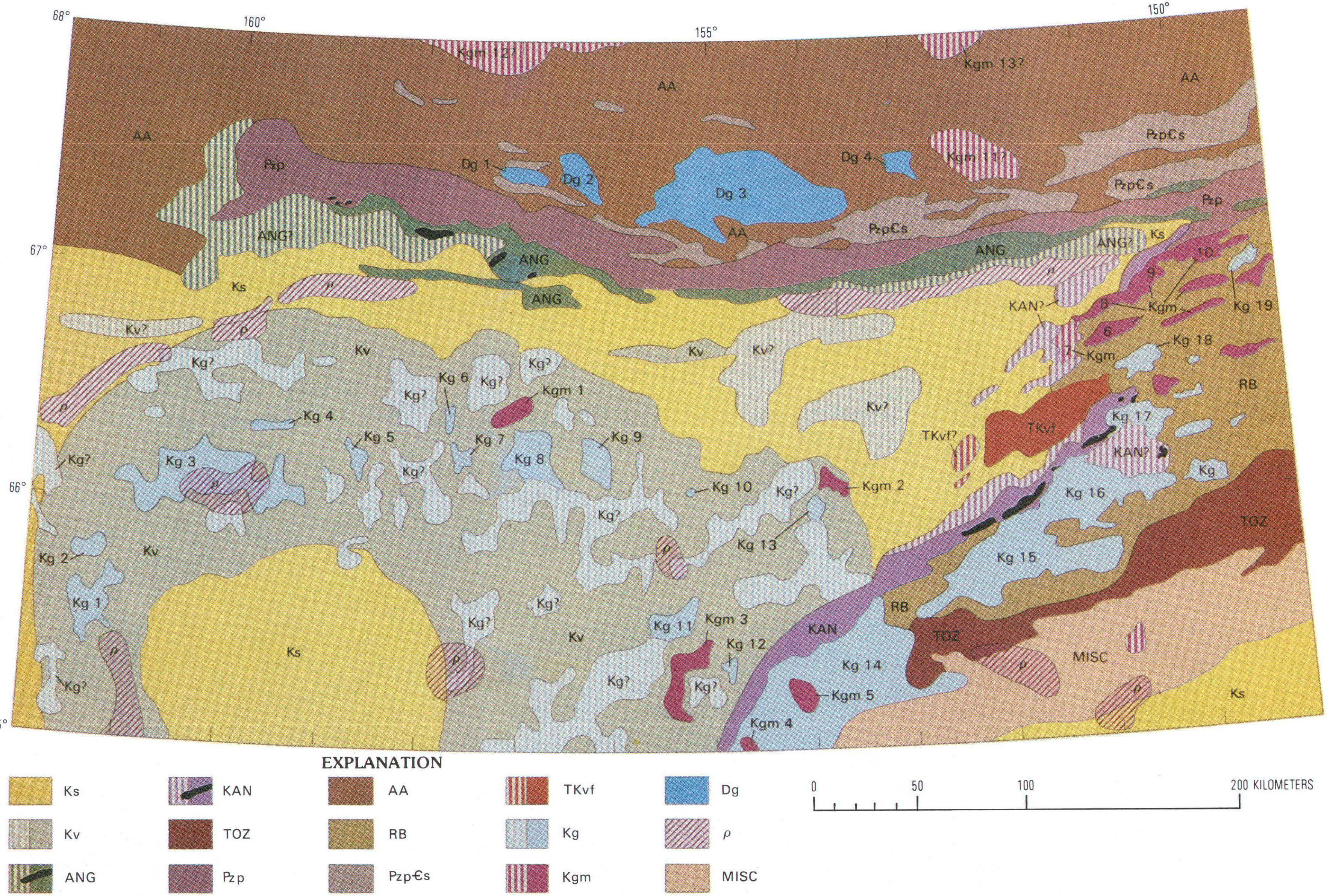


Figure 29. Color-slice contour map of the complete Bouguer gravity anomaly. The nonlinear color scale emphasizes gravity variations in the midrange. Gravity stations shown by black dots. Grid interval 2.032 kilometers. Terrain corrections calculated to a distance of 167 kilometers from the station.


68°
160°
155°
150°
67°
66°
65°
AA
Pzp
ANG?
ANG
Ks
Kv
Kv?
Kg?
Dg 1
Dg 2
Dg 3
Dg 4
Kgm 12?
Kgm 13?
Kgm 11?
PzpЄs
Kgm 1
Kgm 2
Kgm 3
Kgm 4
Kgm 5
Kgm
Kg 1
Kg 2
Kg 3
Kg 4
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PzpЄs
Kgm
MISC
0
50
100
200 KILOMETERS

Figure 30 (facing page). Lithologic map made from interpretation of topographic, gravity, and aeromagnetic maps. Geologic control primarily from Beikman (1980). Boundaries of lithologic units are generally located at changes of character on the aeromagnetic map. The boundaries commonly follow contacts in the subsurface beneath a cover of nonmagnetic rocks. Areas of inferred bedrock are shown in solid colors if any outcrop supports the interpretation; patterned areas show inferred bedrock where there is no known confirmation in outcrops.

Lithologic units (keyed to legend): Ks, Cretaceous sedimentary deposits; Kv, Cretaceous arc volcanic rocks; ANG, Angayucham domain, ultramafic rocks in black; KAN, Kanuti domain, ultramafic rocks in black; TOZ, Tozitna domain; Pzp, Paleozoic graywacke and phyllite; AA, Arctic Alaska domain; PzpЄs, magnetic rocks, commonly mafic schist of Arctic Alaska domain; , undifferentiated dense rocks; MISC, miscellaneous domains outside study area.

Nonmagnetic Cretaceous plutons: Kg1, Granite Mountain; Kg2, Hunter Creek; Kg3, Selawik Hills; Kg4, Inland Lake; Kg5, south end of Ekiek Creek pluton; Kg6, Purcell Mtn.; Kg7, Hawk river stock; Kg8, Wheeler Creek; Kg9, Zane Hills; Kg10, Round Mountain; Kg11, hypabyssal rocks north of Dulbatna Mtn.; Kg12, granodiorite east of Dulbatna Mtn.; Kg13, hypabyssal rocks south of Indian Mtn.; Kg14, Melozitna; Kg15, Ray Mtns.; Kg16, Sithylemenkat; Kg17, Hot Springs; Kg18, Kanuti; Kg19, part of Hodzana pluton.

Magnetic Cretaceous plutons: Kgm1, Shiniliaok Creek; Kgm2, Indian Mountain; Kgm3, Dulbatna Mtn.; Kgm4 and Kgm5, parts of Melozitna pluton; Kgm6, Bonanza; Kgm7?, inferred shallowly buried pluton southwest of Prospect pluton; Kgm8, Prospect; Kgm9, Jim River; Kgm10, Hodzana; Kgm11?–13?, inferred buried plutons in Brooks Range.

Nonmagnetic Devonian plutons: Dg1, "Redstone"; Dg2, "Shish"; Dg3, Mt. Igikpak and Arrigetch Peaks; Dg4, Ernie Lake.

The lithologic map (fig. 30), at an approximate scale of 1:2,500,000, was derived from aeromagnetic maps with a flight-line spacing between 1.2 km and 10 km. It did not make full use of the resolution available in the more closely spaced data. For example, short-wavelength linear magnetic highs are caused by portions of the PzpЄs unit in the Brooks Range and by parts of the units labeled TOZ and MISC in the southeastern part of the map. At a scale of 1:250,000, these magnetic highs can be used to map magnetic mafic schist, layered gabbro and peridotite, and serpentinized ultramafic rocks, respectively. However, existing aeromagnetic maps cannot be used as effective geologic mapping tools at a scale of 1:63,360. Even for 1:250,000-scale geologic mapping, higher quality aeromagnetic maps are commonly required to identify the rocks responsible for the magnetic anomalies. More detailed aeromagnetic maps, accurately draped 300–500 m above the ground with a 500-m flight-line spacing, would lend themselves to 1:63,360 (or 1:50,000) scale geologic mapping. They would also make it much easier to identify the rock type of causative sources in 1:250,000-scale mapping.

RECOMMENDATIONS

A new aeromagnetic survey of the State of Alaska is needed. Although some details of survey design remain debatable, several minimum standards are generally agreed upon.

(1) Maximum flight-line spacing should be about 500 m in areas of exposed or shallow bedrock. Data acquired at wider spacings show anomalies that are too broad for use in 1:63,360-scale geologic mapping. In areas of thick sedimentary cover, spacings as wide as 1 km would be useful. However, for detection of anomalies that are caused by magnetic rocks within the sedimentary section, the 500-m spacing may be required.

(2) Accuracy should be about 0.1–0.01 nT.

(3) Draped flying should be about 300 m above terrain.

(4) Digital data file should include x, y, z-location, raw magnetic field, and field with DIGRF (Definitive International Geomagnetic Reference Field) removed, for both profile lines and tie lines. The surveys must be designed so that additional lines can be interleaved easily by users. Although some aerial survey contractors have expressed a concern that the existence of a public-domain aeromagnetic map with a flight-line spacing of 500 m would inhibit the market for private mineral exploration surveys, I suggest that the opposite is the case. The proposed map will enable explorationists to discover many areas where maps with a

flight-line spacing of 100 m will be required for developing geologic maps at a scale of 1:10,000.
(5) Good geographic bases should be provided for every aeromagnetic map published. It is especially important that 1:63,360- and 1:250,000-scale aeromagnetic maps be published on the same topographic bases that geologists use for field mapping. It is commonly convenient to map geology directly on a published aeromagnetic map.
(6) Smaller scale aeromagnetic maps (1:250,000, 1:1,000,000, 1:2,500,000, 1:5,000,000) should be published in an appropriate combination of color-shaded-relief, color-slice-contour, grey-scale, three-dimensional, holographic, and any number of other existing and future formats.
(7) Data should be archived and made available to the public. There is an opportunity for private vendors to provide services both to the public and to government agencies by publishing standard maps and producing custom products. Compatible formats must be developed to facilitate the overlay or merging of aeromagnetic, gravity, remote-sensing, and digital geologic data sets.

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Notes of the Discussion Group on Western United States: Overview

By Robert C. Jachens

OFFSHORE PACIFIC REGION

The offshore Pacific region, which includes the Pacific Island Territories, is almost entirely covered by water and sediments. Therefore, knowledge of underlying geology is limited to inferences drawn from sparse magnetic coverage, seismic lines, gravity observations, dredge hauls, and shallow borings. More extensive, detailed magnetic coverage would enable preparation of magnetic terrane maps—similar in concept to geologic maps—which would delineate regions of contrasting magnetization and depths to basement; such knowledge is important to the study of both structure and lithology. New magnetic coverage is of economic interest in hydrocarbon exploration because it would help to outline basins, provide improved estimates of sediment thickness, and establish limits on the Curie isotherm, which is used to predict the geothermal gradient that is critical to maturation. From the standpoint of geologic hazards, new magnetic coverage would sharpen the demarcation of fault locations and attitudes near proposed or operating nuclear reactors and would provide additional knowledge about the lengths of fault segments, which in some areas directly correlate with the magnitudes of earthquakes focused on the faults. New magnetic data would contribute to solving such geologic problems as delineating the segmentation of the Aleutian Arc, tracing lithologic terranes across the Bering Shelf, and unraveling the collage of accreted terranes that rim the northeast Pacific margin.

ALASKA

Although much of Alaskan geology is concealed beneath tundra, alluvium, or ice and snow, only about 20 percent of Alaska is covered by magnetic surveys that have flight-line spacings of 1 mi or less. More than any other part of the onshore United States, Alaska needs a geologic mapping program that includes among its highest priorities acquisition, processing, and interpretation of aeromagnetic and other aerogeophysical data. Such new coverage would contribute significantly to economic geology because characteristic magnetic anomalies are commonly associated with gold- or chromite-bearing ultramafic rocks and with base- and precious-metal deposits contained in volcanic, plutonic, and sedimentary rocks (for example, the Brooks Range and Seward Peninsula). Such coverage would also contribute to tracing the locations and attitudes of strike-slip faults as an aid in assessing possible locations of "geometric asperities," where movement along faults may be anomalously inhibited.

CONTERMINOUS UNITED STATES

Although the geology in the conterminous United States is more exposed than in the offshore Pacific region and Alaska, large areas of Washington, Oregon, and California are covered by Tertiary volcanic rocks and alluvium. Improved aeromagnetic coverage would contribute especially to knowledge about geothermal resources in the Cascade Range and Salton Sea area and about petroleum and nonfuel resources in basins that are hidden beneath volcanic deposits, such as the Columbia River Basalt. Such magnetic anomaly data would also contribute to estimating fault traces, offsets, and attitudes in earthquake-prone regions near possible sites of nuclear reactors or high-level radioactive waste repositories and would help to delineate fissuring potential associated with basement geometry. Magnetic data would also provide information relevant to ground-water resources, such as estimates of basin depths, basement faulting that extends vertically to shallow depths, and vertical or subhorizontal barriers to flow. New magnetic data would aid analysis of the mechanics of accretion and obduction in the Klamath Mountains, Blue Mountains, Sierra Nevada foothills, and Oregon Coast Ranges, and would permit studies of magnetic similarities and contrasts of plutonic rocks of the Peninsula, Sierra Nevada, and Idaho batholiths.

Proposed Program Based Partly on Notes of Discussion Group on the Basin and Range Province

By Robert C. Jachens, H. Richard Blank, and V.J.S. Grauch

INTRODUCTION

Problem

The United States has a serious minerals deficit, and the U.S. mining industry remains in decline. The problem is composed of both geologic and economic factors: We are running out of identified domestic deposits and reserves that contain grades and tonnages high enough to be competitive with large foreign reserves which generally are developed with cheap labor and direct government support. If this trend continues, the United States will be ever more dependent on foreign sources of metals. This dependence will reduce our capacity of produce strategic and critical by-product metals and will reduce the ability of the mining industry to respond to National emergencies.

Solution

Past and present production of minerals from the Basin and Range Province of the Western United States has contributed significantly to the economic health and security of the Nation by providing politically stable sources of the raw materials that are needed by U.S. industry. Although current production of most minerals from the province is dropping and will continue to drop as the large, easily located, high-grade deposits are exhausted, renewed exploration and development in the Basin and Range Province provide an extraordinarily rich opportunity to enhance the U.S. position with regard to world-wide mineral resources and to reverse the decline of the domestic minerals industry. The reason is simple: About 50–70 percent of the province is mantled by young, unconsolidated materials and volcanic rocks that conceal rocks that are potential hosts for mineral deposits. In the rich Basin and Range Province, we have so far only prospected in the ranges, not in the intervening basins. Geologic evidence indicates that the number and types of deposits concealed beneath the basins are probably comparable to those exposed in the ranges; nonetheless, the vast basins remain virtually unexplored. The potential for new discoveries here is extremely high, but a systematic program of the scope necessary to realize this potential is beyond the resources of the mining industry. We propose a federally funded, regional-scale geophysical and geochemical data collection program and mineral resource appraisal of the covered areas of the Basin and Range Province as a means to stimulate and focus domestic exploration for new mineral deposits. Inasmuch as this appraisal is primarily directed to covered terranes, we envision a strong emphasis on geophysical, geochemical, and other indirect methods.

Program Rationale

Recent advances in diverse fields make it timely to undertake a regional-scale program directed toward assessing the mineral resource potential of the covered areas in the Basin and Range Province.

(1) Great strides have been made during the past decade in the fundamental understanding of the tectonic events and processes of crustal extension that have dominated the Basin and Range Province during the past 30 m.y. These events and processes controlled the formation of basins and generated the sediments that now mantle much of the region. The increased understanding greatly enhances our ability to predict the nature and geologic framework of the covered rocks; such information is crucial to any assessment of mineral resource potential.

(2) New regional compilations of gravity, aeromagnetic, aeroradiometric, and remote sensing data based on state-of-the-art reduction, filtering, and merging techniques provide a framework for the systematic extrapolation of exposed bedrock lithology into covered areas. These computer-based compilations provide the flexibility to

address specific exploration problems, such as the identification of areas favorable for hydrothermal mineral deposits based on the distribution of concealed plutons. A concealed-pluton map derived from geophysical data was recently produced for the entire State of Nevada as part of a gold resource investigation.

(3) New regional compilations of radiometric, lineament, and limonite maps provide a framework for systematic mapping of surficial geology, including tectonic features and hydrothermal alteration.

(4) Recently available Landsat Thematic Mapper coverage provides new tools for systematic regional mapping of clay types, hydrothermal alteration, and unconsolidated basin fill. In addition, SLAR (side-looking radar) data provide new structural information.

(5) Recent advances in the understanding of the magmatic history of the Basin and Range Province and of the relationship between specific granitoid types and characteristic mineralization demonstrate the feasibility of applying magnetic and gravity studies at a regional scale to define local areas that are favorable for mineral deposits.

(6) New results from mineral deposit models, which are based on analyses of thousands of well-characterized deposits world-wide, provide fresh insights into the relationships between mineral deposits and their tectonic setting, host rock, structural control, environment of deposition, and many other parameters. Knowledge of these relationships is essential to a successful assessment of concealed deposits because the geophysical and geochemical techniques that can "see through" cover only rarely detect the deposits themselves. Such techniques are much better able to detect related structures and environments.

(7) Refined geophysical instrumentation, new accurate positioning systems, and advanced data handling, analysis, interpretation, and display techniques now promise to define subsurface structure and lithology with unprecedented clarity. High-precision magnetometers and magnetic gradiometers permit better resolution of subtle anomalies from buried sources than has been possible in the past. Airborne and ground-based electromagnetic systems that operate over a broad frequency range now allow definition of the electrical properties of the subsurface materials over a wide range of depths, from a few meters to well into the lower crust and upper mantle. Gravity interpretation techniques now facilitate the elimination of anomalies from deep-seated sources and permit more precise definition of density distributions in the upper few kilometers of the crust. Spectral aerial gamma-ray data combined with modern display and analysis techniques provide a new look at surface lithologies and contain information relevant to structural features and geochemical environments. Accurate position information, which is essential to the effective use of new high-resolution data collection systems, can be obtained from long-range ground-based transponder navigation systems and will be much improved with the advent of the Global Positioning System that is currently coming on-line. Recent developments of computer software for manipulating, filtering, interpreting, and displaying the enormous data sets that result from regional investigations will play a key role in the integrated interpretation of diverse data that is required to generate a coherent and well constrained image of the subsurface.

In summary, the needs of the Nation and of the domestic minerals industry have converged with the increased capabilities of geophysics to explore beneath the Earth's surface, with fundamental improvements in our understanding of the geologic processes that have affected the Basin and Range Province, and with a much greater understanding of the relationships between mineral deposits and their host environments. This convergence sets the stage for a major multidisciplinary program designed to provide fundamental geophysical and geochemical data to the mining industry and to evaluate the mineral resource potential of the covered areas of the Basin and Range Province.

DESCRIPTION OF PROGRAM

Objectives and Direction

The primary objectives of the program that we envision would be to provide fundamental geophysical and geochemical data and to produce a systematic mineral resource appraisal of the covered areas in the Basin and Range Province. However, a major difference between the proposed program and the mineral resource appraisal programs of the past is that much of the geologic evidence that traditionally has been used in appraisals will not be directly available but must be inferred from the geophysical and geochemical data bases that were compiled by techniques that "see through" the cover. This requires that the diverse investigations needed to generate the products on which the appraisal should be based must have as their main goal maximization of the ability of geophysical and geochemical interpretations to characterize accurately the subsurface.

Investigations under this program will be directed toward establishing information in four main areas: (1) Tectonic framework of the region; (2) structure and composition of the concealed basement in three dimensions; (3) structure, thickness, and composition of the cover material; and (4) types and characteristics of mineral deposits that are likely to exist within the basement and in the overlying cover material.

Tectonic Framework

Background on the tectonic setting of the region is an ingredient that is critical to assessing mineral resources in general and to focusing exploration activities in particular. Reconstruction of the tectonic setting that predated Basin and Range spreading coupled with studies of deformation and magmatism during the past 30 m.y. are needed to define the tectonic framework of the covered areas.

An important goal would be to produce a tectonic map of the region that identifies ancient rifts, suture zones, terrane boundaries, plutonic belts, and major fault zones and fracture systems. Particularly significant will be definition of the ancient continental margin because the margin represents a first-order boundary in the distribution of mineral deposits that are related to ancient rocks and it may have localized such deposits. The map will depend heavily on the analysis of regional gravity, magnetic, radiometric, and remote sensing data and their derivative products to define tectonic elements and boundaries and to provide the third dimension to the mapped geology. Detailed studies that include combined interpretations of geologic, potential field, electrical, and seismic data along critically placed profiles will served as nuclei from which crustal structure can be extrapolated using the regional data sets. Two such profiles, the PACE (Pacific-Arizona Crustal Experiment) profile across southern California and western Arizona and the lat 40° N. transect recently completed by COCORP (Consortium for Continental Reflection Profiling), already are underway. Additional profiles that transect other important features, such as the Arizona porphyry copper province and the western Utah mineral belts, should be initiated.

Structure and Composition of the Concealed Basement

Reliable lithologic, structural, and plutonic maps of covered areas (basins) require detailed geologic mapping and analysis of the basement that is exposed in adjacent ranges, closely coupled with analysis and interpretation of geophysical and geochemical data over the same exposures. Direct modeling of potential field anomalies over covered areas; tracing of concealed physical property boundaries by potential field, electrical, and seismic measurements; and identification of buried lithologies by means of their geophysical signatures will serve as the basis for a three-dimensional geologic map of the basement. Investigations must include extensive physical property sampling to define the distributions of density, magnetic susceptibility, remanent magnetization, electrical conductivity, and seismic-wave velocity, and their relationships to rock type and geophysical anomalies. Data from basement-penetrating drill holes can provide valuable vertical constraints on geophysical modeling. Analysis of stress on plant communities with deeply penetrating root systems can provide indirect information on metal concentrations.

Thickness, Structure, and Composition of the Cover Material

A systematic mineral resource appraisal should take into account the thickness and composition of the cover material and should include an appraisal of the mineral resource potential within the cover material itself. Pediment mapping, ground-water geochemistry, and analyses of drill-hole and ground-penetrating radar data, coupled with quantitative interpretation of magnetic, gravity, electrical, and seismic data, should permit effective definition of the thickness and composition of the cover material. Remote sensing and radiometric data can be utilized for mapping unconsolidated deposits on a regional scale, which is a subject that warrants more attention in the Basin and Range Province.

Mineral Deposit Characteristics and Relationships

Detailed information on the mineral deposits that are contained within the exposed basement of the Basin and Range Province is essential in the assessment of covered areas. Studies of these deposits will refine mineral deposit models, with special emphasis on characterization of the geophysical and geochemical signatures of the tectonic setting, host lithology, controlling structures, associated alteration, and orebodies themselves. Physical property sampling should be an important component of these studies.

Some of the methods, techniques, background information, and data bases required by this program already exist. Others will have to be developed early in the program, and still other will have to be developed as new questions and problems arise. In some areas acquisition of new geophysical data will be required. From the start, the program will include a component that is directly concerned with the application of appraisal techniques and a research and development component that encompasses topical studies (such as tectonic history, magmatic processes, and ore genesis and deposition), development of new systems and procedures for seeing beneath cover, improved analysis techniques, and new methods for integrating data from diverse disciplines into a coherent geologic interpretation.

Anticipated Benefits

This program will provide a state-of-the-art mineral resource appraisal of a vast, mostly unexplored region of the United States. It will give the Federal Government a much clearer picture of the probable mineral wealth of this part of the Nation for use in economic and strategic planning. The appraisal and the various intermediate data sets and products on which it is based may stimulate exploration activity and focus the limited exploration resources of the mining industry on the areas that have the highest potential for success. This heightened exploration activity may result in new discoveries of ore deposits, thus lessening the dependence of the U.S. industry on foreign sources of raw materials.

Other benefits that will result from the program are:

(1) New appraisal and exploration methods, systems, and strategies (such as the use of broadband electromagnetic techniques to map the depth to and the properties of the basement; the fingerprinting of tectonic features, lithology structure, and mineral deposits according to their geophysical and geochemical signatures; and the combined use of gravity, magnetic, and electrical data for depth sounding) will be directly transferable to the vast covered areas of Alaska, the Midcontinent, and the world.

(2) Refined mineral deposit models with detailed characterization of the deposits in terms of geophysical and geochemical parameters will enhance exploration strategies in exposed as well as covered areas.

(3) Characterization of basin geometries will provide insights into the Cenozoic tectonic development of the province, with possible implications for geologic engineering and hazard mitigation.

(4) Determinations of the geometry and nature of the cover material in the Basin and Range Province will contribute substantially to ground-water resource assessments and ground-water modeling, which are topics that are of critical importance to the increasing permanent population of the province.

Notes of Discussion Group on the Midcontinent

By Lindreth E. Cordell, Thomas G. Hildenbrand, and M. Dean Kleinkopf

INTRODUCTION

In general, the Midcontinent region, defined here to include the continental United States between the Cincinnati arch and the Rocky Mountains, is especially well suited for aeromagnetic surveys because of the extensive cover of alluvium, till, and sedimentary rocks, much of which is less than 1 km thick; the absence of rugged topography; and the particular nature of the geologic problems at hand. Here is where we have the best data, the showiest success stories, and the most clearly defined and urgent fundamental geologic problems that need to be solved. A common view in the geological profession is that the Midcontinent is "the next (mineral) exploration frontier." State geological surveys in the Midcontinent are especially attuned to the use of magnetic methods, and some states, such as Kansas and Minnesota, have active surveying programs of their own.

SUCCESS STORIES AND REGIONAL TECTONIC PROBLEMS REMAINING

The discovery of a major Eocambrian graben that is entirely hidden beneath younger sedimentary rock cover in the Mississippi embayment, and the likely relationship of this graben to earthquakes of the region, ranks about as highly as recognition of sea-floor magnetic stripes as one of the all-time most significant achievements of the aeromagnetic method. Similarly, Precambrian province boundaries that can be seen in outcrop in Canada can now be tracked by aeromagnetic data southward into the United States beneath the seemingly ubiquitous cover. Specific targets for future investigations are the Trans-Hudson belt, the Churchill and Wyoming provinces, the Grenville front, the southern margin of the Superior Province in Iowa, and the northern margin of the Central Plains orogenic belt in Nebraska and Kansas. The aeromagnetic data now need to be studied more closely to determine the attitude in three dimensions and the degree of irregularity of these boundaries. A better understanding of such basic geologic processes as accretion, subduction, and rifting will likely be gained.

A success story of a different sort is provided by the high-quality (¼-mi line spacing) aeromagnetic mapping that was conducted by the State of Minnesota. This program (like similar efforts in Canada, Finland, and elsewhere) points the way and shows how much of the geology may be missed in some of the reconnaissance aeromagnetic data that are now available.

A broad northeast-southwest-trending swath of anorogenic felsic intrusive rocks (about 1.35 b.y. old) that extends from California to Labrador indicates large heat flux into the lower crust, without corresponding tectonic expression at shallow levels. This belt can only be studied by geophysical methods, which incorporate control by sparse drill holes.

Part of the Midcontinent shows characteristic northwest-trending linear features, some of which are probably Archean faults. There is evidence that these faults have been reactivated and have affected sedimentation and facies trends in Phanerozoic strata.

Numerous buried rifts have been mapped geophysically in the Midcontinent. The time of rifting is ambiguous in some cases. Rifting probably first occurred in the early Proterozoic but was also active about 1.35 b.y. ago (Anorogenic period), 1.1 b.y. ago (Keweenawan), and 600 m.y. ago (Eocambrian). In-situ paleomagnetic dating of intrusive bodies, by analysis of their corresponding magnetic anomalies, offers a chance to fill in the uncertain chronology. The rifts also are frequent objects of studies by consortiums, such as DOSECC (Deep Observation and Sampling of the Earth's Continental Crust), which surveyed transects across South Dakota, the Keweenawan rift complex, the Grenville front in Ohio, and the Archean in Iowa, as well as GLIMPCE (Great Lakes International Multi-Disciplinary Program on Crustal Evolution) and COCORP. Future studies should progress outward from areas where basement geology is known into the unknown areas through expansion of state cooperative projects and coordination with other programs such as GLIMPCE, DOSECC, and Canadian studies.

A map of the Precambrian basement of the Midcontinent has recently been completed by Paul Sims and others (Sims, 1985). The discussion group generally agreed that this map represents an end product: Geological and geophysical data resources have been exhausted; all of the known data are in the map, and there is nothing further to be done until new geophysical data are available. There are perhaps other instances where geological mapping has reached a point of diminishing returns and geophysical data are needed, but the case seems especially well made here.

TOPICAL RESEARCH PROBLEMS

The Midcontinent is the birthplace of the concept of "Donovan anomalies" over authigenic magnetic minerals; such anomalies are possibly associated with hydrocarbon exhalative halos. This critical research topic for hydrocarbon exploration is receiving attention worldwide, inherent problems and alternative hypotheses notwithstanding. Other problems of interest include the mapping of stream channels by detrital magnetite, as is being done in Minnesota; the study of anomaly pattern and rock magnetism as a means of mapping metamorphic grade; the direct detection of alteration that delineates unsuspected neotectonic faults; and a magnetic-based petrology of granites, as a means of subdividing and classifying these granites.

In the core area of the Ouachita Mountains, and likely in other favorable areas, crystalline basement rocks are sufficiently deep that, with the improved sensitivity of today's magnetometers and gradiometers, sedimentary strata may have a distinct magnetic expression and thus could be the object of magnetic surveys. We consider it likely that the aeromagnetic method could, in favorable cases, be used to map lithology and, by inference, sedimentary rocks, similarly to the way that the aeromagnetic method is now used to map crystalline rocks.

Many of the goals that were discussed require research in potential-field analysis and instrumentation, if the goals are to be fully realized. It was strongly expressed in the discussion group, as in the full assembly, that new data warrant concomitant support in methodology and analysis. Specific topics targeted include short-baseline gradiometers, stable-platform vector magnetometers, optimal position determination, interpolation of data from lines to a grid, extension of interpretation theory from scalar data to gradient-tensor data, and discrimination of cultural noise.

RECOMMENDED DATA SPECIFICATIONS

Flight-line spacing should be determined by average depth to crystalline basement; the formula that was suggested is spacing equal to basement depth, but neither less than 400 m nor greater than 2 km. Specifically, a 400-m flight-line spacing should be used if basement depth is less than 500 m; 1-km flight-line spacing should be used if basement depth is 0.5–2 km; and 2-km flight-line spacing should be used if basement depth is greater than 2 km. More closely spaced surveys could be useful for local, topical research projects and for gradiometer surveys.

In order of preference, and contingent upon future development in instrumentation, we favored vector measurements, short-baseline gradient-tensor measurements, and long-baseline vertical-gradient measurements. We endorsed the view that all surveys will include at least some type of difference-gradient (optimally, transverse to the flight line) configuration in the very near future.

Flying should be in drape mode and in cardinal directions only, preferably along north-south lines. Tie-line spacing should be five times flight-line spacing, not to exceed 25 km. Surveys should be in blocks of a minimum $1° \times 1°$ area. Scalar-field observations should be to 0.25-nT precision and spaced no greater than 25 m apart along the track. Global Positioning System (GPS) positioning should be accurate to 5–10 m.

Some existing data are satisfactory within these specifications and would not need to be reflown. Other existing data sets, such as those which cover much of Indiana, even where flight-line spacing is satisfactory, would not qualify because of other problems. Loss of primary observational data in digital form, positioning errors, and arbitrary treatment of the geomagnetic reference field are especially troubling in many such surveys.

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Notes of Discussion Group on Eastern United States

By Jeffrey D. Phillips and John M. De Noyer

INTRODUCTION

The purposes of this discussion group were to define specific geologic problems of the Eastern United States that might be amenable to solution using aeromagnetic data and to suggest appropriate aeromagnetic survey specifications and data analysis methods.

GENERAL TOPICS

Rock Magnetic Studies

Rock magnetic studies should be a core component of a National aeromagnetic mapping program. The National Science Foundation (NSF) is sponsoring an initiative on the physics and chemistry of geologic materials. This subject is considered by NSF to be at the "cutting edge" of basic science. A U.S. Geological Survey (USGS) airborne mapping initiative would benefit from association with this NSF initiative.

Rock property studies that relate to aeromagnetic anomalies are uncommon; the few such studies that have been made in Eastern United States, such as in the Carolina slate belt and the Adirondack Mountains, have shown a strong correlation of aeromagnetic anomalies to lithology and metamorphic grade. Unfortunately, oxide and sulfide analyses are not made in standard petrological studies. USGS petrologists need to be encouraged to include such analyses. Good work in this area is being done outside the United States. The most effective way to encourage rock magnetic measurements is to incorporate the data in aeromagnetic interpretations. It is possible to interest petrologists and paleomagnetists in aeromagnetic anomalies.

A USGS airborne mapping initiative should include a firm statement of the need for rock magnetic measurements, including bulk susceptibility and total magnetization vector. Problems to be studied should include standardization of measurements (calibration of instruments, standard samples), relationship of properties of rocks at depth to surface measurements, relationship of properties of a small number of samples to the larger body that produces the aeromagnetic anomaly, and estimation of rock magnetic properties directly from aeromagnetic data in areas of magnetized terrain. The USGS has experience in maintaining a radiometric rock data base. Generally, maintenance of a data base requires either recurrent funding or a person dedicated to maintaining the data base.

Canadian National Aeromagnetic Mapper Program

The Canadian National Aeromagnetic Program involves 20 government employees. A Contracts Group, which consists of six employees, runs the contracting operations, insures continuity of specifications, and monitors the results. An Instrumentation Group attempts to push the state-of-the-art in instrumentation and feeds its results back into the contract specifications. Priorities are set somewhat arbitrarily by committee.

Current data requirements include ¼-gamma sensitivity, noise levels checked in flight, error diurnal variation within 10 gammas, and figure of merit (yaw, pitch, and roll) within 4 gammas. Bernoulli disks are used rather than tape to store data in the air. Exercising, or periodic reading of archived tapes, is not considered cost effective; laser disk technology is being explored for future archiving.

The Canadians seldom seek new contractors. Ongoing professional relationships are best and yield the best data. The companies considered must have all necessary aircraft, instruments, personnel, and computers, and they must be financially solvent. A point rating system is used to evaluate bidders; cost is only one factor in the choice.

The cost of the contracting operation is about $500,000 per year in agency funds. The figure does not include $600,000–$700,000 in salaries or funds received from the Provinces and other Federal agencies. The total is close to $2 million per year.

Geologic problems are decided by the geologists. The aeromagnetic data are published in a form that is readily usable by the geologists; for example, standard colors are used for gradient maps. This encourages the use of aeromagnetic data for geologic mapping. No other promotional effort is needed.

Cooperative Programs Between Government and Industry

The USGS Atlantic Continental Shelf (ACS) survey was a cooperative effort with industry. The USGS bought $600,000 of a $2.5 million effort. The data were time-released to the public over a period of 5 years. The ACS survey was probably a special case, because industry's interest in keeping the data proprietary had a time limit related to Federal lease sales. The academic community would probably object to a time-release contract; this community wants the data while the data are still in the forefront of science. However, releasing the data eventually is probably better than never releasing them.

GEOLOGIC PROBLEMS OF THE EASTERN UNITED STATES

Introduction

The Eastern United States contains some of the earliest aeromagnetic surveys flown by the USGS. Most of these are available only as contour maps at a 20-gamma interval, and are not suitable for analysis using modern digital techniques. More recent USGS surveys, such as those flown over the Atlantic Coastal Plain, suffer from aliasing due to wide flight-line spacing and poor quality control. Many parts of the Eastern United States have extremely poor coverage or no coverage at all. These include large parts of Maine, the Gulf of Maine, southern New Hampshire, parts of Virginia, and southern Florida. The Exclusive Economic Zone (EEZ) is inadequately covered in the vicinity of Maine, Florida, and Puerto Rico. It is safe to say that nearly every part of the Eastern United States would benefit from resurveying using modern high-resolution technology.

Environmental problems of the Eastern United States that can be addressed using aeromagnetic data include earthquake hazards and ground-water contamination. Several areas, including the St. Lawrence River valley, Cape Cod, New Jersey, Virginia, and South Carolina, are sites of active seismicity and occasional large earthquakes. The geologic structures related to these earthquakes are poorly understood. Modern aeromagnetic data could be used to help identify the causes of this seismic activity.

Much of New England is covered by glacial debris which obscures the topography and geologic structure of the underlying bedrock. Because ground water tends to flow within buried bedrock valleys and fault zones, accurate mapping of these buried features is important in the control of ground-water contamination. Similar problems of ground-water flow and contamination are present within the sedimentary units of the Atlantic Coastal Plain. Combined high-resolution aeromagnetic and spectral aeroradiometric surveying are the most cost-effective ways of mapping such structures.

Areas of active mineral exploration in the Eastern United States include Maine, the Gulf of Maine, and all exposed, buried, and submerged early Mesozoic basins. Maine and the Gulf of Maine are known to be underlain by geologic structures that are on trend with the sites of lead-zinc deposits in New Brunswick; tin and chromite also may be present. Accurate assessment of the mineral resource potential is hampered by the poor aeromagnetic and aeroradiometric coverage of this region.

Early Mesozoic basins have long been a source of iron and copper. Currently they are being explored for more exotic strategic minerals, as well as for energy resources. Available aeromagnetic and aeroradiometric data over exposed Mesozoic basins are frequently inadequate for geologic mapping, let alone mineral exploration. Large Mesozoic basins are known to lie buried beneath the Atlantic Costal Plain, both onshore and offshore. Modern aeromagnetic data would help to define the boundaries and thicknesses of these buried basins and to assess their mineral and energy resource potential.

In addition to the early Mesozoic basins, the Appalachian basin and eastern overthrust belt are sites of known or potential energy resources. The Appalachian basin is the site of the earliest commercial petroleum production and is currently producing commercial natural gas. Active exploration and drilling for additional gas reserves continue. Modern high-resolution aeromagnetic data can be used to help map both the thickness of Appalachian basin fill and the basement structures that control folding and faulting of the basin; such mapping would augment knowledge about structural traps that contain oil and gas. Spectral aeroradiometric data could be used to improve mapping of the surface geology of the basin and thereby identify additional geologic units and structures of interest in petroleum exploration.

The eastern overthrust belt is a frontier area of energy resource exploration. Recent, deep seismic reflection profiles suggest that the crystalline rocks of the Blue Ridge Province have been thrust over sedimentary rocks of the Appalachian basin. These buried sedimentary units are potential sites for natural gas deposits. Modern aeromagnetic data can be used to estimate the thicknesses of the crystalline and sedimentary units.

Scientific problems that can be addressed by aeromagnetic surveying in the Eastern United States include the general problem of improved geologic mapping and specific problems such as the structure of the Appalachian Mountains and the origin of Florida. It is a common misconception that geologic mapping is relatively easy in the Eastern United States because of the relatively large areas of exposed crystalline terrane and generally low relief. The problems of glacial cover and Coastal Plain cover have already been mentioned, but even in areas of relatively good exposure of crystalline rocks, mapping is made difficult by extensive vegetation and thick weathering horizons. The availability of high-resolution aeromagnetic and spectral aeroradiometric data over the crystalline rocks of the Eastern United States would lead to greatly improved geologic maps (as would the availability of spectral aeroradiometric data over the areas covered by glacial deposits and sedimentary rocks). Improved geologic maps could in turn result in greater understanding of the structural constraints to be placed on the interpretation of deep-crustal seismic profiles such as those recently collected across the Appalachian Mountains and Southern Coastal Plain.

Maine and the Gulf of Maine

Of all the states in the Eastern United States, Maine contains the largest tracts of land for which mineral rights are available. Most of these large tracts of land are owned by paper companies. In addition, Maine has the largest mineral resource potential of any state in New England. Economic lead-zinc deposits in New Brunswick are associated with sedimentary iron deposits lying along geologic structures that trend into northern Maine. The presence of ultramafic bodies in Maine raises the possibility of occurrences of chromium and other strategic mineral deposits both onshore and beneath the shallow waters of the Gulf of Maine. Shows of tin and the presence of potentially tin bearing granites provide additional incentive for mineral exploration.

Aeromagnetic coverage is very poor or absent for most of Maine and the Gulf of Maine. Much better coverage is needed if meaningful mineral resource appraisals are to be made. Spectral aeroradiometric data are needed onshore for mapping the large areas of glacial cover and would also be useful for identifying potentially tin bearing granites.

Like other areas of New England, the State of Maine is concerned with problems of ground-water flow and contamination. There is a history of radiometric contamination of ground water in southwestern Maine, and the potential for radiometric or chemical contamination exists elsewhere in the State. Aeromagnetic and aeroradiometric mapping would help address these problems.

The Geological Survey of Maine is currently involved in the State Geophysical Maps project of the USGS and can be expected to support actively additional geophysical work within the State.

Georgia and Florida

Recent COCORP (Consortium for Continental Reflection Profiling) deep-crustal seismic data suggest that southern Georgia and Florida have been sutured onto the North American craton. Existing aeromagnetic data in the area of the proposed suture are inadequate for testing the COCORP model. Other recent studies suggest that oceanic fracture zones can be traced completely across the Florida peninsula from the Atlantic to the Gulf Coast. Existing aeromagnetic data in Florida and the adjacent continental shelf are inadequate to test this theory. In Florida, as in most other states, the existing aeromagnetic data were collected primarily for the purpose of making aeromagnetic anomaly contour maps. The specifications of the surveys do not permit the data to be used effectively for quantitative analysis with today's state-of-the-art computer software. High-resolution aeromagnetic data that are amenable to computer processing are needed to address today's geologic problems.

Exclusive Economic Zone

Although much of the Atlantic EEZ is covered by a high-resolution aeromagnetic survey, the relatively high altitude and wide flight-line spacing of this survey may be inadequate in places for addressing the geologic problems that are anticipated as a result of programs such as GLORIA (Geological Long-Range Inclined Asdic). Some parts of the EEZ, such as the Gulf of Maine, the Gulf Coast, and the region around Puerto Rico, are not covered at all. Adequate aeromagnetic coverage is a necessary first step in assessing the mineral and energy resource potential of this huge region.

Atlantic Coastal Plain

A decade ago, aeromagnetic data and total-count aeroradiometic data were collected over the Atlantic Coastal Plain under the auspices of the Coastal Plain Regional Commission with the joint purposes of completing the aeromagnetic mapping and identifying placer deposits of heavy minerals that are associated with monazite-bearing radioactive phosphate. The 1.6-km (1 mi) flight-line spacing and the variable flight-line directions serve to limit the usefulness of these data for studies of the crystalline basement and the overlying early Mesozoic basin deposits which are commonly within 1 km of the surface. Adequate modern coverage of this large and important region would require 0.4-km (¼ mi) spacing, high-resolution aeromagnetic data, and spectral aeroradiometric data.

Radon Hazard

Spectral aeroradiometric data have been mentioned in connection with geologic mapping of glacial deposits, Coastal Plain deposits, Appalachian basin units, and exposed crystalline rocks. In addition to use as a general geologic mapping tool, spectral aeroradiometric data can be used to identify lithologies that are associated with minerals, such as tin and heavy-mineral placers and uranium. Radon, which is a gas associated with the decay of uranium, has been identified as an environmental health hazard. Accurate mapping of the radon hazard should be a primary goal of the USGS airborne mapping program. The State of Pennsylvania is very interested in a spectral aeroradiometric survey for purposes of radon hazard mapping, as well as general geologic mapping and resource appraisal. It is expedient to combine spectral aeroradiometric surveys with aeromagnetic surveys over much of the Eastern United States because in areas of magnetized terrane the data collection specifications for the two kinds of data are much the same: flight lines draped at low altitude over the terrain, and flight-line spacing ideally twice the terrain clearance. The National Uranium Resource Evaluation (NURE) program of the U.S. Department of Energy combined aeromagnetic and spectral aerodiometric techniques in a reconnaissance survey of the United States which resulted in about 5 percent coverage of the country. In the Eastern United States, coverage should be increased to at least 70 percent for the reasons outlined above.

Notes of Discussion Group on Technology

By Frank C. Frischknecht, Richard H. Godson, and Richard J. Wold

MAGNETOMETERS

Because any new National aeromagnetic program will require significant time to be fully implemented, the discussion group considered it to be worthwhile to keep an eye on probable future developments when establishing realistic specifications. Our discussion group generally agreed that 0.01 nT is a desirable and achievable sensitivity. The magnetometer and data acquisition system should be capable of a sample rate of 10 per second, although this density is not needed unless the terrain clearance is small. Some group members advocated routine collection and recording at 10 samples per second; other members thought this placed an unnecessary burden on recording systems and computers to store, read, and edit out unneeded data. The sensitivity of 0.01 nT can easily be met with optical pumping magnetometers that are now generally available, although stability of alkali-vapor magnetometers may be a problem.

COMPENSATION

Various measures of magnetometer performance were discussed, and there was general agreement that a better scheme for measuring performance is needed. Doug Hardwick has a new index, but this is not thought to be the most appropriate measure. There was general agreement that the following manuevers, if conducted at high altitude in a low-gradient area, provide adequate data by which to measure magnetometer performance: Rolls, ± 10°; pitches, ± 5°; and yaws, ± 5°. These maneuvers should be performed in the magnetic north, south, east, and west directions with a period of 3–5 sec to go from the neutral-to-extreme-to-neutral position for each maneuver. At the present time the best figure of merit (the sum of all 12 maneuver errors as measured above) is 2–4 nT. The corresponding state-of-the-art root-mean-square (rms) error is about 0.05 nT. Several methods for compensation were discussed, including use of compensation coils and permalloy strips, real-time compensation by onboard computer using manuever data from a three-component fluxgate magnetometer or other motion sensors, and ground compensation by computer using recorded attitude data. No strong preference for any of these schemes was expressed. The minimum peak-to-peak noise envelope that can currently be achieved under normal low-level survey conditions is about 0.1–0.2 nT. This corresponds to fourth differences of about 1.6–3.2 nT. Computation of fourth differences in flight, as a means of noise evaluation, is a fairly standard procedure.

VECTOR MEASUREMENTS

Vector measurements appear to offer important information that is not available from scalar measurements. More research on the use of vector measurements in interpretation of geologic features is needed. The resolution of vector measurements will probably never be as good as that of scalar measurements. The performance of existing gyros does not match that of the best scalar magnetometers. Stable three-component fluxgate magnetometers are used to obtain vector information. Alternatively, angles can be read from the mechanism of a self-orienting total-field magnetometer such as the ASQ–10. If possible, the reference gyro should be mounted on the same rigid frame as the magnetometer. Flexing of the airframe causes problems if the two devices are attached at different locations. Laser gyros are likely to become standard for vector measurements. A sensitivity of 0.25° in direction is useful in studying geologic problems.

GRADIOMETERS

Technology for measuring vertical and horizontal gradients of total field is available. There was general agreement that serious consideration be given to incorporation of both vertical- and horizontal-gradient measurements in any National aeromagnetic program. Estimates of the increase in cost over single-sensor measurements ranged from "little more" to about 200 percent. This range of opinion seemed to depend on apportionment of a single-time "mobilization" cost (for development and implementation of new equipment) versus a new "operational" cost (for executing surveys), the latter of which may not be much greater than current costs for conventional technology. More research on use of gradients is needed; for example, the possibility of increasing the line spacing when the transverse gradient is measured should be thoroughly investigated. The noise level that currently can be achieved in total-field gradient measurements is about 0.025 nT/m. Although this is useful for many purposes, it would be desirable to bring the noise level down to about 0.003 nT/m in order to use gradient measurements for study of deeply buried magnetic basement.

Superconducting Quantum Interference Device (SQUID) magnetometers are capable of very high sensitivity and high frequency response, and they offer considerable promise for measuring three-orthogonal gradients. The U.S. Navy has done considerable work with these devices, and contractors are beginning to experiment with SQUID gradiometers. The sensitivity of SQUID magnetometers is such that high-resolution gradient measurements can be made using very short baselines. SQUID technology could, in 5 years or less, supply the ultimate magnetometer/gradiometer for the foreseeable future. Optical-fiber magnetomers were mentioned but not discussed.

NAVIGATION AND POSITIONING SYSTEMS

Full implementation of the Global Positioning System (GPS) capability will revolutionize navigation and flight-path recovery of geophysical aircraft. When operated in the differential mode, the system is accurate to within a few meters and should be adequate for almost any airborne survey purpose. It was suggested that the horizontal position of the aircraft should be recovered to within 10 m in the horizontal direction and that the altimeter that measures terrain clearance should resolve distances to 1 m. This specification for horizontal distance can only be met by the GPS system or by ground-based transponder systems. Although radar altimeters that have the desired resolution are available, they tend to average the terrain clearance and respond to trees, buildings, and other objects that extend above the ground. The best accuracy that is achieved by visual means of flight-path recovery (tracking camera or video system) is about 20–30 m; at high altitudes the accuracy is much poorer. Doppler systems provide a continuous track with good relative accuracy, but the absolute accuracy of Doppler systems is no better than that of visual control, despite the fact that visual control is only required at the ends of survey lines. Some members of the group expressed the opinion that, in the interim period before GPS is fully operational, ground transponder systems should be used routinely, despite the additional costs. The use of high-resolution recording barometric altimeters is recommended. However, to obtain good results the barometric altimeter should be compared with the radar altimeter at a suitable location that has a known elevation at least at the beginning and end of each flight. Ideally, the barometric altimeter might be checked as often as twice per hour because pressure changes can occur very rapidly. A ground-based recording barometric altimeter is useful in correcting the aircraft altimeter.

Usual specifications for adherence to flight-line spacing are that flight lines should be separated by no more than one and one-half of their nominal spacing and they should be no closer than one-half of the nominal spacing. There was no general agreement on the permissible length of segments that are separated by the maximum or minimum amount.

TEMPORAL OR DIURNAL VARIATIONS AND CORRECTIONS

A recording magnetometer is always needed at the aircraft base to determine if temporal variations exceed allowable limits for surveying. If ground data are to be used for removal of temporal variations from the survey data, a ground monitor should be located near the center of the survey area. Some contractors recommend use of identical magnetometers in the aircraft and on the ground; in any case, the sensitivity of the magnetometers should be the same. The ground monitor should sample the field at least once per second, and the monitor and aircraft magnetometers should be synchronized with an accuracy of 1 sec or better. There was general consensus that many of the specifications used for allowable temporal variations while flying are not very good. One suggestion was to define temporal variations on the basis of 2-min-long chords; deviations from the chords should not exceed 2 nT south of the auroral zone. In the auroral zone it is necessary to relax the specifications somewhat; otherwise the aircraft will be grounded too much of the time. Ideally, the specifications for allowable temporal variations should be tied to the magnetic latitude. Also, the number of tie lines needed depends on magnetic latitude. Clearly there is a tradeoff between specifications for allowable variations while flying and the number of tie lines that are required. Coupling those specifications could improve surveying efficiency. It was recommended that the ratio of tie lines to flight lines should generally be about 1:10; 1:4 was recommended by some persons, and 1:20 was thought to be too great. Altitude differences between flight and tie lines at intersections should be no more than ± 20 m, assuming adequate aircraft safety.

Further investigation of the diurnal correction problem is needed before final specifications for a National program are developed. In particular, it would be very worthwhile to do research on the use of a network of ground stations for correction of temporal variations when surveying large areas. The Magnetic Observatory program also should be strengthened to permit development and dissemination of improved models of the Definitive International Geomagnetic Field for use in computing anomalies.

DATA PROCESSING

Most data processing procedures are fairly standard; the largest differences between the practices of various contractors are in leveling and gridding procedures. In a National program the USGS should establish uniform standards for formats. The standard coordinate system should be latitude and longitude. Some members of the group thought there should be uniform standards for contouring and gridding as well. The idea was expressed that perhaps the USGS or a separate contractor should do all of the data processing. In any case, quality control is a large and important task. Generally it was agreed that the contractor responsible for data processing must be responsible for quality control but that the USGS or other organization must monitor the processing to ensure that it is done properly. Lists should be maintained of all level adjustments made in going from the raw data to the final product. Any smoothing or other operations must similarly be documented; generally no filtering should be allowed. Contractor preparation of second-derivative maps would be a good means of quality control. It was suggested that acceptance of data might take place in two stages. The first would be to inspect, evaluate, and accept or reject survey data in essentially raw form. Once the raw data are accepted, the objective would be to concentrate on doing a good job of processing. This would eliminate any controversies over the final product due to flaws in the raw data.

The problem of differences in flight heights between adjacent flight lines was discussed in detail. It was generally agreed that in areas where this is a potential problem a race-track pattern for surveying should be adopted. By race tracking, most adjacent lines will be at similar heights although there may be substantial differences between blocks of lines. It was suggested that in processing, data continuation should be used to level the lines to a smooth surface; possibly this procedure is already being used by some contractors. Measurement of vertical gradients would be useful for this purpose in flat terrain but less so in rough terrain. Research on this problem is probably warranted.

Archiving and disseminating aeromagnetic data is an enormous task that was not discussed in much detail. In a National program resources must be allocated to archiving. Available data for visual recovery of the flight as well as electronic navigation and magnetometer data should be archived. Contractors should keep backup copies of all data for a minimum period of, for example, 18 months.

OTHER METHODS

The value and feasibility of using other methods in conjunction with aeromagnetics was discussed. Very low frequency (VLF) electromagnetic measurements would be a valuable addition to aeromagnetics in many areas, and the additional cost would be on the order of $1.00 per line mile provided breaks in the data are acceptable. A simple four-channel radiometric system with a crystal volume of about 1,000 $in.^3$ would add about 30 percent to the cost of aeromagnetic surveys. Radiometric data are thought to be very valuable in many regions; in some areas radiometric data are more useful than aeromagnetics in constructing surface geologic maps. A controlled-source electromagnetic system designed more for resistivity mapping than mineral exploration would be extremely valuable in many areas but would at least double the cost of aeromagnetic surveying. The five-component gravity gradiometer is perhaps 3 years away from being ready for routine application; one estimate of cost for using such an instrument is $60–100 per line mile in 1987 dollars. Specifications for over-water surveys were not discussed in much detail, although the group agreed that a National aeromagnetic program should include surveys of offshore areas. Requirements for navigation are obviously very different for over-water surveys than for over-land surveys; in addition, faster aircraft could probably be used for over-water surveys.

Notes of Discussion Group on Rock Magnetics

By Richard L. Reynolds and Charles M. Schlinger

INTRODUCTION

An essential component of the geologic interpretation of aeromagnetic data is a fundamental understanding of how magnetization depends on petrology. Traditionally this has often been overlooked because of the lack of pertinent data. Aeromagnetic data are numerical data; the link to geology is most effective when the magnetization of representative geologic units can be measured or reliably estimated. We recommend that any National aeromagnetic program should include well-defined and adequately funded provisions designed to bridge the gaps among aeromagnetic interpretation, magnetic properties, and petrology, which will lead to meaningful three-dimensional geologic maps and interpretations.

Research in the area of magnetic properties and petrology would build on existing results and knowledge to address the following problems: (1) The relations of aeromagnetic signals to rock magnetizations in crystalline rocks and the dependence of these magnetizations on bulk rock composition, metamorphism, and hydrothermal alteration, which may be closely tied to mineralization; (2) the magnetizations of sedimentary rocks and the high-temperature (hydrothermal) and low-temperature (diagenetic) modifications of these magnetizations; and (3) the magnetization of the crust as a whole and its lateral and vertical magnetic variations, as well as the tectonic and petrologic significance of these variations.

Rock magnetic research in support of an aeromagnetic program would include field measurements of magnetic susceptibility, as well as field and core sampling and laboratory studies. The laboratory work would investigate magnetic mineralogy, magnetic properties (magnetic susceptibility, remanent direction and magnitude, paleomagnetic stability, and temperature dependence of magnetic properties), and the petrologic controls on magnetizations. In addition, borehole magnetic susceptibility studies should be carried out whenever possible in areas of interest.

MAGNETIC TERRANES AND METHODS OF STUDY

Shallow and Exposed Magnetic Sources

The structural and chronological relations in complex igneous and metamorphic regions can be greatly clarified by aeromagnetic mapping (Hinze, 1985) with support from rock magnetic and petrologic studies of samples at and near the surface. Special attention to the original petrochemical/mineralogical setting of a given unit and its modification by tectonism and mineralization may lead to the recognition of accreted terranes or environments that are favorable for mineral deposits. For example, relations among aeromagnetic signature, metamorphic geology, and rock magnetic properties have proved valuable in identifying areas of the Canadian Shield that are favorable for mineralization (summarized by Grant, 1984/1985a, b). Principles learned in areas of exposed basement can be extended to buried crystalline terranes with thin to moderate cover.

Over thick sections of sedimentary rocks, aeromagnetic methods have potential for detecting the effects of vertically directed alteration plumes. The understanding of such features and their magnetic signatures is currently very limited, but where such an understanding exists, it is based on detailed rock magnetic, mineralogical, and geochemical study (Reynolds and others, 1986). Possible targets include detection of past and present hydrocarbon seepage and of paths of fluid migration in basins leading to mineral deposition (for example, lead-zinc deposits in the Midcontinent and sandstone uranium deposits in the San Juan basin, New Mexico, and in the south Texas coastal plain).

Intermediate Magnetic Sources

Rock magnetic data are extremely limited for the aeromagnetic interpretation of rocks at intermediate crustal levels (2–10 km), below the depths of routine core drilling. Current and future sources of information on the magnetic properties of rocks formed at these depths include (1) tectonically exposed sections, (2) existing drill core and anticipated samples from the deep continental drilling program, and (3) assumptions of rock types and their magnetic properties deduced from shallower rocks of equivalent compositions.

Among the key geologic problems related to structure and events at these depths are the magnetic structure associated with thermal plumes, such as the Yellowstone hot spot (Eaton and others, 1975); the igneous geology and regional tectonics of the Midcontinent region (Sims and Peterman, 1986); and implications for mineralization, hydrocarbon traps, and seismic activity. Aeromagnetic interpretations in these areas will benefit from magnetic property studies of analogous lithologies that are exposed at the surface and in drill core, with corrections applied for anticipated effects of elevated pressure and temperature and for possible mineralogic changes related to crustal depth.

Deep Magnetic Sources

The long-wavelength aeromagnetic signatures of deep crustal (and possibly upper mantle) sources generally reflect anomalous magnetizations that persist throughout extensive volumes of these regions (Mayhew and others, 1985). These anomalies and the causative magnetization contrasts can be best understood in terms of (1) field and laboratory study of exposed crustal sections and xenoliths (Schlinger, 1985; Wasilewski and Mayhew, 1982; Wasilewski and Fountain, 1982), (2) laboratory experimental study of the pressure and temperature effects on magnetization and on magnetic properties, and (3) thermodynamic calculations and experimental study of the stability of magnetic mineral assemblages at depth in the Earth's crust and upper mantle (Frost and Shive, 1985; Haggerty, 1978).

LIMITATIONS

Methods for sampling each of these source regions have limitations. Magnetic properties of rocks now at the surface will presumably differ from those properties of equivalent rocks at great depths, because of possible changes in magnetic minerals and (or) magnetic properties produced by changes in pressure, temperature, and oxygen fugacity that accompany uplift. In some cases surface alteration is important. Understanding the magnetic contrasts associated with deep crustal sources and the magnetic mineralogy at great depth is especially problematic, because only indirect samples are available. Deep-continental drill core will provide valuable but limited samples from intermediate depths in the few chosen settings. Obtaining representative samples from units at or near the surface is even a problem in areas of relatively thin cover or in areas in which magnetic contrasts are caused by alterations that are limited in horizontal dimensions, such as those controlled by faults.

In all cases, the application of aeromagnetic data is most effective when interpretations are constrained by one or more other geophysical data sets, including gravity, electrical, seismic, and radiometric observations.

GENERAL RELEVANCE OF ROCK MAGNETIC–PETROLOGIC STUDIES

Rock magnetic-petrologic studies will have broad applicability to the geologic interpretation of ground, aero-, and satellite magnetic data. In addition, these studies will have a substantive overlap with current national and international initiatives that address (1) the physics and chemistry of rocks and minerals, (2) continental lithosphere, and (3) deep continental drilling.

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WORKSHOP PARTICIPANTS
AND
WORKSHOP PRESENTATIONS

APPENDIX A

Workshop Participants

An ad hoc organizing committee composed of R.J. Blakely, H.R. Blank, J.W. Cady, D.L. Campbell, L.E. Cordell, F.C. Frischknecht, R.H. Godson, V.J.S. Grauch, T.G. Hildenbrand, R.C. Jachens, and J.D. Phillips of the U.S. Geological Survey developed through an iterative process a subject agenda and a tentative list of invitees to the workshop. The original list included more than 100 names of persons renowned in the field of aeromagnetic surveying and analysis. The following shorter list of workshop participants was derived within the constraints of space, time, and funding resources immediately available and in view of the feasibility for attendance on short notice during a major holiday period. Several invitees, some of whom could not attend the workshop, supplied documents of great interest prior to or following the workshop. Special acknowledgments are express to F. Slade Barker, U.S. Naval Oceanographic Office, on the feasibility of using the Project MAGNET aircraft to perform selected aeromagnetic vector surveys; Richard F. Blakely, U.S. Geological Survey, and Gerald G. Connard, Northwest Geophysical Associates, Inc., on the theory and application of aeromagnetic surveying; Joseph C. Cain, Florida State University, Tallahassee, Fla., on satellite-derived global magnetic models; David L. Campbell, U.S. Geological Survey, on profiles showing models of magnetic structures in accreted terranes of south-central Alaska; John W. ("Jack") Corbett, consulting geophysicist, on exploration strategies in the minerals industry; Frank C. Frischknecht and M. Dean Kleinkopf, U.S. Geological Survey, for providing detailed notes taken during the workshop; S. Parker Gay, Applied Geophysics, Inc., Salt Lake City, Utah, on results of the 6th International Conference on Basement Tectonics; James R. Heirtzler, National Aeronautics and Space Administration, on planned magnetic programs involving the National Aeronautics and Space Administration; John F. ("Jack") Hermance, Brown University, on possibilities for future geomagnetics research in the military and civilian sectors; Robert H. Higgs, formerly U.S. Naval Oceanographic Office, Bay St. Louis, Miss., on the airborne vector magnetic survey capability of the U.S. Naval Oceanographic Office; William J. Hinze, Purdue University, for providing notes and illustrations on the need for worldwide magnetic data bases and map inventory; Martin F. Kane, U.S. Geological Survey, for information on contract aerogeophysical data of Saudi Arabia; Elizabeth R. King, U.S. Geological Survey, for serving as a technical reviewer for contributions to this volume and for providing historical data; Douglas P. O'Brien, Comap Exploration Services, Inc., for material on the interpretation and display of the relationship of aeromagnetic features to geochemical anomalies; notes on petroleum exploration data sets and diagenetic magnetic mineral indicators; and illustrations showing filtered magnetic profiles, seismic data, and models of shallowly emplaced concentrations of magnetic mineral enrichment; Mike S. Reford, Geoterrex Limited, on international institutional support for aeromagnetic surveying; John M. Schmunk, Airmag Surveys, Inc., on the precision of measuring microanomalies as determined by the repetition of test flights; Don W. Steeples, Kansas Geological Survey, on the combined use of aeromagnetic and drill-hole data for interpretation of subsurface structure in Kansas; Patrick T. Taylor, National Aeronautics and Space Administration, on activities of the Interagency Magnetic Field Survey Working Group; and Isidore Zietz, consulting geophysicist, for providing historical information about geophysical work in the U.S. Geological Survey.

Working Group abbreviations shown for the following workshop participants are: [W], Western United States; [BR], Basin and Range; [MC], Midcontinent; [E], Eastern United States; [T], Technology; and [RM], Rock Magnetism.

F. Slade Barker, U.S. Naval Oceanographic Office, Bay St. Louis, Miss. [BR, T]

John C. Behrendt, U.S. Geological Survey, Denver, Colo. [E]

Richard J. Blakely, U.S. Geological Survey, Menlo Park, Calif. [W]

H. Richard Blank, U.S. Geological Survey, Denver, Colo. [BR]

Ronald W. Buhmann, National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colo. [T]

John W. Cady, U.S. Geological Survey, Denver, Colo. [W]

Val W. Chandler, Minnesota Geological Survey, St. Paul, Minn. [MC]

Gerald G. Connard, Northwest Geophysical Associates, Inc., Corvallis, Ore. [T]

John W. Corbett, Consulting Geophysicist, Denver, Colo. [BR]

Lindreth E. Cordell, U.S. Geological Survey, Denver, Colo. [MC]

Richard W. Couch, Oregon State University, Corvallis, Ore. [W]

Richard O. Crosby, Aero Service, Englewood, Colo. [T]

W. Minor Davis, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration, Boulder, Colo. [T]

John E. Decker, Alaska Division of Mining and Geologic Survey, Fairbanks, Alaska. [W]

John M. De Noyer, U.S. Geological Survey, Reston, Va. [E]

Frank C. Frischknecht, U.S. Geological Survey, Denver, Colo. (deceased) [T]

Richard H. Godson, U.S. Geological Survey, Menlo Park, Calif. [T]

V.J.S. (Tien) Grauch, U.S. Geological Survey, Denver, Colo. [BR]

Andrew Griscom, U.S. Geological Survey, Menlo Park, Calif. [W]

William F. Hanna, U.S. Geological Survey, Reston, Va. [W, BR, MC, E, T, RM]

Richard O. Hansen, Colorado School of Mines, Golden, Colo. [BR]

Paul C. Heigold, Illinois State Geological Survey, Champaign, Ill. [MC]

James R. Heirtzler, Goddard Space Flight Center, National Aeronautical and Space Administration, Greenbelt, Md. [E]

Thomas G. Hildenbrand, U.S. Geological Survey, Denver, Colo.; currently, Menlo Park, Calif. [MC]

William J. Hinze, Purdue University, West Lafayette, Inc. [MC]

Peter J. Hood, Geological Survey of Canada, Ottawa, Ontario [E]

Robert C. Jachens, U.S. Geological Survey, Menlo Park, Calif. [W, BR]

Martin F. Kane, U.S. Geological Survey, Denver, Colo. [E]

M. Dean Kleinkopf, U.S. Geological Survey, Denver, Colo. [MC]

Don R. Mabey, formerly Utah Geological and Mineral Survey, Salt Lake City, Utah, and currently U.S. Geological Survey, Salt Lake City, Utah [BR]

Michael A. Mayhew, National Science Foundation, Washington, D.C. [E]

Lyle D. McGinnis, Argonne National Laboratory, Argonne, Ill. [MC]

Benjamin A. Morgan, U.S. Geological Survey, Reston, Va. [E]

Douglas P. O'Brien, Comap Exploration Services, Inc., Lakewood, Colo. [T]

Jeffrey D. Phillips, U.S. Geological Survey, Reston, Va. [E]

Gary L. Raines, U.S. Geological Survey, Reno, Nev. [BR]

Mike S. Reford, Geoterrex Limited, Ottawa, Ontario [T]

Richard L. Reynolds, U.S. Geological Survey, Denver, Colo. [RM]

Charles M. Schlinger, University of Utah, Salt Lake City, Utah [RM]

John M. Schmunk, Airmag Surveys, Inc., Philadelphia, Pa. [T]

Paul K. Sims, U.S. Geological Survey, Denver, Colo. [MC]

Richard L. Summerfelt, EDCON, Inc., Lakewood, Colo., [T]

Don W. Steeples, Kansas Geological Survey, Lawrence, Kan. [MC]

Patrick T. Taylor, Goddard Space Flight Center, National Aeronautical and Space Administration, Greenbelt, Md. [T]

Dennis J. Teskey, Geological Survey of Canada, Ottawa, Ontario [T]

Raymond D. Watts, U.S. Geological Survey, Reston, Va. [E]

Richard D. Wold, TerreSense, Inc., Sunnyvale, Calif. [T]

APPENDIX B

Workshop Presentations

(1) Welcome and introduction, by William F. Hanna.
(2) Worldwide aeromagnetic coverage and how we can acquire and make use of it, by William J. Hinze.
(3) Mineral applications of Canadian aeromagnetic coverage and the use of vertical gradiometry, by Peter Hood.
(4) Perspectives on the usefulness of aeromagnetic data in Kansas, by Don W. Steeples.
(5) Aeromagnetic program of Minnesota, allied geophysical studies, and their anticipated usefulness, by Val W. Chandler.
(6) Utility of aeromagnetic data in exploration of mineral district-size or prospect-size areas, by John W. Corbett.
(7) Aeromagnetic anomalies associated with sedimentary rocks and with surface geochemical anomalies, by Douglas P. O'Brien.
(8) Applications of horizontal gradiometry, by Richard J. Wold.
(9) Low-level vector magnetic data from part of the eastern coast of the United States, by F. Slade Barker.
(10) Some examples of high-precision surveys, the use of GPS for navigation, and comments about the reproducibility of total-field and vector surveys, by John M. Schmunk.
(11) Brief review of interpretation techniques and application to the Curie-temperature isotherm problem, by Richard J. Blakely.
(12) Optimal specifications for acquiring aeromagnetic data, by Frank C. Frischknecht.
(13) Merging and display techniques for aeromagnetic data, including examples of colored shaded relief, by Thomas G. Hildenbrand.
(14) A view from afar: Comparison of satellite and aeromagnetic anomalies, by Patrick T. Taylor.
(15) A view from within: Rock magnetism of the sedimentary upper crust and thoughts about the magnetic lower crust, by Richard L. Reynolds.
(16) A State's perspective on a national aeromagnetic program, by Don R. Mabey.

*U.S. GOVERNMENT PRINTING OFFICE: 1990-0-573-049/26005


U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849