66-42

GEOLOGICAL
SURVEY
OF
CANADA

DEPARTMENT OF ENERGY,
MINES AND RESOURCES

PAPER 66-42

CONTRIBUTIONS TO GEOLOGICAL EXPLORATION IN CANADA

(Seven Papers by Officers of the Geological Survey of Canada)

Edited by S.E. Jenness

Price $1.00

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ABSTRACT

These seven papers discuss some recent Geological Survey investigations that relate to geological exploration in Canada. Wright summarizes the functions and distribution of the 112 full-season field projects undertaken by the Geological Survey of Canada in 1965. Wright and Duffell review the progress made since 1952 in geological studies in the northern Canadian Shield. Baragar, Goodwin, and Souther illustrate the close relationship of mineral deposits to volcanism in the Stikine area of British Columbia, in the Coppermine River basalts, Muskox ultramafic complex, and Yellowknife Group in the District of Mackenzie, and in the Porcupine—Kirkland Lake—Noranda 'greenstone' belt in Ontario and Quebec. Hood reviews the revived interest in magnetic methods of prospecting during the past few years and the many types of airborne and ground magnetometers currently available. Bhattacharyya discusses current methods of interpreting aeromagnetic data at the Survey as a direct aid in mineral exploration and to basic geological studies. Collett reports a successful airborne technique using electromagnetic equipment for the reconnaissance surveying of surficial and glacial deposits for glacial and groundwater investigations. Gregory summarizes preliminary successes using colour aerial photography in geological interpretations and airborne gamma-radiation equipment.

CONTRIBUTIONS TO GEOLOGICAL EXPLORATION IN CANADA

INTRODUCTION

From time to time the Geological Survey receives requests from various sources to present papers at scientific conventions or for special technical publications. The seven papers reproduced in this report were prepared by officers of the Survey in October, 1965, in response to one such request for articles for the 1965 Annual Review Number of the Northern Miner. Collectively they provide a clear picture, in language that is not too technical, of some recent investigations by the Geological Survey. As some of the information in these papers is not readily available elsewhere, it seemed proper that they be assembled for distribution in the G.S.C. Paper Series.

GEOLOGICAL SURVEY CONDUCTS CANADA-WIDE INVESTIGATIONS

G.M. Wright

Field investigations by the Geological Survey of Canada in 1965 included 112 full-season projects, many other studies of limited scope or short duration, and six aeromagnetic surveys by contract. The distribution of the main field parties, by scientific function and geological regions, is shown on the accompanying simplified table.

Present-day research by the Geological Survey is truly Canada-wide, and includes major undertakings in the Arctic Islands. Most field parties are led by experienced staff geologists, and a few by university professors and Ph.D. candidates. In its 1965 field program the Geological Survey of Canada also employed about 70 graduate assistants and 140 student assistants, an arrangement of mutual benefit to Canada and to the students' geological careers.

No less apparent from a perusal of the table is the wide spectrum of scientific investigations undertaken by field geologists of the Geological Survey. The range of activities is designed to portray the fundamental geological facts of Canada in their relationships to one another and their significance in regard to mineral occurrences.

The normal progression in what may be called 'regional' geological studies is to apply detailed investigations of topics and areas as a necessary follow-up of reconnaissance and as indicated in support of progress in mineral exploration. Diversity of studies and the development of new methods, techniques, and instruments as aids to the various types of exploration now extant in Canada are a requirement of our times. Examples are the investigation of the three-dimensional aspects of geology, and the application of aerial infrared scanning to the problem of delineating subsurface groundwater aquifers.

Field studies by the modern geologist would be much less productive, in the sense of the value of the ultimate product, were it not for the great variety and high quality of laboratory support available to him. Thus the steadily increasing output of chemical, X-ray, isotopic, and other laboratories, and the presence in them of able scientists with a practical attitude toward the geological implications of their work, adds greatly to the usefulness of the geologist's basic data and permits him to proceed faster and farther in his interpretations and in evolving and testing new concepts in geology.

The field activities of the Geological Survey of Canada are then buttressed by an impressive array of laboratory service and research work, and combined they make a solid contribution both to the mineral industry and to the scientific community.

DISTRIBUTION OF FIELD PARTIES - 1965

Function	Arctic Islands	Cordillera	Western Plains	Precambrian Shield	Appalachia	General	
Reconnaissance[1]	4	9	-	5	2	-	20
Detail[1]	2	8	-	5	3	-	18
Problem[1]	-	1	1	5	-	-	7
Palaeontology	1	5	1	-	1	-	8
Mineral Deposits	1	5	-	3	4	-	13
Glacial Geology	-	4	4	3	3	2	16
Engineering Geology	-	1	1	-	-	-	2
Groundwater	-	1	4	-	1	1	7
Geochemistry	-	2	-	-	1	1	4
Mineralogy and Petrology	-	2	-	2	1	-	5
Geophysics[2]	-	-	1	6	1	-	8
Special	-	-	-	3	-	1	4
	8	38	12	32	17	5	112

[1] Regional or systematic bedrock investigations.

[2] Does not include aeromagnetic surveys by contract.

FOURTEEN YEARS GEOLOGICAL PROGRESS IN THE NORTHERN CANADIAN SHIELD

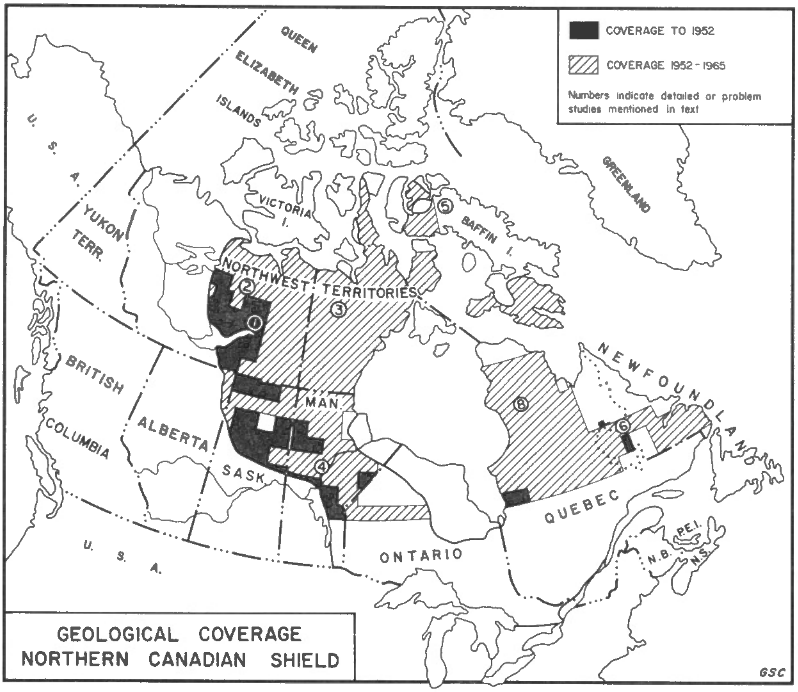
G.M. Wright and S. Duffell

This article deals with that part of the Canadian Shield north of latitude 52 degrees, and the progress made in its investigation by the Geological Survey of Canada since 1952. It is intended to illustrate the tremendous advance accomplished in the gathering of basic geological data on reconnaissance scales and the nature and complexity of the geological problems and investigations that follow naturally from these primary geological studies.

In the Northwest Territories the Geological Survey of Canada has total responsibility for all geological investigation, but within the Provinces its program is designed to complement the many important programs conducted by the Provincial authorities.

The function of government geological surveys whether provincial or federal is to collect, interpret, and synthesize geological data and to make the results available to the public as an aid to mineral exploration and the development of the geological sciences.

The accompanying map illustrates the increase in the rate of reconnaissance geological coverage since 1952. It does not, however, show the numerous detailed studies by provincial and federal surveys.



GEOLOGICAL COVERAGE NORTHERN CANADIAN SHIELD

The greatly increased pace of investigation in the past fourteen years has been due to a number of factors, among which were a general, greater interest in the north, increased staff of the various agencies concerned, and a greater demand for minerals and metals. The most important instrument, however, was the adaptation and application of light aircraft and helicopters to geological surveying. Helicopters of ever increasing efficiency and the introduction of balloon tires on light fixed-wing aircraft, used separately or in combination with helicopters, turned the normal disadvantages of the northern barren grounds into opportunities for efficient geological operations. In the mainland Canadian Shield north of 60 degrees latitude a coordinated series of seven helicopter-supported operations, starting with Operation Keewatin in 1952 and ending with Operation Wager in 1964, studied some 400,000 square miles of previously unmapped terrain using modern methods. Similarly east and north of Hudson Bay since 1957 some 300,000 square miles of unmapped terrain in New Quebec and Baffin Island have been covered. The rate of progress is impressive, but more important is the fact that these results were achieved not only without lowering mapping standards but with increased uniformity and substantially lower costs than were possible with the older traditional methods. At no time were there more than five staff geologists used on these projects.

Reconnaissance studies provide the broad geological framework which, however, requires refinement in many aspects. This can only be done by more detailed studies in specific areas and on specific problems indicated by the primary investigations. Such studies may involve more detailed examination of particular small areas than was possible in the reconnaissance stage or the thorough multidisciplinary investigation of geological problems having regional significance, which must be solved in order to fully understand the geological events and processes involved.

Although part of the Geological Survey's program in the past has been focused on studies of this nature, more and more problems are coming to light that need attention, and it is expected that a greater proportion of future programs will be oriented in this direction.

The following examples will illustrate the scope of recent and current investigations of this type; their locations where appropriate, are indicated by number on the accompanying map.

1. Detailed investigation in the Benjamin Lake area north of the East Arm of Great Slave Lake placed special emphasis on the relationships of known mineral deposits to structures in the sedimentary and volcanic rocks of the Yellowknife Group.

2. Studies of the stratigraphy, structure, and possible correlation of the Goulburn and Epworth Groups of sedimentary rocks in the Contwoyto-Takiyuak Lakes area some 300 miles north of Yellowknife have broad regional implications over a large area west of Bathurst Inlet.

3. Detailed investigation of the constitution and relationships of the essentially flat-lying strata of the Dubawnt Group, which underlies some 30,000 square miles in the central barren grounds, are based on the original helicopter reconnaissance projects, which first outlined and described these Proterozoic sedimentary and volcanic rocks.

4. Of considerable economic interest is the regional, multidisciplinary examination of the major geological boundary (front) between the Superior and Churchill tectonic provinces in central Manitoba. The proximity to this front of the major ore-deposits at Thompson, and the possibility that ore deposition may have also occurred along or near similar fronts elsewhere in the Shield, demand that a thorough examination of all aspects of the geology be made using all available tools and techniques.

5. Recently, major deposits of high-grade iron ore have been discovered in the Mary River area of Baffin Island by mineral exploration endeavours directed originally to these parts as a result of the Geological Survey's findings in northeastern Foxe Basin. Two studies, designed respectively to relate these deposits to the regional geology and to investigate the significant features of the deposits themselves, are being undertaken by the Geological Survey.

6. Detailed investigation of anorthositic intrusions in the eastern Canadian Shield has been underway for the past three years. These rocks are important components of the earth's crust in Newfoundland and Quebec and it is expected that the study of their structure, petrography, age, and mode of emplacement will result in a better understanding of their origin and tectonic significance.

7. Investigation of diabase dyke swarms in the Canadian Shield is a project that obtained much of its basic data on location and trends from examination of air photos, aeromagnetic maps, and maps and reports resulting from reconnaissance surveys. The project has been in progress for the past four years, and has yielded much new information on the extent, age, and tectonic significance of these widespread but little understood rocks. A study of the remanent magnetism of the various dyke swarms has contributed significantly to our knowledge of the pole position during late Precambrian time. It is expected that this work will reveal variations in composition and age of the swarms, and thus will contribute substantially to our knowledge of the upper mantle.

8. An investigation by geologists and chemists of the regional distribution of elements within the Canadian Shield, including the three heat-producing elements potassium, uranium, and thorium, is based on the availability of large representative sample collections from reconnaissance helicopter operations. The average surface compositions of several large areas provide the most accurate estimate of the composition of large Precambrian cratons ever obtained, establish major regional variations in metamorphism, and contribute to our understanding of the development of the crust.

9. A development of major significance within the past five years is the division of the Canadian Shield into tectonic provinces, each with its own age and tectonic style. This study follows naturally from the development of isotopic age-dating techniques and reconnaissance coverage of the shield areas. It has contributed immensely to our understanding of the tectonic history of the shield and has been done as part of the larger project of constructing a tectonic map of Canada.

Any discussion of the advances in geological knowledge of the Canadian Shield must include the role played by the supporting disciplines available to the present-day geologist. Modern geologists have a major advantage not shared by earlier workers. This is the impressive array of allied disciplines marshalled in their support. We refer here not only to such aids as chemical analyses and isotopic age determinations available in abundance unheard of a few years ago, but to the many aspects of geophysics and geochemistry, which are invaluable aids to the geologist. The actual products of the laboratories are of vital service to the field geologist, but their value is greatly enhanced by the presence, in close collaboration, of the scientific minds that produce them. Where a multidiscipline assault is required for the unravelling of a complex problem, it is readily available. This approach is now more the rule than the exception and the investigation of more and more problems will be team rather than solo efforts.

The ultimate objective of detailed and problem investigations using all available allied disciplines, superimposed on the broad fundamental geological framework determined by reconnaissance, is a complete understanding of the geological history of the Canadian Shield, the relationships of its component parts, and a thorough knowledge of the processes that produced it and its contained mineral deposits.

VOLCANISM AND MINERAL DEPOSITS

W.R.A. Baragar, A.M. Goodwin, and J.G. Souther

Introduction

Some types of ore deposits have long been credited to volcanism but only recently has the possible extent of this class of deposits in Canada been perceived. Several major metalliferous fields reexamined in recent years (Bathurst, Noranda, Porcupine) are now widely considered to be of volcanic origin and the number can be expected to grow as criteria for recognizing them are further developed. In this article we will discuss briefly theoretical aspects of the relationship between volcanism and ore deposits and scan some Canadian regions where it seems to be evident.

Mineral deposits of volcanic origin may be (1) direct products of volcanism, or (2) concentrations at a later time of metals brought to, or near, the surface by volcanism. In the first case the mineral deposit is formed directly from the volcanic agent, for example hydrothermal fluids or lavas, in the second it is formed at a later time by mobilization and concentration of minor constituents in volcanic materials (gold in some lavas would require a concentration factor of as little as 1,000 to make ore). The event responsible for later concentration is unlikely to be directly related to the volcanism.

Deposits of direct volcanic origin are of two classes, those deposited within or immediately around the magma and those that have been deposited at a distance from the magma by the agency of magmatic fluids. Both types may have surface or subsurface manifestations, for example fumarolic deposits or metal concentrations in lava on the one hand and fissure veins or sulphide deposits of sill or dyke association on the other.

Characteristics of various types of deposits should reflect their mode of origin. Surface deposits are stratigraphic units with a unique time relationship to the host rock; subsurface deposits are younger, but otherwise bear no necessary time or geometric relationship to the enclosing rock. Deposits of direct volcanic origin should cluster around the parental volcanic centres. Those formed by later concentration of constituents from volcanic materials might be expected to show closer affinity to the agency that concentrated them than to the original volcanic source, although, in a general way, geographic correlation with the volcanic rocks should still be evident.

Cordillera

A close spatial relationship between mineral deposits and volcanism is well shown in the Stikine area of British Columbia (Fig. 1), where copper deposits are associated with Triassic volcanic rocks. Exploration directed at this area in recent years has resulted in the discovery of a great many mineral occurrences including several potential copper producers. It is noteworthy that most of these copper occurrences are found in or near a thick, marine facies of the Upper Triassic volcanic sequence.

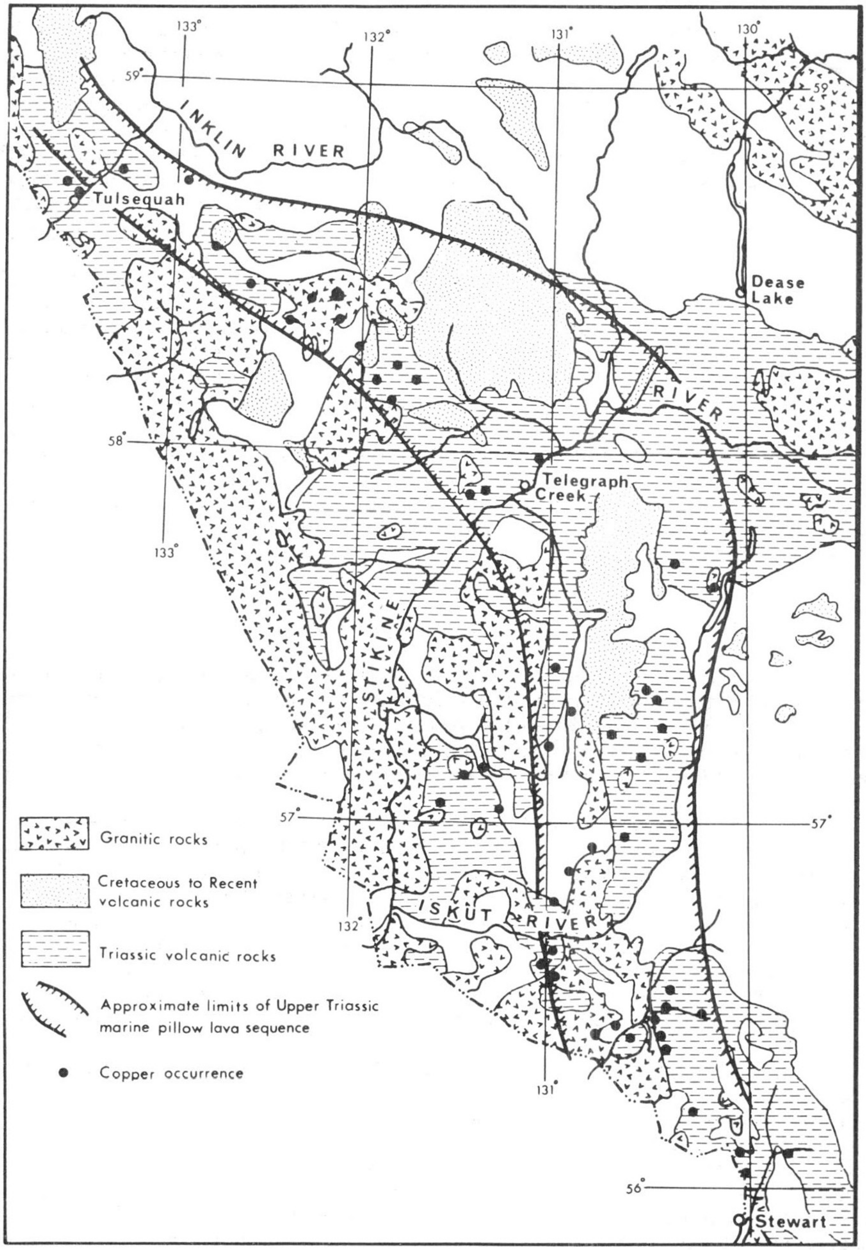


Figure 1. Map of the Stikine area, northwestern British Columbia, showing the distribution of copper occurrences and their relationship to granite and volcanic rocks.

Whereas the copper deposits of the Stikine area appear to be related to a Late Triassic cycle of igneous events, occurrences of molybdenum and antimony-gold-silver appear to be related to a Late Cretaceous–Early Tertiary igneous cycle. The volcanic products of this latter cycle are represented, in the Stikine area, by acid and intermediate flows and pyroclastic rocks of the Sloko Group. Intrusive rocks related to the same episode of igneous activity are represented by large bodies of quartz monzonite and small stocks, dykes, and necks of quartz-feldspar porphyry. Of particular economic interest are the same pipe-like porphyry bodies intruded at shallow depths and those that reached the surface as feeders for the eruption of Sloko volcanic rocks. Many of them are highly fractured and veined by a box work of quartz stringers with traces of molybdenite. They are surrounded by extensive zones of hydrothermal alteration, including much pyrite. The altered rock is frequently veined by quartz-carbonate-stibnite stringers, which in at least one property presently under development contain significant amounts of gold and silver.

Late Tertiary and Recent centres of basaltic eruptions mark the final episode of Cordilleran igneous activity. Although the centres are not in themselves of economic importance they are clearly located along major lineaments that may reflect the position of deep-seated faults that have served as channel ways for older igneous rocks and mineralizing solutions.

District of Mackenzie

The District of Mackenzie provides excellent examples of metal deposits with direct volcanic affiliations — copper deposits of the Coppermine River flows, and copper-nickel deposits of the Muskox Intrusion. In addition, gold deposits of the Yellowknife Group may have an indirect relationship to volcanism.

The Coppermine River basalts (Fig. 2) form a succession of gently tilted lava flows, each 100 to 200 feet thick, that reach 11,000 feet in aggregate thickness. Vesicles (former gas bubbles) concentrated in layers near the upper, or more rarely the middle, parts of individual flows contain in places native copper. Fracture zones that cut the flows locally are mineralized with copper sulphides and gangue minerals. Almost certainly the copper was deposited in vesicles and fractures by residual fluids remaining after much of the lava had solidified. Its source, therefore, was the lava itself and the copper was concentrated by the process of solidification.

The Muskox Complex (Fig. 2) is an intrusive body about 70 miles long, a maximum of 5 miles wide, and several thousand feet thick. It crystallized from basaltic magma through a complex succession of stages now marked by layered structure in the body. Copper-nickel sulphide deposits are distributed around the complex and a chromite layer with minor values in platinum and palladium occurs within it. Both types of deposits were unquestionably derived directly from the magma, but the role of the magma in volcanism is less certain. Modern volcanoes give evidence of being joined to magma chambers at depths of from 1 kilometre to 7 kilometres below the surface. These are resting points in the ascent of the magma from much deeper levels. The Muskox Complex fits the requirements of such a magma chamber admirably and probably was connected with volcanic outlets on the surface.

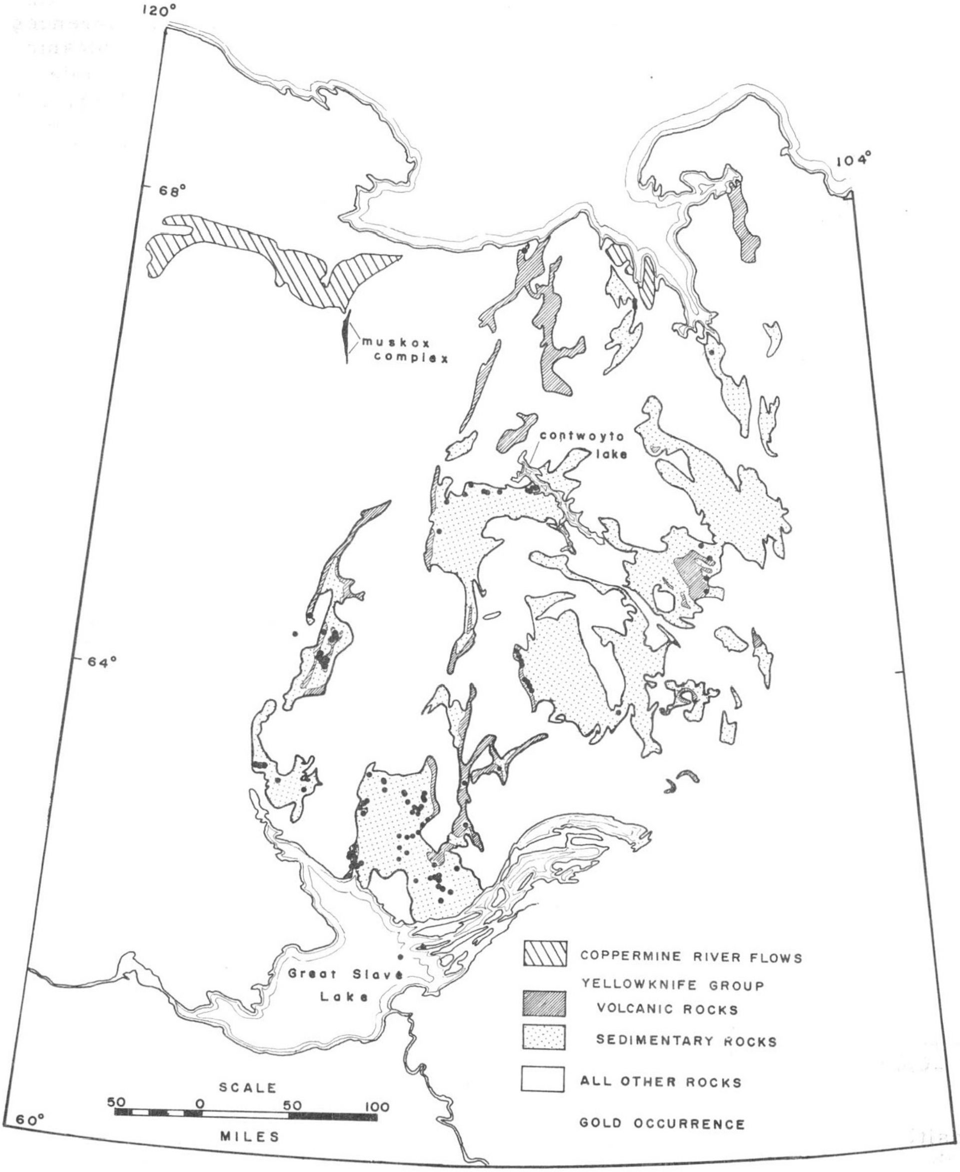


Figure 2. Map of part of the Mackenzie District showing the spatial relationship of gold occurrences to the Yellowknife Group rocks.

The Yellowknife Group of volcanic and sedimentary rocks occurs in scattered remnants throughout a region of about 70,000 square miles. Its distribution is essentially coincident with the distribution of gold occurrences in the district (Fig. 2). The lower member of the group comprises volcanic rocks, which are as much as 40,000 feet thick; the upper member consists mainly of greywacke-type sediments derived in part from the underlying, and partly contemporaneous, volcanic rocks. The producing mines (Giant, Con, Discovery, and Tundra) are within or closely associated with the volcanic rocks, but numerous occurrences of gold are found in both members. Most of the gold is in structures - fractures, shear zones, folds - imposed by deformation that post-dated volcanism and was presumably unrelated to it. Nevertheless the close physical association of gold occurrences and the Yellowknife Group suggests a close genetic relationship. One study[1] of the Giant and Con orebodies reached the conclusion that the gold was concentrated from the volcanic host rock during a later episode of deformation. In recently discovered Contwoyto Lake occurrences gold is confined to certain amphibolitic beds of possibly mixed volcanic-sedimentary origin, in the Yellowknife Group sedimentary sequence. There it is difficult to escape the conclusion that the source of the gold was the amphibolitic hosts, even though later events may have been responsible for concentrating it. Thus there is some basis for suggesting that gold in the Yellowknife Group is also from a volcanic source, although the relationships are greatly blurred by later events.

Superior Province

The Superior Province of the Canadian Shield contains a large number of Archaean 'greenstone' belts, each composed of volcanic, sedimentary, and intrusive rocks, and mutually separated by intervening tracts of granitic and metamorphic rocks. Great mineral wealth is present in the 'greenstone' belts in the form of gold, base metal, and iron deposits. Indeed, by far the greatest part of the mineral production in this part of Canada comes from such deposits.

Volcanic rocks are principal components of the mineralized 'greenstone' belts and stratigraphic successions of volcanic rocks are recognizable in many of them. Significantly the patterns of mineralization commonly bear direct relationships to the volcanic successions.

The sequential pattern of Archaean volcanism is as follows: great broad accumulations of basic lava flows are overlain by irregular piles of acid extrusive rocks, the latter commonly interstratified with, and overlain by sedimentary rocks. One or more such basic-acid successions may be present, the total stratigraphic thickness commonly ranging from 20,000 to 30,000 feet.

Mineral deposits occupy preferred spatial and stratigraphic positions in the volcanic piles. Thus, banded iron formations commonly lie either in the upper, acid tuffaceous volcanic rocks or in thick sedimentary

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[1] Boyle, R.W.: The geology, geochemistry, and origin of gold deposits of the Yellowknife district; Geol. Surv. Can., Mem. 310, 1961.

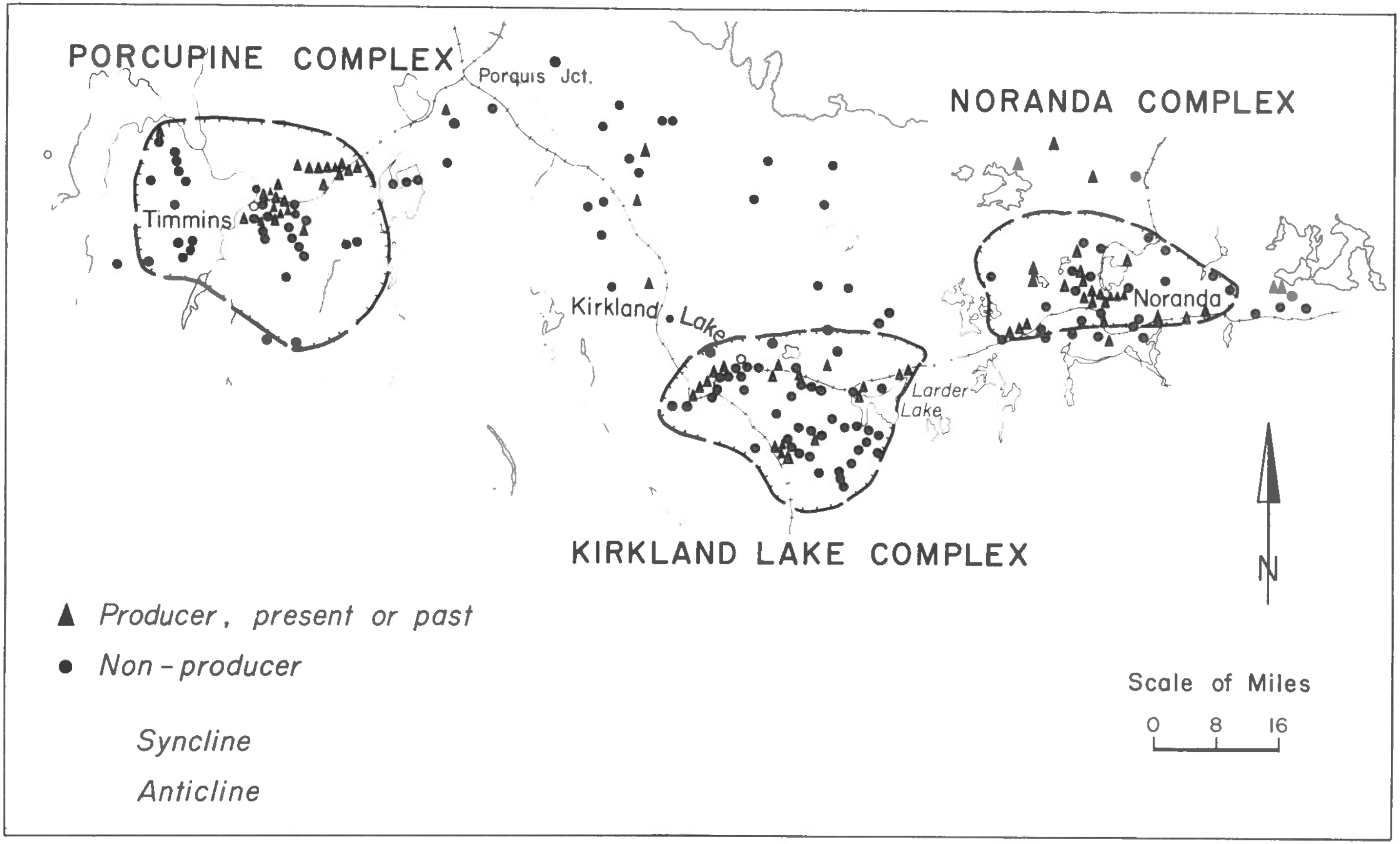

Figure 3. Location of volcanic complexes and mineral occurrences in the Porcupine–Kirkland Lake–Noranda region.

assemblages marginal to the volcanic piles. Gold and base-metal deposits are commonly located in, or near the upper acid part of the piles, either at the contacts of small, contained granitic stocks or in the form of veins, stringers, and irregular masses in siliceous volcanic units.

To illustrate this relationship, the Porcupine – Kirkland Lake – Noranda 'greenstone' belt of northeastern Ontario and northwestern Quebec contains three well-defined volcanic complexes, each with high proportions of acid volcanic, sedimentary, and associated intrusive rocks. At least 200 significant gold and base-metal deposits, including 73 producers, past and present, occur in the region. A salient feature of the regional mineral distribution is that the large majority of occurrences, including most producers, fall within the boundaries of the three volcanic complexes (Fig. 3). Specifically, 80 per cent of the occurrences, including 87 per cent of all producers, past and present, are so enclosed. In stratigraphic terms nearly all producers and occurrences of note are located in, or close to, the upper acid to intermediate volcanic and sedimentary rocks of the three complexes.

Similar volcanic-mineral relationships prevail in other Archaean 'greenstone' belts. In the Michipicoten belt of central Ontario all 93 recorded mineral occurrences, mainly iron and gold, are clustered about thick acid volcanic piles and associated granitic stocks. In the Birch-Uchi lakes belt of northwestern Ontario, of 50 recorded gold occurrences, 34, including all past producers, are directly associated with acid to intermediate extrusive rocks. Common to these and many other Archaean belts is this volcanic-mineral accord. It is considered likely that in many cases the valuable minerals and the volcanic hosts represent consanquineous products of common magmatic parentage, a relationship that has controlled their present general spatial association.

Concluding Statement

This brief resumé of volcanism and its relationship to mineral deposits has covered some theoretical and practical aspects of the problem pertaining to Canada. Clearly, a relationship commonly exists between mineral deposits and volcanic rocks. Equally clearly, the nature of this relationship varies greatly from place to place. Whatever the relationship may be, it is considered that a clearer understanding of volcanism will provide significant insight into ore-forming processes. Many broad areas of volcanic investigation exist, each with economic aspects, including: (1) the nature, origin, and preferred tectonic settings of volcanic activities and products; (2) sequential patterns in volcanic piles; (3) hot-spring, fumarolic, and other surface and near-surface manifestations; (4) sub-volcanic intrusive activities; and (5) the parental association of deeper-seated magmas. A program of volcanic studies requires careful attention both to ancient volcanic piles in which the deeper, sub-surface parts are now laid bare of folding and erosion and modern volcanic areas where surface activities may be directly observed. Such a broad study of volcanism may be expected to provide a clearer understanding of ore-forming processes and hence contribute substantially to long-term mineral exploration in Canada.

A RENAISSANCE IN MAGNETIC METHODS OF PROSPECTING

Peter Hood

There appears to have been a renaissance in magnetic methods of prospecting in the last several years judging by the volume of articles on the topic appearing in the scientific press. There are a number of reasons why there has been a resurgence of interest in magnetic prospecting techniques. There has, of course, been an increasing acceptance of geophysical methods in general over the years by exploration management, which has been considerably helped by a number of spectacular geophysical discoveries, the most recent of which has been the Texas Gulf Sulphur zinc-copper-silver orebody at Timmins. Another factor which has some bearing is that the rate of production of aeromagnetic maps published by Canadian government agencies has sharply increased since the start of the Federal-Provincial Aeromagnetic Survey Program in 1962.

Actually aeromagnetic surveys produce the most useful reconnaissance information on a given area for the least cost of any type of exploration survey. In prospecting an unknown area for mineral deposits, an unqualified recommendation can be made that a reconnaissance-type aeromagnetic survey be carried out to precede the start of the main exploration program.

A decade ago there essentially was only one magnetometer in standard use for aeromagnetic surveys, namely the fluxgate type. In 1955 Varian Associates of California introduced the first airborne proton free-precession nuclear magnetometer. At the present time there are 5 basically different magnetometers being used, which are the fluxgate, electron beam, proton free-precession, Overhauser, and optical absorption beam magnetometers (see Table 1), all of which measure the total intensity of the earth's magnetic field. The magnetometers are by no means equivalent, because the optical-absorption variety, namely the rubidium- and cesium-vapour and metastable helium types, has better than an order of magnitude greater sensitivity than the fluxgate. Thus there are many more magnetometers used in aeromagnetic surveying at the present time than there were ten years ago.

Some geophysicists will query the need for magnetometers of increased sensitivity and maintain that the fluxgate magnetometer, which is usually considered to be a half-gamma instrument, is good enough. As far as the production of standard one-mile aeromagnetic maps is concerned, this is perfectly true. But there appear to be a number of interesting possibilities for the new generation of magnetometers. Perhaps the most promising application of high-sensitivity magnetometers appears to be their use as magnetic gradiometers. For instance, at high magnetic latitudes, geological contacts are readily delineated by the zero contour of the first vertical derivative of the total intensity of the earth's magnetic field. Of interest in petroleum prospecting is the evidence that magnetic effects seem to be present in at least some sedimentary formations, and these give rise to 'fine-structure' in the recorded magnetic profiles. Thus the development of high-sensitivity magnetometers has given a 'new look' to aeromagnetic surveying techniques, and there is little doubt that even more sensitive magnetometers will appear in the near future.

Table 1. Commercially-produced airborne magnetometers.

Magnetometer	Principle	Type	Manufacturer	Model Number	Readout (A-Analog D-Digital)	Sensitivity in gammas (γ)	Mount
Fluxgate	Saturable core	Peak voltage	Gulf Oil Co. (U.S.A.)	Mark 3	Continuous A	<1γ	Inboard
		Second harmonic	(USSR)	AM-13	Continuous A	1γ	Bird
Electron Beam	Deflection of moving electron		Elliott Bros. (UK)		Continuous A	25γ	Inboard
Proton Precession	Free precession of hydrogen proton	Reciprocal	Varian Associates	V-4910 V-4912	Every 0.5 sec. A	1γ	Bird
				V-4914	Every 0.6 sec. A	<1γ	Bird or inboard
			Elliott Bros. (UK)	EMD-14	Every 0.5 sec. D & A	1-3γ	Bird or inboard
		Direct reading	Barringer Research (Canada)	AM 101-A	Every 1 sec. D, A, and visual	1 or 5γ	Bird or inboard
			Varian Associates (USA)	V-4937	Every 0.5 or 1 sec.	1 or 2γ	Bird
			Prackla (Germany)	PM-22 PM-24	Every 1 sec. D & A	2γ	Bird
			(USSR)	AYaAM-6	Every 1 sec.	1γ	Bird
Overhauser	Forced precession of hydrogen proton		Sud Aviation (France)	MP 121 MP 122	Every 1 sec. D & A	0.1γ	Bird
Optical Absorption	Optical pumping	Rubidium vapour	Varian Associates (USA)	V-4916	Continuous D & A	.05γ	Bird and inboard
		Cesium-vapour	Compagnie Générale De Télégraphie Sans Fil (CSF) (France)		Continuous D & A	.03γ	Bird
		Metastable helium	Texas Instruments (USA)		Continuous D & A	.05γ	Bird

Aside from the development of more sensitive magnetometers, there is a pronounced trend towards the digital recording of aeromagnetic survey data in order that the compilation of the final maps may be automated as much as possible. One of the main difficulties to complete automation is the fact that the cheapest positioning method is to use 35 mm vertical photography, and this will probably remain the basic track location method for some years to come. By recording in a digital format it should be possible to produce at very little additional cost maps other than the total intensity variety, such as first and second derivative, running average, and a number of other more exotic possibilities.

The Geological Survey's efforts in this field have been mainly carried out in cooperation with the National Research Council. During the 1962 field season a 25,000 line-mile survey of part of the Scotia Shelf was carried out to the south of Halifax. The survey instrument used was a modified military fluxgate magnetometer, which recorded the magnetic field values on printer and punched paper tape. The values were in the form of a five-digit number using binary coded decimal, the least significant digit being a tenth of a gamma. The computer was used fairly extensively on such tedious jobs, for example, as the correction of errors on the punched paper tapes and the removal of the regional gradient. The resultant aeromagnetic maps will be printed in two colours. The total intensity contours will be printed in red; the flight lines, which are also the purple Decca lines of the Nova Scotia Decca Navigation Chain, and 25-foot bathymetric contours will be printed in grey.

During the 1965 field-season the NRC-GSC cooperative project group carried out a detailed aeromagnetic survey of part of central Hudson Bay as a contribution to the main Hudson Bay 1965 Oceanographic Project. The primary navigational aid used was the 6F Lambda Decca chain on loan from the Polar Continental Shelf Project, which was installed in the south-western part of Hudson Bay. A rubidium-vapour magnetometer was used to digitally record on magnetic tape the total magnetic intensity at two heights together with two Decca coordinates and WWV time. As both the navigational and aeromagnetic data have been digitally recorded, it is hoped to automate the compilation of the total intensity maps as much as possible. One of the main difficulties in producing the final aeromagnetic maps "untouched by human hands" is in carrying out the basic control levelling of the aeromagnetic survey lines.

One interesting discovery made during the Hudson Bay survey was the location of an area of intense magnetic anomalies about 60 miles north-northeast of Cape Churchill, where the depth of water is about 300 feet. Anomalies greater than 5,000 gammas in amplitude were recorded, and it is inferred that these are produced by magnetite iron-formation. Preliminary plots of the aeromagnetic data indicate that the magnetic zone is approximately 14 miles long by 5 miles wide and is centred at 59°37 1/2'N, 92°40'W approximately.

Another interesting development is the successful completion by S. Washkurak and P. Sawatzky in the Geological Survey of an airborne telemetering magnetometer system aptly named Telmag. This is a direct-reading proton free-precession magnetometer in which the proton signal is telemetered from the survey aircraft to a ground station. The diurnal variation of the earth's magnetic field may be removed directly by mixing the telemetered signal with the output from a proton-precession ground station magnetometer. One advantage to this system is that the equipment carried in the aircraft may be reduced to a minimum, enabling a light aircraft to be utilized. The system probably has its greatest potential use in the aeromagnetic surveying of mountainous terrain where contour flying necessitates the use of light aircraft. Considerable experimentation has already been carried out in eastern British Columbia by the Geological Survey.

Most of the basic magnetometer research carried out recently in the GSC has been experiments by S. Washkurak involving the Overhauser or spin-precession magnetometer. He has been able to set up a continuously recording working instrument, and much effort has gone into the problem of obtaining a liquid sample that has more permanent atomic properties for the coil system.

Electronic magnetometers have now replaced to a large extent in Canada the more classical magnetic-balance type of instrument (see Table 2). The development would have been impossible before the advent of the transistor and one wonders what might be the ultimate in ground magnetometers. It is interesting to speculate on the possibilities. Ground magnetometer surveys are often carried out using a regular grid, and so it is relatively straightforward to compile the final magnetic map using an electronic computer. Second derivative and other types of maps may also be produced from the basic data directly from the grid values on the computer. It would therefore be most expeditious if the field data were recorded in a format that could be fed directly into the computer, and probably the most compact system would use digital magnetic tape. Thus the information to be inserted at a given survey station would be the location, the magnetic and vertical gradient values, and occasionally the time of the day for use in carrying out a diurnal correction if this appears necessary. For the results to be directly comparable with the aeromagnetic map the magnetometer should be the total-intensity type and the head should be insensitive to orientation. It would also be desirable if the instrument would continuously indicate the magnetic field on a meter so that the instrument operator could observe the highs and lows and any sudden changes in walking between survey stations. The potential usefulness of such an instrument would also be increased if it were capable of being installed in an uncompensated light aircraft for use as a 25-gamma airborne 'carpet-bag' magnetometer. For highest survey efficiency, there would be some advantage to having a gravimeter incorporated in the system as an optional feature, with its output recorded digitally on the same magnetic tape, and perhaps one that could measure the vertical gradient of gravity as well. Now the foregoing may appear rather far-fetched except that the reader should bear in mind that such a system is entirely within the capability of present-day technology.

One of the neglected factors in magnetic interpretation has been the effect of remanent magnetism in producing the anomalies to be found on magnetic contour maps. The Geological Survey has a continuing program to investigate the magnetic properties of rocks, and for this purpose instrumentation has been and is being developed for laboratory and field use. As an example, one requirement was for a portable in situ susceptibility meter. The specifications were drawn up; the instrument was contracted out to industry and two units were built for the Geological Survey. The instrument is now available on the open market for purchase by any private company.

Field investigations were carried out in 1963 and 1964 on Precambrian magnetite iron-formation in the Kapiko Iron Range, which is located about 45 miles north of Nakina in northern Ontario. Some of the preliminary conclusions were that the remanent magnetism component alone accounted for the major part of most magnetic anomalies recorded during the survey, because the remanent was usually much greater than the induced component. Thus the magnetic survey data could not be used to indicate zones of highest magnetite tenor directly because the remanent magnetization of the iron-formation is only partly dependent on the magnetite content. A very interesting result of the survey was that the magnetite content of the iron-formation could be estimated to within a few per cent using the in situ susceptibility meter, which had been previously calibrated using magnetite and sand mixtures.

Table 2. Commercially available ground-prospecting magnetometers

Type of Magnetometer (M = Mechanical E = Electronic)	Principle of Operation Magnetic field balanced by	Manufacturer	Model Designation	Field Measured T=Total, V=Vertical, H=Horizontal, Intensity	Readout Device	Sensitivity (Maximum) in gammas (γ)	Instrument Mount
Mining Dip Needle (M)	Gravity	E. Sharpe & Associates (Canada)	Magcrometer ES180	Mixture of V and H		35 γ/degree	Handheld
		Sharpe Instruments (Canada)	D-2 D1-M A-3		Graduated circles	200 γ/degree 60 γ/degree 180 γ/degree (dependent on H)	Handheld tripod handheld or mount
Reconnaissance (M)	Magnetic field of magnet	Sharpe Instruments (Canada)	A-3	V	Scale (null configuration)	Variable	Handheld
	Magnetic field of magnet and couple due to torsion wire	Levanto Oy (Finland)	Arvela		Dial	500 γ/div.	Handheld
	Magnetic field of coil	Sharpe Instruments (Canada)	A-4		Graduated scales in telescope	20 γ/div.	Handheld
Schmidt Variometer (M)	Gravity	Sharpe Instruments (Canada)	A-2	V or H	Graduated scales in telescope	usually set at about 25 γ/div.	Tripods
		Ruska Instruments (USA)	V, H, and Scout				
		Hilger & Watts (UK)	SG1 SG2				
		Askania (Germany)	Gf6				
		(USSR)	M2				

Torsion (M)	Torque of torsion wire	Askania (Germany)		V	Dial	3 γ/div.	Tripods
		Jalor (Sweden)			Dial	200 γ/div.	
		ABEN (Sweden)	MZ-4		Micrometer	3 γ/div.	
		(USSR)	M-14 M-15 M-18		Dial	10 γ/div.	
Fluxgate (E)	Saturable core	Sharpe Instruments (Canada)	MF-1 MF-1-100 PMF-3	V (All instruments use a vertical suspended flux-gate element)	Metre scales	20 γ/div. 2 γ/div. 100 γ/div.	Handheld with carrying strap around operator's neck.
		McPhar Geophysics (Canada)	M500A M700			20 γ/div. 20 γ/div.	
		Optillinen Tehdas Oy (Finland)	Jalander Type 46-65			50 γ/div.	
		Levanto Oy (Finland)	Finnmaster			20 γ/div.	
		(USSR)	M-17			10 γ/div.	
Proton Precession (E)	Free precession of hydrogen proton	Barringer Research (Canada)	GM102	T	Counter - 3 sec.	10 γ	Handheld
		Varian Associates (USA)	M49A		Reed Freq. Metre - 6 sec.	10 γ	
		Littlemore Scientific Engineering (UK)	Elsec Type 592		Metres - 1 sec.	1 γ	
		Izmiran (USSR)	PM-5		Metres	1 γ	
Overhauser (E)	Forced precession of hydrogen proton	Sub-Aviation (France)	MP-101 MP-102	T	Metre	0.5 γ	Handheld
Optical Absorption (E)	Optical pumping, using cesium-vapour	Varian Associates (USA)	Model 4920	T and vertical gradient	Continuous and digital	0.1 γ	Handheld

QUANTITATIVE INTERPRETATION OF AEROMAGNETIC INFORMATION

B.K. Bhattacharyya

A few years ago a research project was initiated in the Geological Survey of Canada to probe into the available methods and to develop new and better tools for quantitative treatment and interpretation of aeromagnetic data. In the course of this study a few promising techniques have been developed for fast and accurate processing of the data by digital computers.

The first step in this work is to "digitize" the magnetic field values from an aeromagnetic map, which is normally available on a scale of one inch to one mile. For detailed studies of aeromagnetic data, the spacing normally chosen for digitizing is 1/4 of a mile along both x and y axes. This digitizing of the data is considerably aided by the EAI Electronic coordinatograph and Recording System.

The "regional" or latitude variation of the field is then taken out from the data by mathematically fitting a quadratic surface to the data by least squares method. What is left over in the data after the "regional" (trend) is eliminated is called the "residual".

The "residual" is next represented by a two-dimensional Fourier series, which gives an analytical expression for the data. Once it is obtained, upward or downward continuation fields at any level and derivatives of any order can be evaluated easily with high accuracy by a digital computer. For an area under study, we usually determine the following:

1. Second vertical derivative of the total field. The second vertical derivative maps are found to be of much use in approximately delineating the boundary of the body causing a magnetic anomaly. In a second derivative map the effects of the near-surface geology are enhanced while those from the deeper sources are subdued. Because of this, there is better correspondence between near-surface geology and the second derivative map than there is in the case with the raw total field data as appears on the standard aeromagnetic map.

2. Total field reduced-to-the-pole and its second derivative. This reduction to the pole gives an expression of the total field as though the magnetized rock mass were physically carried to the magnetic pole, and the direction of total magnetization were made vertical by the artificial transformation. The resulting anomaly is free from the distorting effects of the non-vertical earth's magnetic field. An accurate method has been developed for evaluating this potential at any latitude and for any orientation of the polarization vector.

The second vertical derivative maps of the observed total field and of the "reduced" field are of considerable help in estimating the location of the origin and the orientations of the two horizontal axes of the body. When these items of information are available, it is possible to calculate from a magnetic anomaly the following:

1. horizontal dimensions,
2. depths to the top and bottom of the body, and
3. intensity and direction of magnetization.

A rectangular prismatic model is assumed for these calculations. An iterative method of calculations has been developed in the Geological Survey for this purpose.

In addition to the study of aeromagnetic data for sources near the surface of the earth, studies are also being conducted to delineate deep crustal magnetic sources from the total field data. The continuous spectrum of the total field anomaly due to rectangular three-dimensional bodies suggests a method for stripping the data of near-surface high-amplitude components in order to study effectively the anomalies arising out of deep-seated magnetized masses. This method has been used with a reasonable amount of success in the delineation of deep crustal sources in some areas in Canada. Because of this, a program for preparing the following maps for the whole of Canada has been undertaken by the Geological Survey:

1. Regional magnetic map showing the very broad anomalies caused by sources in the core-mantle boundary;

2. Residual filtered magnetic map showing the anomalies due to deep-seated magnetized bodies in the crust of the earth;

3. Residual magnetic map showing the anomalies due to shallow sources on and near the surface;

4. A map showing the depth to the Curie-point geotherm (the depth at which the rock magnetism is destroyed by the heat);

5. A map showing the depth to the top of bodies close to the surface of the earth;

6. Maps showing the trends in orientation of the magnetized bodies of both shallow and deep-seated origin.

Some of these aeromagnetic interpretation maps when completed should be of very direct use for mineral exploration, while others will be more important for their contribution to the basic geological science, which is aimed at understanding the major deep structures of the Canadian Shield.

AIRBORNE RESISTIVITY SURVEYS USEFUL FOR OVERBURDEN TESTS

L.S. Collett

Since 1950, a great deal of attention has been directed toward the development of airborne techniques in mineral exploration. Airborne electromagnetic (E.M.) surveys have been accepted on a world-wide basis as a standard and proven exploration tool. With the rapid advance of this technology, the application of E.M. devices has taken on broader uses such as soil mapping, trafficability of soils, and ice thickness measurements.

In mineral exploration conductive overburden such as surficial and glacial deposits, swamps, and lake bottoms often mask the detection of mineral deposits by E.M. methods. The conductivity of these overburden deposits approaches the same order of magnitude as that of some of the ore deposits. With the advent of the International Hydrological Decade on January 1st, 1965, the Geological Survey of Canada embarked on an experimental program to study the electrical properties of soils and surficial deposits to see if any E.M. method could differentiate between clays, tills, and sands and gravels with the possibility of delineating buried aquifers. This technique, especially if it could be used as a rapid reconnaissance method, similar to the use being made of airborne magnetic surveys, would be most helpful to the mapping of surficial deposits by groundwater and Pleistocene geologists and for delineating fresh water aquifers for municipalities, industries, and farms. From experience gained in this study, it is hoped that techniques can be devised that can be applied to the conductive overburden problem in mineral exploration in the Precambrian Shield.

To carry out this rapid reconnaissance study, the INPUT (Induced Pulse Transient) system was selected. The basic system was developed by Barringer Research Ltd. for Selco for prospecting for minerals. INPUT differs from the other electromagnetic systems in that a pulse is transmitted and a signal is received from the ground following the termination of the pulse. This pulse of about 1.3 milliseconds duration creates a strong magnetic field, which induces eddy currents in conductive earth materials. These circulating eddy currents induced in the ground take a finite time to decay. It is during this period after the abrupt cessation of the pulse that the receiving circuit samples these 'relaxation' or transient signals. The collapse of the eddy currents in the ground following the termination of the pulse is approximately exponential and is accompanied by the collapse of an associated secondary electromagnetic field. This field is detected in a vertical axis-orientated coil, which is housed in a 'bird' and towed about 250 feet behind and below the aircraft. The voltage induced in the coil is sampled at six different periods of time following the termination of the pulse. Each sample is fed into separate amplifiers and smoothed over approximately a three-second period. The voltage output from each amplifier or channel is recorded in analogue form on a multi-channel paper chart recorder. The time-isolation principle eliminates the interference effects between the transmitter and receiver caused by air turbulence. Improvements in the signal-to-noise ratio are continually being made by increasing the current in the transmitter and by using better filtering techniques in the amplifiers.

From ground DC resistivity surveys it was found that resistivity of clays and silty clays range from 5 to 20 ohm-metres, of tills and sandy tills 10 to 30 ohm-metres, and of sands and gravel beds from 40 to 650 ohm-metres. Bedrock shales (saline) have a resistivity of 3 to 6 ohm-metres and sandstone, limestone, and gypsum range from 100 to 1,000 ohm-metres. As the content of sand increases in clays and tills, the resistivity increases. Also, as the electrolyte concentration in the groundwater increases, the resistivity decreases accordingly. The amplitudes of the transients produced from the low resistivity deposits such as clay are the largest and decrease as the resistivity increases. Over sand and gravel deposits, very low signals are recorded.

The INPUT system was flown at a height of 500 feet, with flight lines spaced 1 mile apart, over the Winkler area, Manitoba. The airborne survey agreed very well with a ground DC resistivity survey done in 1963 by J.E. Wyder, of the Geological Survey of Canada, and the resolution of changes in the lithology was if anything better defined by the airborne survey. Further detailed drilling of the aquifer in areas of interest to the east and west appears to be warranted. It was not realized until a model was made of the aquifer from drill hole information how quickly the thicknesses of clays, tills, sands, and gravels varied laterally. Other areas that were flown in 1965 are the Oak River Basin in Manitoba, and the Steelman-Frobisher and Nokomis areas in Saskatchewan.

Although the airborne surveys do not give the apparent resistivity values as measured by ground DC resistivity surveys, the amplitudes of the transient responses do delineate areas of different resistivity contrasts. The method is able to detect sand and gravel beds with thicknesses of a few tens of feet lying beneath clay and till deposits up to 75 feet in thickness. Another important factor is the time taken to do a survey; for instance, the ground DC resistivity survey at Winkler took 3 months, while the airborne survey took a total of 3 hours operating from the Winnipeg airport. Local power lines do not interfere with the measurements. High tension cross-country power lines, however, do blank out the measurements for approximately 200 feet on each side of the power line. Power lines over small towns and oil fields also blank out the transient pulses.

It is safe to conclude that the airborne INPUT method is an important new tool for reconnaissance surveying of surficial and glacial deposits. It will aid the groundwater hydrologist and Pleistocene geologist in their mapping programs, in the same manner as airborne magnetic maps are now used by the geologist. It should be able to pinpoint in a direct way where to concentrate drilling programs for exploring for local municipal and farm water supplies. In Precambrian areas where the resistivity of the bedrock is much higher than the overburden, there is a good possibility that the method can be used to map the relative thicknesses of the conductive overburden.

REMOTE AIRBORNE SENSING

A.F. Gregory[1]

The Remote Sensing Section of the Geophysics Division of the Geological Survey of Canada is concerned with the development and use of various sensing devices that measure any portion of the electromagnetic spectrum having a frequency greater than about 1,000 mc. Research is directed toward (1) the remote measurement of various physical properties of rocks and minerals and (2) the geological interpretation of these geophysical data. Measurements may be made from aircraft or vehicle, by portable instruments, and in the laboratory with equipment purchased, leased, or built as warranted. The field of interest includes infrared, ultraviolet, microwave, radar, multi-spectral photography, and gamma radiation. However, to date, research in remote sensing at the Geological Survey of Canada has been directed primarily to natural gamma radiation and aerial colour photography.

Interpretation of the aerial colour photography has not been completed, but preliminary results obtained by D.T. Anderson[2] of the Geological Survey suggest the following advantages and disadvantages:

Advantages:

1. Despite diurnal variation in colour rendition, different lithologies and other geological features may be distinguished on the basis of colour distinctions that do not appear as tonal contrasts on simultaneously obtained panchromatic photography at the same scale.

2. The recognition of outcrop areas and, in particular, separate small outcrops is greatly facilitated by the use of colour photography of appropriate scale.

3. Colour film is capable of much greater enlargement than panchromatic, without loss of detail, because it does not exhibit the grain of panchromatic film normally used in aerial photography.

Disadvantages:

1. Colour films and prints are somewhat more expensive than panchromatic films and prints. The cost ratio is between 1.3 to 1 and 3 to 1, depending on type and format of film, size of survey area, number of prints, etc.

2. Colour transparencies are more difficult to use and annotate in the field.

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[1] Now Department of Geology, Carleton University, Ottawa.

[2] Now Department of Geology, University of Manitoba.

It is concluded from these preliminary results that aerial colour photography is practical and superior to panchromatic photography where colour, rather than texture, is a major criterion for recognition of geological features. With increased use, the cost of aerial colour photography should be reduced appreciably and approach the cost of panchromatic photography.

Recent research in gamma radiation at the Geological Survey of Canada has centred mainly on investigations of the fundamental processes of gamma-ray attenuation in rocks, air, and water.

Some years ago, a technique of interpreting regional aeroradiometric surveys was developed in the Geophysics Division of the Geological Survey of Canada. The observable contrasts in radiation attenuation suggested that the measurement of differential energy spectra might be a more useful technique. Thus, in conjunction with J.L. Horwood of the Mineral Sciences Division of the Mines Branch, a series of experiments was designed to evaluate the effects of source thickness and of air scattering on the energy spectra of gamma radiation from mineral sources. A 100-channel gamma-ray spectrometer was used in the study. Significant variations in response of the scintillation detector were observed as a result of changes in temperature of the photomultiplier tube.

Major conclusions from the study of the effect of variation in source thickness on the differential energy spectrum are:
(1) rocks and soils that contain U, Th, and K emit characteristic gamma-ray spectra that reflect the proportions of those radioelements present in significant quantities;
(2) the Compton continuum resulting from scattered photons does not overwhelm the main photopeaks;
(3) the major variations in both spectrum and intensity occur within the first twelve inches or rock closest to the detector;
(4) for common rocks, except carbonates, radiation from potassium predominates over that from either uranium or thorium and may exceed their sum.

Major conclusions from the study of the air attenuation of gamma radiation from mineral sources are:
(1) with an appropriate measuring time, significant gamma-ray spectra may be measured at distances at least as great as 700 feet;
(2) gamma radiations from U, Th, and K attenuate at the same rate for air distances from 300 feet to 1,400 feet;
(3) as Berger has theoretically shown, the response of a gamma-ray detector may be significantly altered near a density interface such as the surface of the ground;
(4) for simple gamma spectra (e.g. K-40), the ratio of photopeak height to integral count may be a useful measure of distance between source and detector; however, this is not true for more complex spectra, such as U and Th;
(5) the relative contributions of U, Th, and K to the integral response of a detector will vary greatly with the counting threshold of the detector and, to a lesser extent, with the air distance between source and detector;
(6) the practical use of an airborne gamma-ray spectrometer is presently limited to regional surveys in which the incident spectrum is measured over a relatively long counting time.

Following these investigations, the Geological Survey of Canada supported the development of a portable gamma-ray spectrometer by R. Doig, Department of Geology, McGill University. A transistorized three-channel spectrometer was built for the in situ determination of K, U, and Th in rocks. Total weight of the unit is 20 pounds; it can be operated on field surveys by one man. The spectrometer was calibrated and tested on a variety of rocks in the field. For counting times of 5 minutes, and for the range of activities found in ordinary rocks, the following analytical accuracies have been determined:

K: 5% plus 0.1% K
U: 10% plus 0.2 p.p.m. U
Th: 10% plus 0.5 p.p.m. Th

With sources of higher activity, accuracy can be improved or the counting time shortened. While the instrument was designed for rock analyses, it is readily adaptable to the specific recognition of uranium, thorium, or potassium in radioactive mineral occurrences.

From these studies we conclude that radiation detection techniques will continue to dominate over geochemical or other direct exploration methods, particularly in pinpointing discrete, exposed concentrations of uranium, thorium, and potassium. Spectrometric methods may be particularly useful in identifying and assessing the specific radioelement content of such mineral deposits.