GEOLOGICAL
SURVEY
OF
CANADA

DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

PAPER 65-6

SOME GUIDES TO MINERAL EXPLORATION

A Collection of Papers by Officers of
British Commonwealth Geological Surveys

Edited by E. R. W. Neale

Price 75 cents

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CONTENTS

PREFACE

This collection of papers was issued in mimeographed form as Special Publication S.4 by the British Commonwealth Geological Liaison Office. Five of the papers were contributed by officers of the Geological Survey of Canada and have a fairly obvious Canadian appeal. The other papers, from various parts of the Commonwealth deal with common problems of mineral exploration.

It seemed appropriate to reissue all these papers in the G.S.C. Paper series, not only will this ensure a wider distribution, especially in Canada, but it may also be regarded as a Canadian contribution to the work of the British Commonwealth Geological Liaison Office, which for the past two years has been under the direction of Dr. E.R.W. Neale of the Geological Survey of Canada.

Minor changes have been made to some of the figures to suit the smaller format, but no technical or editorial changes have been made to the text.

February 16, 1965,
Ottawa.

Y. O. Fortier,
Director, Geological Survey of Canada.

INTRODUCTION

E.R.W. Neale
British Commonwealth Geological Liaison Officer

This collection of papers grew out of a letter we addressed to the directors of various Commonwealth survey establishments in November, 1963. Among other things, it sought advice on appropriate subjects for inter-survey information exchange through the medium of our Geological Liaison Office publications. This brought almost unanimously enthusiastic response in favour of a topic that would cover new approaches in the search for ore deposits. The hope was that this topic would attract papers describing new projects underway or at the serious contemplation stage in some of the larger surveys and serve as a guide to the smaller surveys.

A long period of inertia then set in - common to all special collections of papers, symposia and the like. During this period, a good many reasons came to light for calling this venture off. Not the least of these was the feeling that papers on ore search methods properly belong in established journals and that our own meagre resources would be better spent on subjects not covered elsewhere.

Just at this moment of truth manuscripts began to drift in - some were expected but at least half were 'out of the blue' - almost as if in response to reflex actions --a deadline had passed so a number of people automatically sat down and dashed off papers to save the editor at zero hour. The papers are good - but this is not surprising when you consider who wrote them and the organizations they represent. Also, our early fears were ill-founded, and although individually you could find any one of these papers in established national or international journals, together they are a rather unique collection with a distinct Commonwealth flavour. The surprising thing about these contributions is that they form a well-balanced whole. Although the authors were virtually left to choose their own topics, it turns out that every major field of ore search is represented in one way or another and, together, the papers form a rather smooth and logically progressive guide to mineral exploration.

We begin with John Fortescue's paper on Exploration Architecture which outlines both the need of and suggestions for scientifically designed exploration programmes to suit specific targets and areas. Not everyone will agree with all aspects of Fortescue's proposals - modern architecture is a controversial subject in whatever context - but all will agree that he has presented some stimulating ideas for the men who plan major exploration programmes. One of these is the suggestion that governments should produce 'consumer guides' to exploration case histories. The next paper, which concerns future mineral exploration in New Zealand, was contributed by David Kear who acts as Secretary of the Mineral Resources Committee which is advising Government on the direction mineral investigations should take in that country. This paper is especially valuable on the mineral economics side and developing countries within the Commonwealth should profit from a study of New Zealand's problems, plans and decisions on priorities.

Having covered the planning stage rather thoroughly, we move on to some of the actual procedures involved in exploration, starting with one so obvious that it is often overlooked, namely the need to marshal and analyze all available data before beginning the project. In a deceptively short and simple paper on this subject, Gordon Gross points out the advantages of summarizing earlier work, preferred methods of recording it, and the importance of Geological Survey establishments maintaining systematic records of mineral occurrence information.

W.D. McCartney follows with a description of his work on the metallogenetic development of the Canadian Appalachian region as one example of a working hypothesis applicable to post-Precambrian folded belts. Based on the relationship of mineralization to tectonic environment, McCartney's paper suggests an approach to selecting target areas for specific minerals or groups of minerals that has reputedly been very successful in the U.S.S.R.

J.E.G.W. Greenwood discusses the value of air photographs to mineral exploration and cites excellent, little known examples of their useful application in many Commonwealth countries and elsewhere. V. Venkatesh's contribution deals specifically with present use of air photos for mineral exploration in India and, hence, nicely complements Greenwood's paper.

The paper which describes the Australian Bureau of Mineral Resources' geochemical equipment and programme will be read with interest by officers of those surveys which plan to either begin or to expand present activities in this field.

Roger Cratchley has summarized a hitherto unpublished paper (in which he shares authorship with L.Z. Makowiecki and A.S. King) which describes a carefully controlled field experiment designed to compare and contrast three airborne electromagnetic methods of prospecting. This will be of great value to survey staffs and geophysicists everywhere and we are very indebted not only to the authors but to the Directorate of Overseas Geological Surveys for permission to present this summary paper prior to publication of the longer, more detailed exposition which they have in press. Another very useful geophysical contribution is made by Len Collett who reviews both the Induced Polarization method and the even more recent INPUT method of exploration, cites examples of the field applications of each and gives some suggestions where each method may be used to advantage.

No matter how the exploration programme is arranged and what techniques are used many aspects of it will hinge around ideas concerning both the classification and origin of mineral deposits. It is, therefore, right and proper that we conclude with papers on these subjects. Stu Roscoe's reflective discourse on the need for a classification system to guide mineral exploration and his analysis of the pitfalls and strengths of existing systems will lead you to carefully re-examine your own thoughts on this subject. Arthur Darnley ties together much new data on paleomagnetism, crustal heat flow, the ocean floor, and the ultimate origin of certain igneous rocks and comes up with a stimulating, speculative hypothesis that seeks to relate petrogenesis and ore genesis to mantle convection.

Our thanks are due first to the authors who have contributed these thought provoking papers on various aspects of mineral exploration, and then to the directors of the six large Commonwealth survey establishments who kindly permitted their inclusion in this series - with special thanks to Dr. Y.O. Fortier, Director of the Geological Survey of Canada who offered to reprint for a wider distribution in the more elegant format of a GSC Paper. Thanks may also be due to some old friends here and there, for example Peter Harker of Canada, who may have wielded the little hammers that started the 'reflex actions' that led to the zero hour submission of some almost unexpected, but very welcome, papers. Mrs. J.H. Doughty of D.S.I.R. designed the cover and J.S. Dunbar of O.G.S. and Miss J. Henning of C.S.O. advised on reproduction techniques. Typing has been left to our Miss Muirhead who will sandwich it in between regular jobs and probably stay after hours to get it out in time. Miss Newman will be left to 'see it through press' and read proofs. Reproduction of figures and text has been and will be due to the cooperation of S.A. Carne and Mrs. K. Ramswell of C.S.O.

EXPLORATION ARCHITECTURE

J. Fortescue
Economic Geology Division
Geological Survey of Canada

INTRODUCTION

Exploration for metal mineral deposits in a given area of country is always a unique problem in applied geology. Problems of this kind are solved by means of direct or indirect exploration methods or - more commonly - by a combination of both approaches. Direct methods involve the observation of native metals (or minerals in which these elements occur as major constituents) or of rocks of the type in which mineral deposits occur. Indirect methods involve the application of one or more specialized techniques of geology, geophysics, air photography or geochemistry to gain indirect information about the presence of mineral deposits. The art of successful mineral exploration today lies in the correct choice and proper application of those direct and indirect methods which are most effective in solving an exploration problem within a given area.

At the present time it is general practice to stress the origin of specialized aids to the geologist in mineral exploration (i.e. "geophysical methods" or "geochemical methods") rather than to consider all the methods which may be used at a single level of detail of an exploration programme. Similarly it is often assumed that one exploration method is as reliable as another under a given set of local conditions, or that the scope, and, especially, the limitations, of a given method are well known. The object of this paper is to discuss some principles of the organization of modern mineral exploration programmes, especially in relation to the level of detail at which they are carried out and the stage of development of individual techniques employed. In order to focus attention on these aspects the term 'exploration architecture' has been introduced. At the end of the paper some ways in which government can foster the development of the 'exploration architecture' approach to the finding of economic mineral deposits are outlined briefly.

The principles of mineral exploration discussed here are based on experience gained in different parts of the world. Space does not permit the detailed discussion and comparison of examples of typical case histories in mineral exploration. In order to test out the feasibility of this approach to mineral exploration described here, the reader must draw on his own experience or consult published data - for example the publication by Kelly and Westrick (1957).

EXPLORATION ARCHITECTURE

At the turn of the century prospecting for metal mineral deposits in Canada was generally carried out by direct methods involving the observation of native metals or minerals in outcrop. Since then these direct methods have been supplemented, from time to time, by indirect methods involving the application to exploration of principles derived from branches of science other than geology. This trend began with the introduction of geophysical methods, and has continued with the introduction of methods based on air photography and geochemistry. Often with the introduction of a new technique there was a belief in some quarters that the new method would become universal and that it might render existing methods obsolete. This tendency was at times fostered by those who introduced new methods because they tended to overstate their case - which led to confusion in the minds of exploration geologists - until the true scope and limitations of the new method were established.

As the number of these scientific aids to mineral exploration grew, it became evident that they could be grouped together according to the level of detail at which they were most effective. More recently, another trend has become apparent. It has been found that the integrated interpretation of different kinds of exploration methods (i.e., geochemical, geophysical and geological) is a more effective approach than an examination of the results of each survey considered individually. Thus the idea has arisen that there is no 'universal method' of mineral exploration, on the contrary it appears that geophysics and geochemistry each merely are aids to the geologist in solving geological problems. This point has not always been stressed in textbooks on geophysical or geochemical exploration methods which sometimes give the impression that geophysics and geochemistry are mutually exclusive in metal mineral exploration. In order to correct this view there is a need for a textbook of case histories which stresses the coordinated approach to metal mineral exploration - e.g. along the lines pioneered by Kelly and Westrick (1957).

As long as direct and indirect methods of mineral exploration were few and relatively easy to carry out with a limited budget it was common practice to adopt the "shotgun approach" to prospecting. All possible methods were applied in the area being prospected in the hope that one might "hit the jackpot". Unfortunately at the present time mineral exploration programmes are usually so large and costly that this approach cannot be seriously considered. As a result more and more interest is being shown in the scientific design of exploration programmes.

The relationship between the "shotgun approach" and the "designed" approach to exploration is similar to the relation between building and architecture. It is clear that a shack in the bush can be constructed without a detailed plan, in contrast to a modern home which is designed by an architect to fill a specific site and is constructed according to the details of the architect's plan. Just as the architect designs a home for a given site so an 'exploration architect' will design a programme to look for mineral deposits to suit a given set of local conditions. Further, one may draw a parallel between the number and kind of storeys and rooms in a house with the number and kind of levels of detail and individual methods to be included in an exploration programme, always bearing in mind that the 'walls' of an exploration programme involve the geological framework within which the other methods function. The terminology used to describe the parts of a house, is, of course, generally accepted. Unfortunately, in the case of exploration programmes there is no generally accepted, simple, terminology used to describe case histories of exploration. The advantage of such terminology is that it would facilitate the detailed comparison of the results of exploration programmes carried out in different parts of the world.

Figure 1 is an attempt to set up the framework for the general organization of exploration programmes based on a simple terminology, some aspects of which may be new to readers. It will be seen that the programme is divided up into four stages, three of which (I, II and IV) require no further discussion. Stage III allows for the possible parallel application of various kinds of direct and indirect geological and specialized methods at each of three levels of intensity called here the REGIONAL LEVEL, the FOLLOWUP LEVEL and the DETAILED LEVEL. The map scale at which any of these levels of surveying is carried out will vary with different kinds of deposits but, it is the writer's opinion that the objectives, as stated below, for each level of detail will be the same. As a general rule REGIONAL LEVEL exploration includes areas of over 1,000 square miles and DETAILED LEVEL exploration less than 10 square miles.

The object of REGIONAL LEVEL exploration is to select surveyed areas of interest (within which mineral deposits are most likely to occur) and distinguish them from the major part

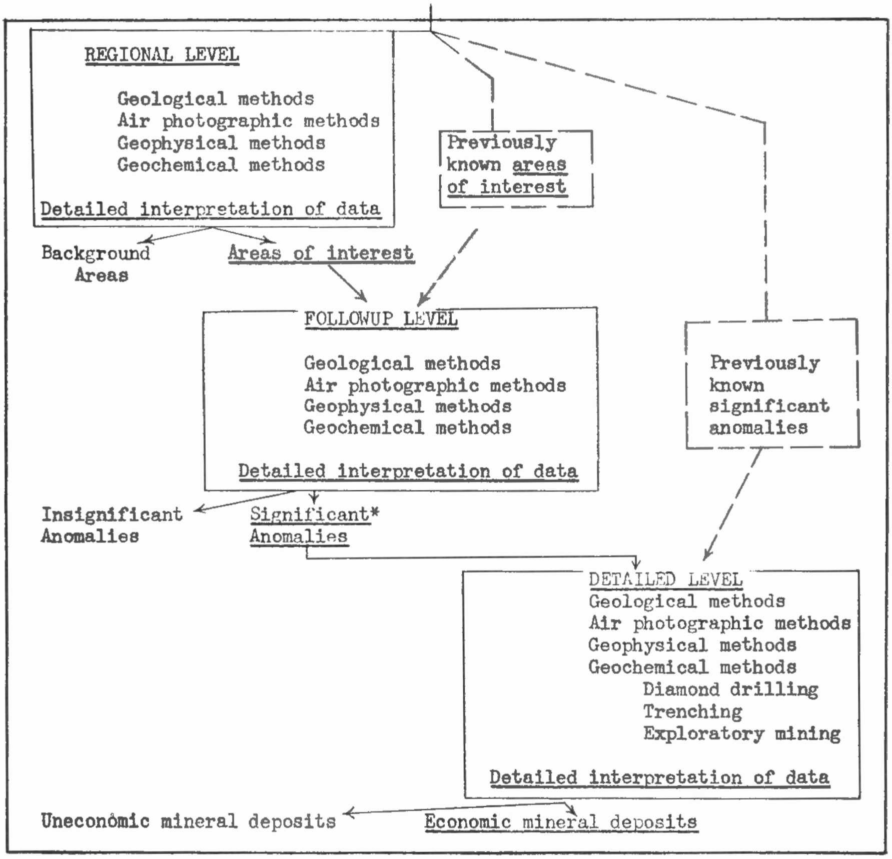
STAGE I – REGIONAL PLAN

- the limits of the area to be surveyed are defined,
- the kinds of mineral deposit looked for are stated,
- a compilation of all known geological and mining information about the area is made,
- case histories of previous exercises in exploration architecture carried out under similar types of local conditions and/or for the same types of mineral deposit are studied in detail,
- a general statement is made of the expected duration and cost of project.

STAGE II – DEFINITION OF OBJECTIVES

- exploration objectives at each level of detail are stated,
- geological, geophysical, geochemical, and airphotographic methods to be used at each level of detail in the project are selected,
- a provisional timetable drawn up for the sequence of application of individual methods at each level of detail at which the project will be carried out.

STAGE III – DETAILED PROJECT PLAN



STAGE IV – RESULTS

- proven economic mineral deposits,
- proven uneconomic mineral deposits,
- integrated case history of an exercise of exploration architecture.

* anomalies can be surface mineral showings or geological, geochemical, geophysical or air photographic

Figure 1. Layout of a generalized example of Exploration Architecture

of the region in which the presence of mineral deposits is less likely (i.e. background areas). At this level of detail, it is important that the observations are made at an equal intensity over the whole area. If the mineral deposit being sought is considered as a fish of known minimum size, then the frequency of observations made in the area is like a net designed to catch that fish. The 'net' for airborne geophysics is the trace of flight lines over the area and for sediment geochemistry it is the network of drainage channels. It is essential that the 'net' has no unknown holes in it. If for some reason there are holes (for example, in the case of geological observations where the overburden is extremely thick with few or no outcrops) then they should be clearly marked on maps and considered during the interpretation. In the past, mineral deposits (e.g. in New Brunswick, Canada) have been missed because the intensity of observations in regional surveys was not sufficient to locate areas of interest under a given set of local conditions and therefore it was presumed that an area was unfavourable (i.e. background area) when slightly more intensive application of a REGIONAL LEVEL method would have located mineral deposits.

On the FOLLOWUP LEVEL the objective is to locate exactly on the ground the extent of anomalies present in areas of interest resulting from REGIONAL LEVEL surveys or from previous geological observations within the area. Small, well defined areas of interest discovered by air geophysical methods should always be checked by FOLLOWUP LEVEL surveys on the ground prior to the application of DETAILED LEVEL methods. This is because such areas of interest may not be exactly located on the REGIONAL LEVEL maps due to movement of the aircraft or instruments.

The object of DETAILED LEVEL surveys is to distinguish between anomalies due to economic mineral deposits and those due to uneconomic mineralization or other causes. In Canada today little distinction is made between FOLLOWUP LEVEL and DETAILED LEVEL methods. Strictly speaking they have quite different objectives, although they may be carried out concurrently in the field. It should be noted that diamond drilling, the most common DETAILED LEVEL method, is also the most costly of all exploration techniques to carry out.

THE APPLICATION OF THE PRINCIPLES OF EXPLORATION ARCHITECTURE

There are twenty six letters in the alphabet but one does not use each one in each word. Similarly there are numerous possible exploration methods applicable at the different levels of an exploration programme but not all these methods are used at any one time. It is appreciated that most exploration projects which are carried out by private industry are based on calculated risks and aim at the maximum of success with the minimum of expenditure. In these cases very few - perhaps only one - exploration method may be included in a programme at each level of detail. Clearly even with a programme of such restricted scope the results can be written up using the terminology of Exploration Architecture so that the report can be compared directly with other, similar, case histories.

Sometimes the principles of Exploration Architecture are modified by local conditions, especially with respect to timing. For example, in many areas it is possible to carry out FOLLOWUP or even DETAILED LEVEL surveys in the vicinity of known mineral deposits before REGIONAL LEVEL surveys are completed. Another possible modification to the principles of Exploration Architecture is with respect to the scale of operations. In some countries vast areas may be covered by special methods - which are less intensive than REGIONAL LEVEL methods - in order to locate the most favourable regions in which Exploration Architecture can be carried out.

The writer is well aware of limitations to this concept of Exploration Architecture. The reader must judge for himself just how these principles can be applied in any one case within his experience.

STAGES IN THE DEVELOPMENT OF EXPLORATION METHODS

A few, specially selected, exploration methods are usually included in each sample of exploration architecture. Such methods can be chosen with confidence only if the choice is based on reliable knowledge of the scope and limitations of each method under local conditions. Results from previous case histories (involving the parallel application of more than one kind of exploration method at a given level of detail under a given set of local conditions) are the best way to evaluate the relative effectiveness of a given set of exploration methods. For example, if a biogeochemical method at the FOLLOWUP LEVEL (involving the chemical analysis of plants for their nickel content) is first tried out in an area of known nickel mineralization along lines where magnetic, electromagnetic and soil sampling have already been carried out, the relative effectiveness of the biogeochemical method compared with the others can be demonstrated directly.

It is evident that at a given instant in time all mineral exploration methods which exist can be classified according to their degree of development for use within a given set of local conditions. The three stages of development of an exploration method are laid out in the following table.

Table I

Stages in the development of an exploration method

I - EXPERIMENTAL STAGE

- the initial tests of a new principle of exploration,
- field areas chosen to give favourable results,
- the cost of apparatus and field work usually quite low,
- the results appear in publications drawing attention to the feasibility of the proposed method.

II - DEVELOPMENT STAGE

- the approach is tested out under several kinds of local conditions,
- the field areas are chosen so that results may be checked against those of better established methods,
- the capital and field costs are usually high owing to the need to explore several parameters under different kinds of local conditions,
- the cost of prototype instruments and qualified personnel to operate them are high, progress is usually slow because of frequent breakdowns and because methods are constantly being changed,
- the papers published on the method outline the scope and limitations of the new approach but give special emphasis to its advantages.

III - ESTABLISHED STAGE

- the method is carried out as a routine exploration method,
- the location of field areas is dictated by location of exploration programmes,
- the capital costs are relatively low and the equipment may be used by unskilled personnel,
- publications describe the successful and sometimes even the unsuccessful application of the method.

Exploration methods often require an orientation survey to be carried out in the vicinity of known mineralization of the type sought in order to establish a reliable procedure for use in a new area. Clearly a method may be in the established stage in Canada but only in the experimental stage in another part of the world, or vice versa.

Figure 2 is an attempt to list the degree of development and kinds of exploration methods which are in use, or are being experimented with, in Canada at the present time. The term 'remote sensing' has been used to include three types of air photography two of which are at a very early stage of development at the time of writing.

The examples cited in Figure 2 are all taken from the book edited by Kelly and Westrick (1957). Although this publication is somewhat dated it affords a valuable introduction to modern mineral exploration. When the articles are compared with the flowsheet on Figure 1 it is evident that much information of interest to the exploration architect is missing from them. When reading through these case histories one should remember that most of them record successful mineral exploration programmes and that the number of successes in this type of endeavour is often small compared with the number of failures.

THE ROLE OF GOVERNMENT IN EXPLORATION ARCHITECTURE

Most geological surveys, or bureaus of mines, exist to facilitate the exploitation of the natural resources of the country. They generally do this by carrying out geological mapping of the country on different scales and by compiling records of the occurrence and nature of prospects and mines within the country as this data becomes available. In many countries the actual exploration is carried out by private industry. If the 'exploration architecture' approach were to be adopted by a government agency several other functions would form part of its programmes. This agency could act as a kind of 'consumer's guide' to case histories and individual exploration techniques as they were published in the world literature or in the country itself. The results of these investigations would be published annually to facilitate the dissemination of current views on mineral exploration in a form which could be easily read by busy exploration geologists (who might not have ready access to foreign publications). The government (in some cases in close cooperation with private industry or universities) could spend money on costly basic research programmes aimed at the further refinement of exploration methods. This kind of operation would probably be on a scale beyond that at which most single companies or universities could act.

Another role of the government would be to set up and maintain a number of 'experimental mineral deposits' (like the experimental farms of agriculture) where individuals could be shown comprehensive examples of exploration architecture. In these areas parallel surveys by all suitable experimental, development and established methods could be carried out at the REGIONAL, FOLLOWUP and DETAILED levels of detail, as well as experimental research work of general interest not necessarily connected with the techniques of mineral exploration. A pioneer investigation along these lines is presently being carried out by D.R.E. Whitmore and other officers of the Geological Survey of Canada (in cooperation with private industry) in the vicinity of the Coronation Mine, Saskatchewan, where results of REGIONAL, FOLLOWUP, and DETAIL LEVEL surveys are being prepared as a case history in mineral exploration. Results of observations made at these "experimental mineral deposits" would be included in the annual government publication mentioned above.

If such "experimental mineral deposits" were set up they would afford excellent sites for the training of young exploration geologists as well as for geologists of the newly developing, emergent countries. Suppose six months field work and six months university study were carried out by pairs of young geologists - consisting of one from an underdeveloped country and one from the host country - then at the end of the year's training the pair might spend a further year in the underdeveloped country where they could act as a team to set up an exercise in exploration architecture based on their year's mutual experience. In this way the "experimental mineral deposits" could perform a service not only to the country in which they were located, but also to train exploration geologists for foreign countries in the most practical way - in the field.

DEGREE OF DEVELOPMENT AND LEVEL OF DETAIL OF AIDS TO THE GEOLOGIST IN EXPLORATION USED IN CANADA AT THE PRESENT TIME

Kind of Method	Degree of development at REGIONAL level of detail	Degree of development at FOLLOWUP level of detail	Degree of development at DETAIL level of detail	Number of examples by Kelly and Westrick (1957)
Remote Sensing				
- Black and White	E	E		1
Air photography - Colour	X	X		
Radar photography	X	P		
Infrared photography scanning	P	P		
Geophysics				
Airborne methods				
Magnetics	E	E		6
Electromagnetics	E	E		17
Radioactivity	E	E		
Ground methods				
Magnetics	E	E	E*	17
Electromagnetics	D	E	E	7
Induced polarization		E	X*	-
Self potential		E	P*	6
Gravity	X	E	E	5
Resistivity		E	E*	8
Seismic		E	P*	1
Radioactivity		E	E*	1
Geochemistry				
Rock geochemistry	X	X		
Soil geochemistry	-	E		2
Stream sediment geochemistry	D	E		1
Water geochemistry	D	D		
Plant geochemistry	-	D		1
Glacial geological methods				
Heavy mineral analysis	X	E		
Boulder tracing	X	E		
Analysis of drift sections	X	X		
Specialized direct methods				
Diamond drilling	X	E	E	
Trenching		-	E	
Exploratory mining		-	E	

P: possible X: experimental E: established D: development
* within diamond drill holes

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FUTURE MINERAL EXPLORATION IN NEW ZEALAND

David Kear
New Zealand Geological Survey

INTRODUCTION

For many years, mineral exploration activities in New Zealand had been at a relatively low level. Apart from coal, there have been few recent major mineral enterprises and this lack of large mineral or oil producers has been reflected in a lack of adequate exploration finance. In addition, since the decline of gold mining, public confidence in prospecting and mining has been insufficient to ensure an adequate flow of exploration capital from small investors, and it had become commonplace to disparage New Zealand's mineral potential.

More recently, however, there has been a rapidly growing interest in New Zealand's mineral resources. This has been stimulated by a number of factors: the problems of overseas exchange; increasing industrialization, with consequently increasing demands for constructional and industrial minerals; increased staffing of the relevant government agencies since the war; the local success of overseas oil exploration companies; and the economic problems of regions, such as the West Coast of the South Island that are largely dependent on declining gold and coal production. As a direct result of West Coast problems, the Mineral Resources Committee was set up in 1963 to survey present activity in mineral development, to consider what could and should be undertaken additionally, and to allocate desirable priorities within a realistic yet vigorous programme. Its report was completed by the end of the year, and has been adopted in principle by Government. It recommended a five-year programme, aimed at stimulating all mineral resources activities, it noted the growing importance of non-metallic minerals, it recommended particular minerals and particular areas for priority investigations, and it reveiwed past work and particularly stressed the recent advances relating to oil and gas, bentonite, perlite, clays, coal, geothermal power and the proposed iron and steel industry.

This present paper discusses the mineral development scene in New Zealand wholly from a geological point of view. It considers the principles that should lead to the most rewarding results in the particular environment of New Zealand. In all such activities, supplies of money and manpower are necessarily limited, regardless of how far-sighted governments, private companies, individuals, or universities might be. Priorities are therefore essential, and will prescribe the types of mineral to seek, the best areas and environments in which to search, and the best methods of exploration to use.

New Zealand's geological environment must first be summarised. Mesozoic and older rocks are predominantly greywacke-type sediments, with granitic rocks being restricted to western parts of the South Island, ultramafic rocks to parts of Nelson and Otago (north and south-west of South Island), and carbonates to parts of Nelson. Upper Cretaceous and Tertiary beds are moderately soft, and include thick sequences in many basins, with common basal coal measures and with limestones in the Oligocene. They were locally strongly folded and faulted by late Cenozoic orogenic movements. Volcanic rocks are represented throughout the column, but are of especial importance in the Quaternary of central north-western North Island, where hydrothermal alteration can be important. Non-volcanic Quaternary rocks largely comprise thick glacial gravels in the South Island, in part auriferous, and alluvium and coastal sands, including ironsands, in the north. Weathering effects are very variable, being shallow, and even glacially shaved, in the far south, but subtropical, uneroded and over 100 feet deep, in the far north.

The rugged topography hinders prospecting in some regions, and is one factor that increases freight costs.

MINERALS TO BE SOUGHT

Exports, Import Savings, Etc.

There are three basic mineral categories - exports, imports, and those for less essential local consumption.

Gold and kauri gum have been New Zealand's most valuable mineral exports - to a total value of some £125,000,000 and £25,000,000 respectively, but both have now declined. In the future, a revival of the gold industry, and a start in base metal mining, are among the hopes for direct mineral exports, but indirect exports (e.g. of clays in ceramic products) could become far more important.

Many minerals, that are essential to modern civilisation, must be imported if they cannot be found locally. New Zealand spends between £10,000,000 and £20,000,000 annually on imports of petroleum products and of steel, so that these represent the greatest future challenge for mineral exploration in its widest sense. Cement was once in a similar category but now three new cement works have produced a surplus for export. Local china clay is being used increasingly both for whiteware manufacture and as an industrial filler.

Road metal, building aggregate, sand, and even limestone and household coal, are good examples of the third category. Such minerals improve living standards in providing good arterial roads, airports, large concrete building structures, hydroelectric dams and other works, as well as style and comfort in the home; but substitutes will be found if they are not readily available.

Clearly, except in time of major economic depression, export earnings have no advantages over import savings. In fact, assured markets and prices may make the latter more beneficial in the long run. The production of both categories of minerals, however, aims at improving living standards indirectly, and therefore, can demand little increased priority over local minerals that are worked to improve those standards directly.

It is therefore concluded that if all other things are equal, there is no clear advantage in exploration aimed at minerals in any one of these three categories, rather than at those in any other.

Mineral Priorities

Increased relative priority in mineral exploration is demanded by the following factors:

1. Greater Total Value: On the New Zealand scene, this factor applies particularly to such important potential savers of overseas funds as oil and steel. The former demands regional geology, geophysics and drilling; the latter requires the satisfactory (and it is hoped imminent) solution of metallurgical and economic problems.

2. Greater Chances of Discovery: Discovery chances depend upon: the relative abundance in New Zealand of the normally favourable geological environments; the accessibility of suitable areas (which also affects subsequent prospecting and mining), and the ease of recognition with known New Zealand skills and knowledge.

3. Increased New Zealand Content, i.e. those minerals that are possible exports after beneficiation or manufacturing. New Zealand is developing useful export markets in various ceramic wares and in paper, both of which are preferable exports to raw china clay. Groundwater is a less obvious, but equally important example - for it indirectly increases agricultural exports.

REGIONAL PRIORITIES

The recent Mineral Resources Committee's report implied that there were greater chances of mineral occurrence in Nelson, Westland and West Otago in the South Island, and Northland, and the Hauraki (Coromandel) goldfield in the North Island. These regional priorities for exploration depend upon the geological environments, and include most of New Zealand's areas of granitic, ultramafic and ancient carbonate rocks (South Island) and young but extinct volcanics (North Island). Those of the South Island are likely to contain the important but traditional mineral deposits such as precious and base metals, asbestos, talc, dolomite, and chromite.

It is most important also, however, that full advantage be taken of the geological setting and especial attention given to those rock groups that are better developed in New Zealand than in most countries overseas. Although there are no highly mineralised shield areas, the rocks that are present in abundance must not be neglected. New Zealand's most common rocks, greywacke and its associates, have only restricted uses, most of which depend upon their hardness and bulk. The North Island's great variety of volcanic rocks, however, have already yielded some important minerals, and are of continually increasing interest as new minerals, new uses, and new areas, are discovered. Metal sulphides have long been known to be associated with them, and show a clear fundamental relationship between volcanism and mineralisation. A base metal lode is being successfully prospected within them at the present time. Volcanic rocks have long been used in the constructional industries; e.g. basalt and andesite for road metal, aggregate, and even building stone; pumice and, more recently, expanded perlite, as light-weight materials. Finely ground natural pumice ("pumicite") is finding increasing uses as a substitute for imported diatomite. The titanomagnetite ironsand deposits of the west coast, on which a New Zealand steel industry will probably be based, were presumably derived from the volcanic rocks of Mt. Egmont, and its eroded ancestors to the north.

The best-known exploration in volcanic areas is probably that concerned with geothermal steam. Over 150 MW of electric power are currently being produced at Wairakei in the centre of the North Island. Future research into the Wairakei hydrothermal system will undoubtedly be used to assist with the fundamental problems of the extinct hydrothermal system of the Hauraki Goldfields and thereby in the exploration for both clays and metallic minerals at that locality. Careful studies at Hauraki may also assist in predicting conditions at greater drilling depths at Wairakei.

EXPLORATION METHODS

Regional Geology

Regional geology is probably the most important tool for mineral exploration under New Zealand conditions, particularly in view of the relatively early stage of much exploration, and of the increased interest in non-metallics. An adequate regional knowledge is necessary to prospect effectively for stratified deposits (e.g. coal, limestone, bentonite), for stratigraphically and structurally controlled gases and liquids (oil, groundwater, geothermal steam), for deposits that occur within the wide variety of Quaternary settings (ironsands, detrital gold, diatomite), and for all bulk constructional materials whose distribution can be rationalised by a variety of aspects of regional geology.

Metalliferous lodes, particularly in the volcanic environment of New Zealand, have a close genetic association with their "country rocks". Thus the volcanic and hydrothermal sequences, the geochemistry and mineralogy, the tectonic history and present structure, and the weathering and erosional pattern of the "country rock", can all hold important clues to the occurrence and variability of the lodes, and demand an adequate knowledge of regional geology.

Many examples could be given of the way in which regional geology can localise, rationalise and minimise mineral exploration under New Zealand conditions, but four will suffice: the published results of regional mapping of the Hawk Crag Breccia throughout the West Coast led to the very rapid finding of many additional uranium localities following its first discovery in that upper Jurassic non-marine formation; the distribution of bauxite was successfully related to the total time of weathering, and hence to the age, of Pliocene-Quaternary basalt lava flows in subtropical Northland; the richest North Island titanomagnetite sands have been shown to be beach deposits formed during a period of sea-level

(? the European "Tyrrhenian") about 135 feet higher than present, a factor which is important in directing prospecting for the proposed steel industry; and serpentinite occurrences, which are quarried for the fertilizer industry in southern Northland, are known through regional mapping to occur only as huge casual boulders in a widespread, near-superficial chaotic slump deposit, many hundreds of feet in thickness.

Regional geology in New Zealand is predominantly the concern of the Geological Survey. Its 1:250,000 mapping project is now nearing completion, and is already providing valuable background material for mineral exploration. Mapping will now return to the 1:63,360 scale, with the added precision that that implies. Undoubtedly, many future areas for survey will be selected because of economic potential discovered during the 1:250,000 programme; but if these future surveys are to be of greatest value for mineral exploration, the traditional form of reconnaissance investigation and publication will require amendment. At least as much attention as paid to stratigraphy and petrology in the past must be given to details of weathering, hydrothermal alteration and geochemistry in the future, whereas the requirements of oil search, etc. will demand a detailed and dynamic review of sedimentation, volcanism, and tectonism.

Two examples of these future trends will suffice. First, an adequate knowledge of lateral and vertical analytical variations may allow the use of common and accessible calcareous sandstones as fluxes, rather than exhaustible and distant supplies of high grade limestone and silica. Second, recent fieldwork has shown that in many areas of Northland, earlier-mapped Upper Cretaceous and Lower Eocene rocks exist, not as solid formations, but as huge blocks in a superficial chaotic breccia which may reach many hundreds of feet in thickness, and many cubic miles in total volume. In many places this breccia has been shown to overlie and conceal thick sequences of Oligocene and Miocene rocks, whose presence had not previously been suspected. Northland outcrops are isolated and weathered, so that obscure relationships are almost the rule. The total stratigraphic thickness from Upper Cretaceous to Miocene appears to be measurable in many thousands of feet. It now seems that, despite comparatively rugged topography, widespread Cretaceous fossils in surface outcrops of impermeable rocks are no guarantee that thick, marine, permeable Tertiary rocks are not present at depth. This fact has already proved to be important in the investigation of cold and hot groundwater, and it might also prove important in geothermal steam and oil investigations.

Paleontology, Petrology and Mineralogy

New Zealand's future mineral development will rely heavily upon the traditional assistance of paleontological, petrological and mineralogical services.

With a largely edemic fauna and flora, a time-stratigraphic subdivision of purely local New Zealand series and stages has been adopted by New Zealand paleontologists. The resulting fineness of subdivision has assisted greatly in mineral exploration, particularly for oil, coal and groundwater.

Petrology and mineralogy have proved particularly important in deterioration studies of constructional material, thereby assisting future quarry selection. Petrographical and mineralogical research into the Wairakei geothermal field has shown important mineralogical changes with depth and temperature-pressure environment. The possible value of this work in studies of the Hauraki Goldfield, to the north of Wairakei and of the Central Volcanic Region, has already been mentioned.

Geophysics

Government sponsored geophysical surveys are undertaken by Geophysics Division, D.S.I.R. Following the report of the Mineral Resources Committee, plans have been announced for airborne surveys of the more favourable mineral areas of South Island. These will extend the Division's growing coverage in regional geophysics which should prove invaluable in future mineral prospecting.

In the past, detailed geophysical surveys in New Zealand have been applied more commonly in engineering than in mineral exploration, although electrical methods have been tried on some sulphide deposits that proved too small to be economic, and magnetic methods have been used successfully to prospect for serpentinite in Northland. Geophysics has been found invaluable, however, both in the oil search in Taranaki, where the initial work by Geophysical Division attracted additional excellent work by overseas oil companies, and in the search for geothermal steam, where geophysical anomalies and measurements provide important additional guides to drilling.

Geochemistry

Geochemical prospecting has been introduced recently into New Zealand, and a few methods have been tested usefully under New Zealand conditions, where the generally high rainfall will probably demand different techniques from those established elsewhere. However, as geochemical prospecting will probably be restricted to supplying detail within metalliferous areas that have been located broadly by geology and geophysics, it seems unlikely to make a great impact on the present New Zealand scene, in view of the present lack of metal mining.

Geochemistry, in its wider sense, however, should prove valuable in mineral exploration, in investigating vertical and lateral analytical variations in rock formations, and in helping to rationalise the complexities of hydrothermal systems.

Beneficiation and Utilisation

Even in the purely geological context of this paper, the need must be stressed for close cooperation with workers in the field of beneficiation and utilisation. With the move from the age of metallics to one of non-metallics, the question of what represents an economic mineral deposit has become far less clearly defined, and it may depend heavily upon the discovery of efficient yet economic beneficiation and utilisation techniques. The New Zealand geologist must appreciate not only what is possible now, but also what might be feasible in the future with known national skills and facilities. Topical examples are the non-swelling bentonites of Canterbury, the talc-magnesite deposits of Nelson, and the quartz-feldspar sands of several localities. The successful development of each will demand close liaison between geologist and laboratory.

CONCLUSIONS

The upsurge of interest in New Zealand's mineral deposits means that far more work into all aspects of their exploitation will be inevitable. It is therefore desirable to review, very critically, the relative returns that may be expected in relation to the money and effort expended - as regards the minerals sought, the areas investigated, and the methods used. The following points seem the most important, given the particular conditions that prevail in New Zealand:

1. Minerals should be afforded no relatively increased priority in exploration because they earn export revenue or save imports, rather than just improve living standards directly.

2. They should be afforded increased priority because of their relatively greater total value, greater chances of discovery under actual New Zealand conditions, greater potential in uses and marketability, and greater opportunities for increased national content prior to export.

3. The world-wide trend towards increased non-metallic production, and a reduced relative importance of metal ores, is well reflected in New Zealand, and must be an important factor in selecting priorities in mineral search. Under New Zealand conditions, oil, clay, groundwater, geothermal steam, and the many raw materials for a steel industry (ironsand, coal, limestone, silica, dolomite, etc.) are perhaps the most immediately important.

4. The most important mineralised areas are the western half of the South Island and the Hauraki Goldfield; but great importance must also be given to the relatively unique and accessible volcanic areas with their increasing variety of mineral production.

5. Regional geology is undoubtedly the most important tool in mineral exploration under New Zealand conditions, but increased attention must be paid to weathering, hydrothermal alteration, lateral and vertical variations of formations, paleogeography, and tectonic and sedimentary histories.

6. Palaeontology will continue its traditional support of stratigraphy; but mineralogy and petrology may make mutually invaluable contributions in studying both the Wairakei geothermal system and the clay formation and metallic mineralisation of the extinct hydrothermal areas of Hauraki and Northland.

7. Regional geophysics will be of major importance.

8. Geochemical prospecting is unlikely to be important immediately, but adequate geochemical studies of all individual formations and of hydrothermal systems will be invaluable.

9. The quest for many non-metallic minerals will demand close liaison between geology and mineral beneficiation and utilisation.

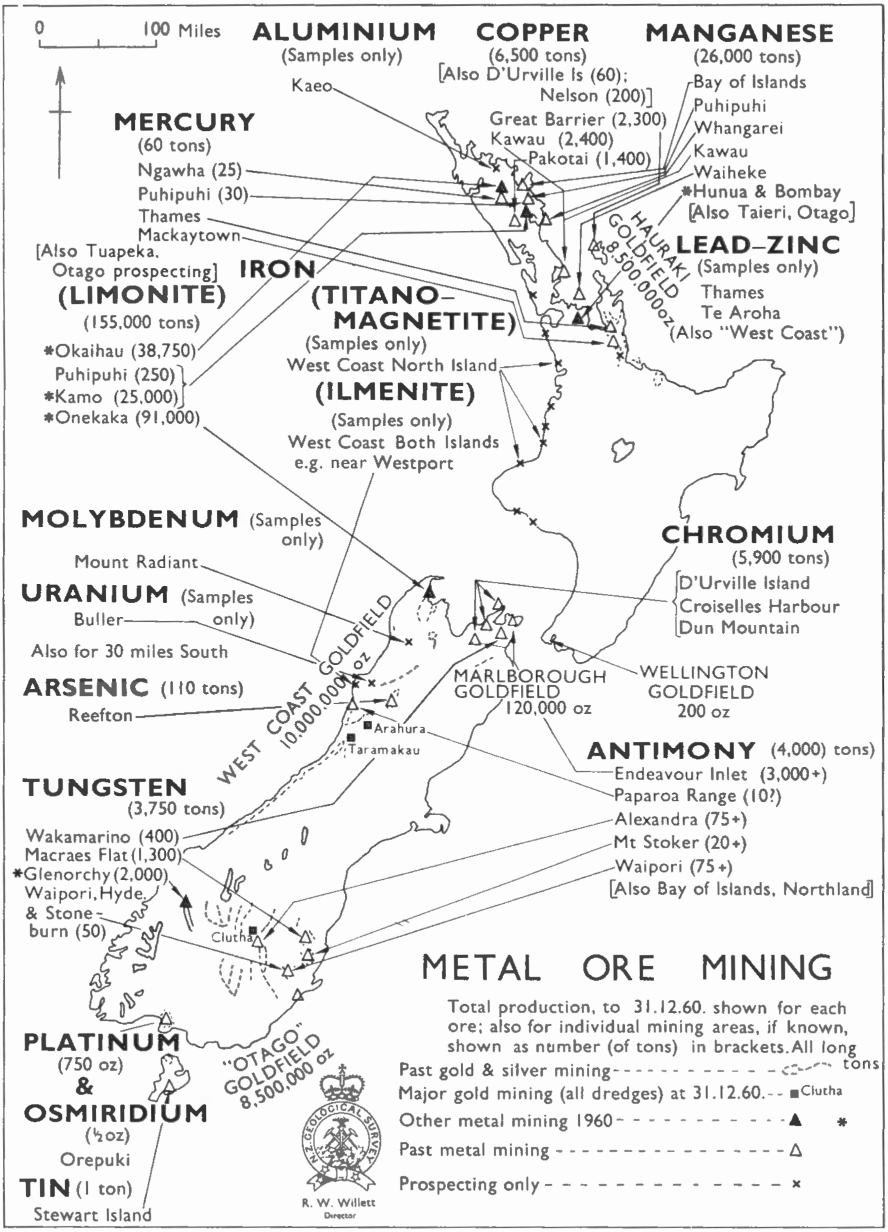
NEW ZEALAND MINERAL PRODUCTION to 31 December 1963

MINERAL	1963 value (£)	1963 Quantity, and as % of average for 1953-62		Total Quantity to 31.12.63
FUELS				
Coal	8,027,163	2,742,411 tons	105%	158,000,000 tons
Natural Gas	1,257	4,573,800 c.ft.	80%**	55,000,000 c.ft.
Oil, shale	-	-	-	14,000 tons
Petroleum	10,877	139,700 galls.	70%	6,800,000 galls.
Petroleum condensate	9,080	121,350 galls.	***	235,532 galls.
METALS				
Antimony	-	-	-	4,000*tons
Arsenic	-	-	-	110 tons
Chromium	-	-	-	5,900 tons
Copper	4,600	230 tons	***	6,750*tons
Gold	168,881	14,206 oz	45%	27,200,000 oz
Iron	15,634	3,074 tons	140%	163,000 tons
Manganese	-	-	-	26,000 tons
Mercury	-	-	-	60 tons
Osmiridium	-	-	-	1/2 oz
Platinum	-	-	-	750 oz
Silver	105	286 oz	2%	34,430,000 oz
Tin	-	-	-	1*ton
Tungsten	1,425	5 tons	25%	3,750 tons
NON-METALLICS				
Aggregate, rock, sand	9,890,366	19,832,993 tons	140%	Very Large
Asbestos	19,868	392 tons	115%**	4,900 tons
Bentonite	21,252	1,660 tons	115%	20,500 tons
Clay (brick)	162,230	289,217 tons	100%	Very Large
Clay (pottery)	45,676	7,713 tons	140%	220,000*tons
Diatomite	25,659	1,603 tons	130%	16,500 tons
Dolomite	11,759	4,387 tons	125%	80,000 tons
Feldspar	-	-	-	Minor
Fullers Earth	-	-	-	1,000 tons
Limestone:				
agricultural	818,554	856,759 tons	75%	Very Large
cement	382,542	1,186,705 tons	130%	Very Large
industrial	62,555	57,983 tons	140%	Large
Magnesite	5,522	781 tons	125%	10,700 tons
Mica	-	-	-	4 1/2 tons
Perlite	11,107	564 tons	195%**	3,200 tons
Phosphate	-	-	-	190,000 tons
Pumice	15,454	16,606 tons	75%	400,000*tons
Salt	150,000	11,000 tons	115%	95,000 tons
Sand (silica)	126,286	63,820 tons	170%	4,800,000 tons
Sand (industrial)	125,902	200,634 tons	330%	Large
Serpentinite	164,392	134,296 tons	130%	1,710,000 tons
Stone, cut	47,735	12,481 tons	70%	950,000*tons
Sulphur	-	-	-	22,000*tons
Talc	-	-	-	100 tons
Wollastonite	105	9 tons	***	15 tons

* = estimate ** = average available for under 10 years
*** = no average available, or for less than 3 years

12 months exports of Kauri Gum to July 1963 - 1,051 cwt, worth £11,481.

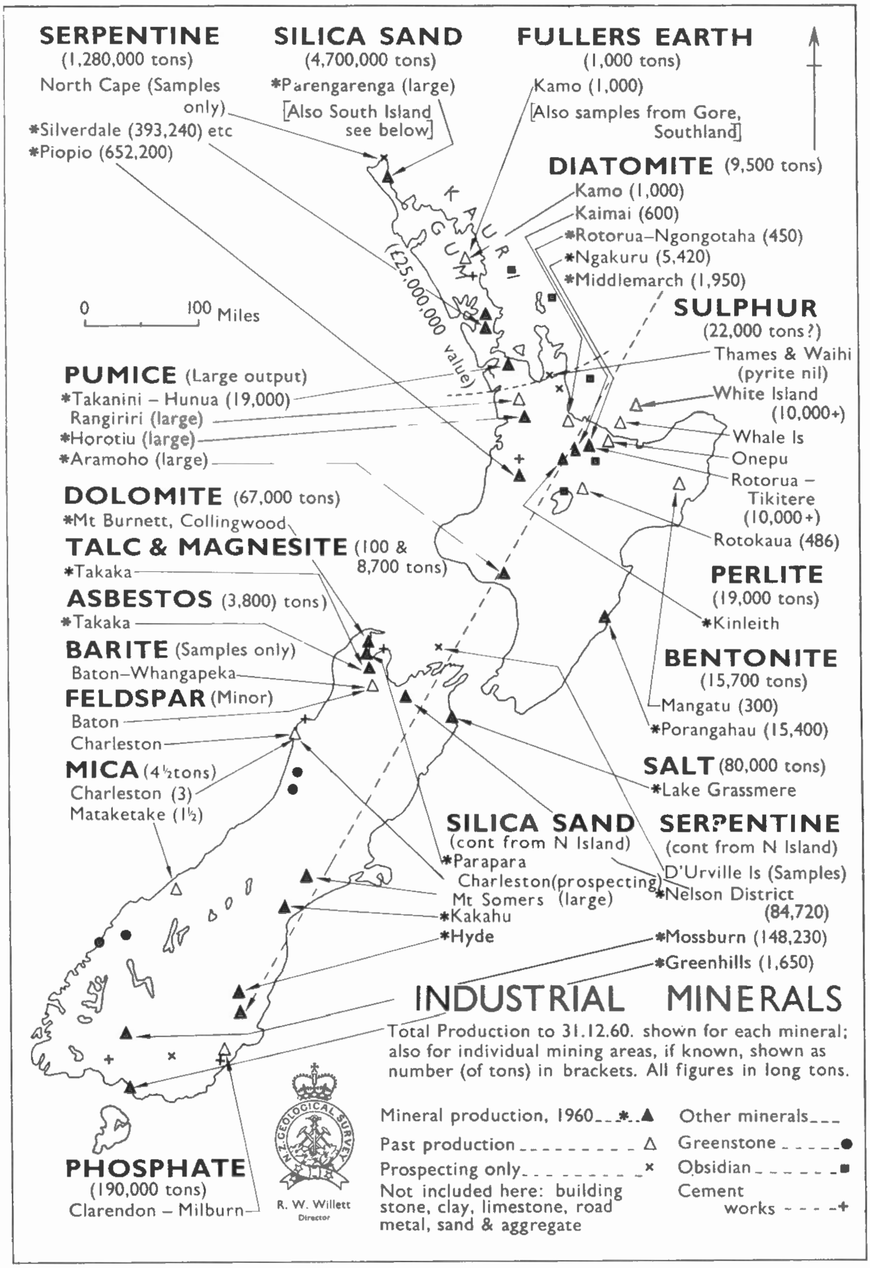
N.Z. Geological Survey — Industrial Minerals and Rocks of New Zealand — Map I



Published by the Department of Scientific and Industrial Research 1964.

R.E.Owen, Government Printer.
Wellington, New Zealand.

N.Z. Geological Survey Industrial Minerals and Rocks of New Zealand Map 2



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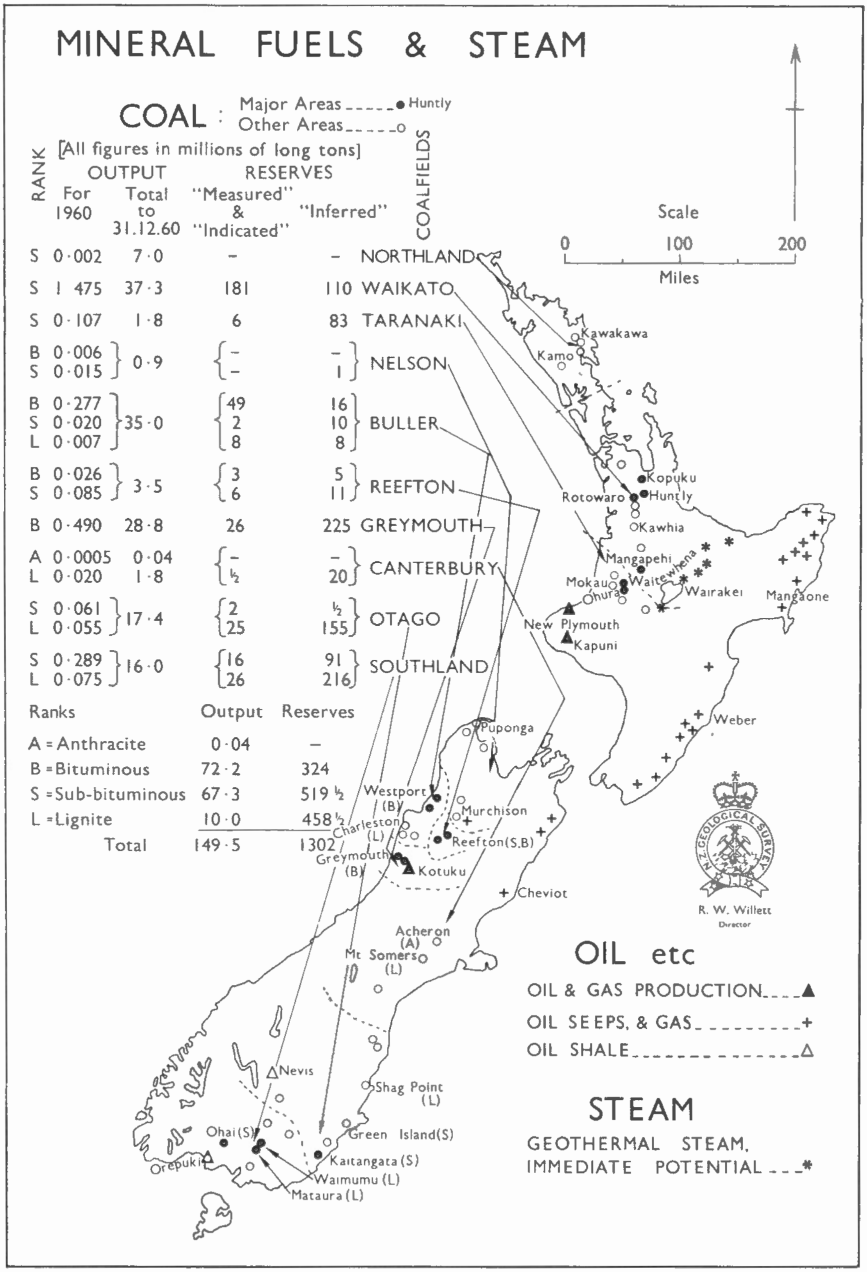
MINERAL FUELS & STEAM



COAL

Major Areas ● Huntly
Other Areas ○

[All figures in millions of long tons]

RANK	OUTPUT For 1960	OUTPUT Total to 31.12.60	RESERVES "Measured" & "Indicated"	RESERVES "Inferred"	COALFIELDS
S	0·002	7·0	–	–	NORTHLAND
S	1 475	37·3	181	110	WAIKATO
S	0·107	1·8	6	83	TARANAKI
B	0·006	0·9	–	–	NELSON
S	0·015		–	1	
B	0·277	35·0	49	16	BULLER
S	0·020		2	10	
L	0·007		8	8	
B	0·026	3·5	3	5	REEFTON
S	0·085		6	11	
B	0·490	28·8	26	225	GREYMOUTH
A	0·0005	0·04	–	–	CANTERBURY
L	0·020	1·8	½	20	
S	0·061	17·4	2	½	OTAGO
L	0·055		25	155	
S	0·289	16·0	16	91	SOUTHLAND
L	0·075		26	216	

Ranks	Output	Reserves
A = Anthracite	0·04	–
B = Bituminous	72·2	324
S = Sub-bituminous	67·3	519 ½
L = Lignite	10·0	458 ½
Total	149·5	1302

OIL etc

OIL & GAS PRODUCTION ▲
OIL SEEPS, & GAS +
OIL SHALE △

STEAM

GEOTHERMAL STEAM, IMMEDIATE POTENTIAL ✱

Published by the Department of Scientific and Industrial Research 1964.

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ADVANTAGES OF MARSHALLING AND ANALYZING AVAILABLE DATA

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Many factors are combined in a successful exploration programme and there is no simple set of rules for finding mineral deposits. It is possible with the development of many sophisticated exploration techniques and elaborate survey methods that one essential primary phase of a programme may be overlooked or minimized. This phase consists of marshalling and analyzing available data and using it to full advantage in our search and exploration for ore. Systematic search of published reports and regional documents frequently turns up a surprising amount of scientific and descriptive information on mineral deposits in many relatively unknown areas. This information can be of inestimable value when it is compiled, classified, summarized and examined in the framework of recent scientific concepts and ideas.

The compilation and analysis of available scientific and descriptive data is one of the most essential, least costly and most rewarding steps in mineral exploration and evaluation. Unfortunately, the observations of previous explorers, surveyors, and naturalists are usually reported in a variety of publications and media and the value and significance of much of the information is lost unless it is collected, classified and plotted on maps. The importance of starting a prospecting programme in the library with compilation of existing information is not always recognized.

In the first stages of a survey of iron ore potential in Central Canada in 1958 all occurrences of iron-formation and iron prospects reported in the literature were plotted on geological maps. Most of this Precambrian area has been covered since that time by airborne magnetometer surveys which distinctly show the locations of known iron ranges. No new iron ranges of significance were found by these geophysical surveys that were not indicated in previously published reports and it can be assumed that most of the areas with potential iron ore are now recognized. All of these areas were revealed by a systematic search of the literature and vital information had been available for some time. The distribution pattern and metallogenetic significance of the iron-formations could not be fully assessed without compilation of the data on maps.

An appreciation of the metallogenesis of a region is gained from a synthesis of regional geology and tectonic features, geophysical data and description of mineral occurrences. Vast sums of money are spent for geophysical and geological surveys but a minimum of emphasis is placed on examination of known mineral occurrences and on orienting them within broad scale geological features. This is one of the most significant steps in a metallogenetic study.

The importance of relating a certain type of mineral occurrence to large scale geological features was dramatically illustrated in the history of the Blind River uranium camp in Ontario. Having recognized the nature and type of uranium occurrences present in the area and the fact that they occurred in a distinctive stratigraphic unit, Dr. Franc Joubin then turned to a map published many years earlier by the Geological Survey of Canada which showed the distribution of the conglomerate bearing formation. Existing copies of this critical map, which was then out of print, proved to be an invaluable guide to the distribution of one of the world's largest reserves of uranium ore. In this case, recognition of the type of mineral occurrences combined with information on the regional geology already available in published maps provided the necessary guidance for a dramatic mineral discovery.

Existing references to mineralized zones, especially if they are sketchy and descriptions are incomplete, are frequently overlooked or not considered in planning exploration. These do, however, provide positive information and direct evidence about the type or kinds of mineralized zones in a region. Whether or not known mineral occurrences appear to be large enough to be of economic importance, they constitute direct evidence that natural processes have operated in a region and effectively concentrated certain elements under special circumstances. Any knowledge or appreciation of the mode of occurrence and geological setting of these small mineral zones is a positive step toward visualizing the possible location of larger mineral deposits.

The history of the Bathurst mining area in New Brunswick, Canada, illustrates the importance in exploration of known mineral prospects and occurrences. A number of copper, lead, zinc and silver sulphide mineral occurrences are mentioned in Geological Survey of Canada reports published prior to 1936, and some of these prospects had been known for nearly half a century prior to that time. Although information is rather sketchy it indicates some of the types of mineral occurrences and their geological setting in the area. Little attention was given to these occurrences or reports about them until about 1953 when the area was intensively explored using geophysical methods followed by diamond drilling. Major orebodies, some containing more than 100 million tons of ore, were located on or near the sites of nearly all the previously reported prospects and other orebodies were discovered in adjacent areas where geological conditions are similar. Evidence of copper-zinc mineral zones had existed for several generations before their full significance was appreciated.

The sequence of steps suggested for handling available data includes compilation of existing references to mineralized zones, classification of information with regard to type of mineral occurrence and its geological and mineralogical features, and indication of any apparent relationships of mineral occurrences to regional geological and tectonic features. This type of classified information can be depicted easily on a geological map by using symbols to designate mineral zones that have similar features and are of a specific type. These are, in effect, the first steps in the development of a metallogenetic map. The usefulness of the map will naturally increase as the quantity and quality of information on mineral occurrences and geology increases and evidence regarding the genesis of specific mineral deposits is accumulated. By classifying the mineralized zones on the basis of their chemical, mineralogical and geological features and relating them to larger scale geological features the first steps are achieved in gaining an appreciation of the metallogenesis of a region. Such maps constitute a major step in the synthesis of scientific information and provide a basis for guiding exploration. The information shown will be decidedly more instructive than some common types of plots that show the distribution of a mineral commodity by elemental symbols.

Geological Surveys sponsored by governments have to fulfil a very necessary role in the exploration and development of mineral resources. One of their primary functions is maintaining records and descriptions of mineral occurrences and preparation of metallogenetic and mineral distribution maps. This is a scientific service for mining companies and government agencies that is expected from Geological Surveys and one for which they are uniquely qualified. Many Geological Survey organizations, for various reasons, have emphasized only the mapping of regional geology in their programmes. The full benefits to be gained from this essential work for mineral development are minimized if systematic recording and analysis of mineral deposit information is not carried out as an equivalent and coordinated part of the overall geological programme.

Many of the advantages of collecting and analyzing data on mineral occurrences are obvious and scarcely need elaboration. Some of these are listed as a reminder of what may be gained in this phase of mineral exploration study.

1. Various elements that are concentrated locally and present in amounts greater than their average content in the earth's crust are indicated.

2. An indication is given of the nature of the concentrations of various elements or types of mineral deposits.

3. The distribution of types of mineral occurrences with respect to geological, tectonic, or topographic features is shown.

4. Areas may be outlined where similar geological conditions exist and where new mineral occurrences may be located that are similar in type to reported occurrences.

5. Locations are shown where direct observations on mineral zones have been made and where additional information can be obtained from outcrop and exposed mineral zones.

6. The plots showing distribution of known mineral occurrences may give an idea of the type and regional extent of previous exploration and study. If a plot shows mineral occurrences located only along obvious and easy travel access routes it suggests that large tracts of country may never have been examined.

7. A graphical analysis of data may provide an invaluable guide for determining the type of survey method or technique that is applicable and most appropriate for a region.

8. Some indication may be given as to what geological features should be mapped in detail, and what features may be worthy of special attention.

9. A plot of available data will show known mineral zones and new discoveries or rediscoveries can be recognized easily.

10. The amount of mine development in a region may be indicated if producing mines and those that were worked in the past are shown along with scientific and descriptive data.

11. A graphical analysis of mineral deposit information and regional geology is a necessary step in establishing a scientific basis for testing hypotheses regarding the origin and distribution of mineral zones.

12. Preliminary plots of available data may not be entirely representative of the metallogenesis of an area but they usually indicate where further scientific investigation is needed most.

METALLOGENY OF POST-PRECAMBRIAN GEOSYNCLINES

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INTRODUCTION

This paper outlines the tectonic and interrelated metallogenic development of the Canadian Appalachians as an example of one working hypothesis applicable to post-Precambrian folded belts.

Field and office investigations were in part initiated in response to the future needs of the Subcommission for the Metallogenic Map of the World established by the International Geological Congress in 1956. Insofar as most other Commonwealth countries are involved in this Subcommission, a few words on our programme are in order. The Geological Survey of Canada from 1957 to 1960 published nation-wide maps showing the distribution of uranium, beryllium, molybdenum and iron (Lang, 1958; Vokes, 1958, 1959; Gross, 1959), and compiled manuscript maps for 12 other elements. Some unpublished maps were incorporated in a review of progress by Lang (1960). In 1960, it was decided that, whereas the series to date provided a useful index to localities and references, the small scale (1:7,603,200) made it difficult to discern the relations between mineralization and geological features. In part in preparation for the I.G.C. Subcommission needs and also to guide further metallogenic studies within Canada, I began in 1962 a metallogenic study of our best known geosynclinal belt, the Canadian Appalachians. In addition, in 1963, S.M. Roscoe undertook a regional study of a well-mapped belt in the Canadian Shield with numerous mines and occurrences. While these are primarily metallogenic research projects, it seems obvious that mineralization forms part of the geological framework of all our countries, thus all geological research which better defines this framework should contribute to our better understanding and exploitation of those regular and recurring geological features which control mineralization. In particular, a pattern of mineralization is becoming established in various post-Precambrian mobile belts of the world, interrelated to the whole spectrum of geological events which comprise a geosynclinal cycle. Within this tectonic framework, much detailed information can be effectively synthesized, new classifications of mineral deposits may be defined and refined, and new exploration aids and genetic implications should emerge.

Classification is discussed by S.M. Roscoe in another paper in this collection but mention should be made here of the type of classification proposed by Gilmour for copper deposits (Gilmour, 1962; McCartney, 1962) and the general classification advocated by Pereira (1963) both of which should be encouraged and refined. This type of classification follows logically from the tectonic approach to mineralization.

Within the British Commonwealth as elsewhere, the need for synthesis of mineral-tectonic features of mobile belts is apparent if individuals are to grasp the common patterns which probably exist. For example, the excellent synthesis of Campana and King (1963) on tectonism, sedimentation and mineralization in West Tasmania seems entirely compatible with that of the Canadian Appalachians as summarized below, except that post-orogenic mineralization in Tasmania is poorly developed. My impression, gleaned only from fragments of the literature, is that this type of synthesis would also be applicable as an exploration guide throughout the poorly known central parts of the eastern Australian mobile belt. The British Isles, on the other hand, seem to display mainly the middle (orogenic) and post-orogenic types of mineralization judging by the summary of age relations of mineralization by Dunham (1952). Other post-Precambrian mobile belts, such as the western Cordillera of North America, are tectonically very complex and only the Mesozoic-Tertiary events may eventually yield to simplified metallogenic synthesis.

METALLOGENIC SYNTHESIS, CANADIAN APPALACHIANS

The Canadian Appalachians, a northeastward continuation of the classic Appalachian geosyncline, comprise the eastern provinces of Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick and part of Southeastern Quebec.

Precambrian rocks form the basement of this Palaeozoic geosyncline but their Precambrian history and mineralization is not included in this synthesis.

The line of investigation used in this study was drawn from the writer's early attempts to understand the tectonic development of Newfoundland and some seemingly related types of mineralization. This led to a search and subsequent selected translation of Soviet literature. Principal Soviet metallogenic views were surprisingly complete and were summarized in an earlier paper (McCartney and Potter, 1962). Since then, field studies have supported the working hypothesis. German workers had described similar patterns but emphasized mineralization of the initial and early stages of geosynclinal history. Soviet tectonic views had been used earlier in the Canadian Appalachians (Neale et al., 1961).

Figure 1 is a highly diagrammatic model of the tectonic development of the Canadian Appalachians. Known mineral deposits, age and facies of their wall rocks and their relative present position in the geosyncline are fairly factual. We hope to produce another, more realistic, cross-section of the Appalachians within the very near future.

Initial and Early Tectonic Stages

The initial and early stages of the Canadian Appalachian geosyncline in Cambro-Ordovician and Silurian time comprised limestones of the shelf facies on the northwest passing eastward into spilitic-volcanic belts of southeast Quebec and north-central Newfoundland, with clastic sediments further to the southeast.

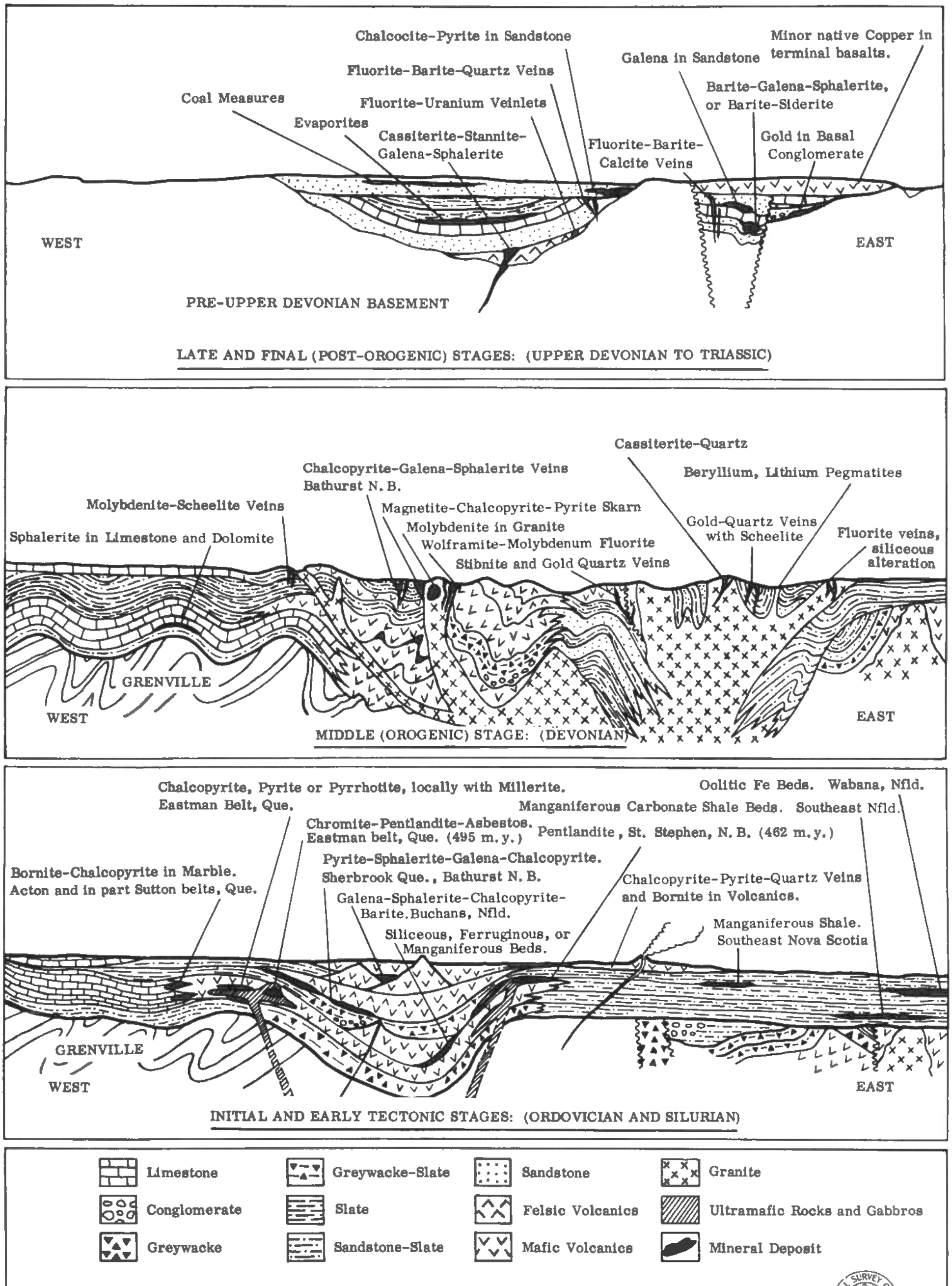
A good sampling of mineral deposits in the western portion of the geosyncline is afforded in southeastern Quebec, although similar deposits occur in similar environments in New Brunswick and north-central Newfoundland. Béland et al. (1962) provide a synthesis of most types of Quebec deposits in relation to their regional geological setting.

Principal deposits in rocks of this age include:

1. Chalcopyrite-bornite in marble in the Eastern Townships (Acton and part of Sutton belts) where limestones of the shelf facies merge with mafic volcanics (Acton mine).

2. Deposits of chromite, nickel, asbestos and magnesite in ultramafic bodies (Thetford district).

3. Pentlandite in gabbro associated with ultramafics at St. Stephen, New Brunswick. This deposit is of interest because it was formerly considered Devonian in age. It thus appeared to clash with this metallogenic model, as formerly discussed (McCartney and Potter, 1962, p. 84). Biotite-gabbro dated for the writer by K/Ar in G.S.C. laboratories indicated an Ordovician age of 460 m.y., an age which agrees with the working hypothesis.



GEOLOGICAL SURVEY OF CANADA 1842

AN IDEALIZED METALLOGENIC MODEL OF THE CANADIAN APPALACHIANS, DEPICTING SOME KNOWN TYPES OF MINERAL OCCURRENCES IN RELATION TO THEIR TECTONIC SETTING AND THE FACIES AND APPROXIMATE AGES OF THEIR WALL-ROCKS

Figure 1

W.D. McCartney
March, 1964

4. Semiconcordant, massive pyrite or pyrrhotite-chalcopyrite deposits in dominantly mafic volcanics with ultramafic intrusives (Eastman Belt, Eastern Townships; Yves, Smith and Huntingdon Mines). Lead and zinc is minor or lacking, but nickel may be present (Eastern Metals) as millerite and siegenite.

5. Slightly younger acidic and mafic volcanics enclosing semiconcordant, massive pyrite-galena-sphalerite-chalcopyrite bodies (Bathurst, New Brunswick, and the Sherbrooke Belt, Eastern Townships). The higher proportion of acidic volcanics in these lead-zinc-copper belts as opposed to 4 above may be significant.

6. Considerably younger pyroclastic and volcanic rocks enclosing massive barite-galena-sphalerite-chalcopyrite as at Buchans, Newfoundland.

7. Chalcopyrite, pyrite-quartz veins and chalcopyrite and bornite in amygdules in mafic Silurian volcanics on the Mascarene Peninsula, southern New Brunswick.

In addition, the important chalcopyrite-molybdenite skarn deposits at Murdochville, Quebec, appear to have formed near the end of this early tectonic stage. Selected, biotite-feldspar-porphyry associated with mineralization collected by the writer has been dated as 390 m.y. (R. Wanless, personal communication). This appears to clarify the problem as discussed in an earlier paper (McCartney and Potter, 1962, p. 84). Some aspects of the mineralization resemble porphyry copper deposits which commonly belong in the post-orogenic tectonic stage. Pyrite, chalcopyrite, molybdenite and native bismuth are found in the skarn zone and in sericitized quartz-feldspar porphyry dykes.

The sedimentary mineral deposits known in this stage include cherty iron and/or manganese beds in the eugeosynclinal environment, and manganiferous shales and oolitic iron deposits in the sedimentary rocks to the southeast.

Middle (Orogenic) Tectonic Stage

The orogenic or middle tectonic stage is represented by the Acadian orogeny during Devonian time. Elements such as tin, tungsten and molybdenum form discrete deposits (as opposed to accessory traces) for the first time in the geosyncline's history. These deposits may be a function of the first appearance in the geosyncline of anatectic granites. They could result from a concentration of elements such as tin in the pre-orogenic sediments and subsequent downbuckling of the sedimentary pile. Such genetic questions can be suggested by this tectonic approach, and regional geochemical-stratigraphic studies could be suggested to seek supporting evidence.

The principal deposits associated with this orogenic tectonic stage include:

1. Molybdenite-quartz veins associated with granitic rocks. An interesting example near the St. Cecile stock in the Eastern Townships of Quebec contains molybdenite and minor stannite and scheelite in a gangue of quartz, lesser feldspar and minor muscovite gangue. Selected muscovite samples collected by the writer recently yielded an age of 360 m.y. (R. Wanless, personal communication) and the nearby stock had formerly been dated as 362 m.y. (Lowdon et al., 1960).

2. Gold-arsenopyrite-quartz veins occur in Ordovician sediments near Devonian granites in southern Nova Scotia and southern New Brunswick. Locally, as at West Gore, Nova Scotia and Lake George, New Brunswick, stibnite-quartz veins occur and may be similar in age.

3. Cassiterite is known at New Ross, Nova Scotia associated with Devonian granite.

4. Wolframite in quartz veins with associated molybdenite occurs at Burnt Hill and Square Lake, New Brunswick associated with a late facies of a large Devonian granite body.

5. Pegmatite deposits, including beryllium and lithium-bearing varieties, are known in southern Nova Scotia.

6. Fluorite veins accompanied by silicification of their Devonian granite wall rock are mined at St. Lawrence, Newfoundland.

Late and Final Tectonic Stages

During the post-orogenic tectonic stages, post-Devonian, mainly Carboniferous and Triassic, sediments up to 20,000 feet thick were deposited in downfaulted and downwarped basins. As in other mobile belts, post-orogenic fault movements and tilting, with some folding and epeirogenic movements, occurred during sedimentation. These movements are reflected in rapid facies changes in clastic sediments, both locally and regionally.

Post-orogenic rhyolitic volcanics occur in southern New Brunswick and Cape Breton near the base of the Carboniferous section. They are accompanied by cassiterite-stannite-molybdenite-galena-sphalerite at Mount Pleasant, and by fluorite-uranium veinlets in rhyolite at Harvey Mills, New Brunswick. However, post-orogenic igneous activity is comparatively sparse in the Canadian Appalachians compared to many other mobile belts. Mercury, epithermal gold and post-orogenic porphyry copper deposits, common to these tectonic stages elsewhere, may possibly be weakly developed in the Canadian Appalachians but more likely are not present.

Fissure veins of fluorite-barite-calcite cut Mississippian (i.e. Lower Carboniferous) rocks at Lake Ainslie, Nova Scotia, and a vein of fluorite-barite-quartz cuts and in part replaces red Uppermost Devonian shale at East Memramcook, New Brunswick.

The plateau-type Triassic basalts contain minor occurrences of native copper.

The remaining deposits, characteristically associated with sediments in these late and final tectonic stages, are well represented. Many more may be as yet undiscovered. They are, or are in part, controlled by sedimentary, stratigraphic, and related factors, and have very large tonnage potential. They include coal, evaporites, gold and base metals.

Coal measures are widespread in Pennsylvanian sediments. Modest amounts of oil and gas have long been produced from Mississippian beds near Moncton, New Brunswick, and numerous oil showings are known.

Evaporites are especially widespread in Mississippian Lower Windsor beds, commonly associated with limestone. Gypsum and salt are being produced, and potash minerals occur in the salt mines of Malagash and Pugwash, Nova Scotia. The known salt domes have not been fully investigated and exploration for potash seems to have been neglected in the past.

Low grade gold ore was mined at Gays River, Nova Scotia in a Mississippian polymict, basal conglomerate with numerous slate pebbles and boulders. There is little doubt that the deposit represents a fossil placer concentration and that the gold was derived from nearby gold-quartz veins in the Meguma sediments; an interpretation strengthened by study of palaeocurrent directions. Quartz pebble conglomerate rather than polymict conglomerate, where encountered in beds near the base of the Mississippian could be of better grade and should be checked for gold, tin, tungsten and radioactive minerals.

Two types of mineralization of demonstrated or potential economic importance remain to be mentioned and may be interrelated. These are, first, the suite of barite-lead-zinc, barite-siderite, lead-zinc and probably the recently discovered celestite deposits in Lower Mississippian Windsor limestone, characterized by the deposits at Walton, Brookfield, Smithfield, and Loch Lomond in Nova Scotia; and second, disseminated copper-uranium or lead deposits in grey sandstones or siltstones in the overlying Carboniferous red-bed sequences. The latter types are represented by copper-uranium occurrences in sandstone near Northumberland Strait, and a large tonnage of stratified, lead-bearing, possible ore at Salmon River, Nova Scotia.

CONCLUSIONS

Application of these concepts to exploration should sharpen our awareness of the most likely types of mineralization to be expected in a given tectonic environment. Suitable exploration techniques and most favourable areas can be selected. Unusual minerals, such as scheelite, cassiterite or stannite with lead-zinc mineralization can, in some environments, be specifically searched for rather than accidentally overlooked as in the past.

Applied to the preparation of metallogenic maps and, later, to prognostication maps, this approach points out the variation in geological features which require inclusion in the base map to emphasize relations to various types of deposits. For example, background features of importance to mineralization of the main orogenic stage would include compositional variations of granites and both the composition and the structure of host rocks, whereas many types of late stage mineralization are, in general, more dependent on such factors as facies changes, basement topography, palaeocurrent directions and palaeogeography.

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AIR PHOTOGRAPHS IN ECONOMIC MINERAL EXPLORATION

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ABSTRACT

Air photographs are of growing importance in mineral exploration. Examples of the application of photogeological methods to ore search are given, and the advantages of integrating photogeological with other prospecting methods are stressed.

INTRODUCTION

The use of air photographs in geological studies is not new; indeed as early as 1919 H.H. Thomas referred to 'aeroplane photography' as a method of investigating some branches of physical geology (Thomas, 1920); but much of the developmental progress has been achieved since the time of World War II. Today the general value of photogeology, including its application to mineral exploration, is widely accepted, but maximum exploitation of the method is far from routine.

METHODS OF APPLICATION IN GENERAL

In unmapped or poorly mapped regions the value of air photographs for planning traverses and access routes would alone more than justify their use; as a means of preparing a base map they become of increasing importance, and ultimately it is clear that the prior preparation of a photogeological map will immeasurably assist mineral exploration.

The detailed application of air photographs to mineral exploration is generally indirect, their use being mainly to permit the inference of conditions favourable for economic mineralisation. Such conditions may include the presence of fault or fracture zones, lithological contacts, unconformities, major igneous intrusions, dykes and pegmatites. Successful exploration commonly depends upon locating favourable structural conditions. Structural data are among those most reliably obtained from air photographs. At a relatively early date Tuzo Wilson demonstrated the value of photogeology in structural research on the Canadian Shield, where patterns of linear features were mapped rapidly over a large area, and major lines of tectonic weakness were inferred. If the hypothesis is valid that ore formation, as well as faulting, follows fundamental lines of weakness, such structural studies can be of great economic value. Wilson remarked the fact that many major mining camps occur at the junction of plotted lineaments (Wilson, 1948). More recently, interpretation of deep-seated structure by analysis of surface features visible on air photographs has received attention. Mollard (1957) suggested that intersecting linear features seen on photo-mosaics of Saskatchewan and Manitoba, might reflect bedrock fractures, despite the fact that bedrock is in many cases concealed by up to 200 ft. of unconsolidated material. The study of fracture traces, i.e. fracture analysis, on air photographs is also assuming increased importance, promoted by the ease and efficacy with which the azimuth, the frequency, and the length of lineations can be measured on photographs. Statistically processed data can reveal structural and stratigraphic anomalies and fracture analysis is a useful tool in mineral exploration.

Structural data are desirable supported by lithological identification. In the main such identification presents a difficult problem in photogeology and one yet to be solved satisfactorily. Nevertheless, a recent major development has been the demonstration that photogeology can be practised effectively in igneous and metamorphic areas, thus opening prospects for photogeological study of vast regions of basement terrain. In this connection, Stringer did important pioneer work in recognising on air photographs a province of ring structures and intrusions in southern Nyasaland. By a detailed study of Chambe Plateau he showed this to be composed of three concentric ring dykes with a central plug, these members being differentiated by changes in morphological expression. (Stringer, Holt, and Groves, 1956). This work proved that photogeological study can detect minor variations in plutonic rocks and reveal information not apparent on the ground. It was also of potential economic significance insofar as such ring structures may be associated with carbonatites containing pyrochlore.

In the arid region of the Protectorate of South Arabia, where rocks are exceptionally well exposed, field and photogeological work by Overseas Geological Surveys indicates that granites of clearly intrusive type can in some cases be differentiated from autochthonous granites. This knowledge may be combined with radiometric data on some of the granites to make a provisional forecast of the age and origin of the granites of this region. The significance of such work in mineral exploration needs little elaboration, especially if a general knowledge of the region permits the linking of a mineral species with a certain type of granite. For instance, with regard to the distribution of beryllium in granitic rocks of Tanganyika, Rushton (1960) noted that analysis of some 284 specimens shows this mineral to occur most frequently in late orogenic granite, less frequently in post-orogenic granite, and least frequently in synorogenic granite. In terms of age the incidence of beryllium is said to be greatest in early Archaean granite.

It is commonly possible to differentiate between the major types of plutonic igneous rocks on air photographs. Ultrabasic rocks, for example, may be indicated by a stunted or poor vegetation cover, caused possibly by an excess of magnesia, or more probably by a high content of chromium or nickel in the soil. In the heavily forested terrain of British Borneo (now part of Malaysia) field work by Whittle confirmed his prior interpretation of ultrabasic plutons. The presence of chromite was later proved by a mining company. (Personal communication from G. Whittle, Overseas Geological Surveys).

Geomorphological information from air photographs may also be of use in mineral exploration; for example, the recognition of surfaces favourable for the formation of laterite may assist a search for bauxite; or the study of slopes and drainage systems may guide procedure in sampling for heavy minerals or in geochemical surveys.

An instance of more direct use of air photographs may be cited from former Somaliland Protectorate. Rutile was known to occur in certain quartz veins of the north-east coastal region but, in the reconnaissance survey planned, time was not available to check the whole area. Patches of light-toned quartz float derived from quartz veins were visible on photographs and by arranging traverses to include the more significant of these, cassiterite in exploitable quantity was found, as well as further occurrences of rutile. Cassiterite crystals reaching 65 lbs. in weight were taken in subsequent surface exploitation (Greenwood, 1960).

In suitable terrain, air photographs may give direct evidence of the presence and areal extent of ore (using the term in its widest sense). Thus in Somaliland and South Arabia outcrops of gypsum/anhydrite are shown by light photographic tone and intricately dissected drainage pattern. Salt domes may also be directly located on air photographs, as in South Arabia.

Colour Photographs

Recent advances in the development of improved types of colour film are likely to increase the importance of this medium in mineral exploration. Zones of hydrothermal alteration, or oxidation around orebodies can produce detectable colour anomalies. In Nevada, lead-zinc deposits are known to be associated with zones of manganosiderite discolouration visible on photographs. Uranium fields on the Colorado Plateau cause minor colour anomalies. Jerome (1963), discussing porphyry copper deposits, states that the combination of pyrosomatic alteration and mineralisation effects, after exposure to arid weathering, produces a significant, often very extensive, area of colour anomaly, which however, is not appreciated until viewed on colour air photographs. In southern Arizona several porphyry copper districts show large reddish areas near the orebodies.

Research into the applications of colour photography, and into the use of airborne infrared sensors may help in the problem of rock identification, and thus also in mineral exploration, from the air. Colour photographs have been used as an intermediate product in the process of re-photographing colour film in black and white with the object of enhancing tonal contrasts between selected features. A colorimeter is employed with the colour photographs to obtain data permitting the selection of appropriate film and filter combinations to achieve this. Studies of the spectral zone, including part of the middle infrared band, suggest that rocks and minerals may have characteristic absorption, reflection, and emission spectra in this range.

INTEGRATION OF SURVEY METHODS

The above brief reference to some lines of research gives an indication of the untapped potential of air photographs. Development of this potential is now being promoted by the integration of photogeology with other survey methods. In this connection the integration of photogeology with airborne geophysics deserves note. Complementary data from these sources will often provide satisfactory converging evidence where evidence may otherwise be equivocal: information derived from the combined study exceeds the sum of data obtainable from air photographs or geophysics when studied independently. Domzalski (1963) has discussed the interrelation of photogeological and airborne geophysical methods in a paper drawing attention to evolutionary trends in mineral exploration.

He gave an example of combined interpretation in Ontario where a study of air photographs and aeromagnetic map disclosed an iron formation and the boundary between granitic and metavolcanic rock. In another case a shear zone inferred from photographs and aeromagnetic map was subsequently proved in the field and found to contain disseminated sulphide mineralisation.

A combination of photogeological and airborne geophysical interpretation in Uganda illustrates the use of convergent evidence in deducing structure and giving information of value in mineral exploration. A photogeological interpretation of part of the Karamoja District, which consists of high grade metamorphic rocks, mainly gneisses, distinguished 3 main structural directions, an E-W lithological layering, 'A', a N-S foliation, 'B', and another more strongly expressed foliation direction, 'C', which cuts across the first two. These structural directions can also be recognised and find confirmation on the total magnetic intensity map. Following a study of both geophysical and photogeological data, 'A' was interpreted as a compositional direction, 'B' as an axial planar foliation superimposed upon 'A' by tight folding, and 'C' as a "straightening zone", in which shear folding on vertical axial planes entirely replaced pre-existing structure. This interpretation was confirmed, in essentials, by field examination. Practical aspects of this study include the fact that in the south-west of the area the undisturbed 'A' direction appears to be bedding and may determine the disposition of magnetite-rich layers. This control disappears where the later superimposed 'B' and 'C' directions are dominant. Fieldwork proved that pegmatites are preferentially associated with the 'C' structures. Acknowledgments are due to J.V. Hepworth of Overseas Geological Surveys for this example of combined interpretation.

The successful combination of photogeology with geochemical prospecting in Sierra Leone is worth citing. At the Baomahun prospect, near Bo, geochemical testing for arsenic, as a gold indicator, resulted in the detection of several notable anomalies. Later attempts at large-scale geological mapping were thwarted by slumping and by a thick soil and vegetation cover. In 1962, a study of air photographs showed obvious joints in granite, which continued as fracture traces into adjoining schists and amphibolites. The proven geochemical anomalies lay along the line of these fracture traces and further testing along their continuation proved additional positive anomalies. The work proved that mineralisation is primarily controlled by north-south fractures which, in most cases, were hardly distinguishable on the ground even after location on air photographs. (Personal communication from J. Middleton, Geological Survey, Sierra Leone).

Russian experience in using air photographs for locating kimberlite pipes in Yakutia (Siberian Plateau) raises some interesting points. Attempts to use photographs of 1:60,000 scale failed, mainly because the scale was too small. Photo scales of 1:5,000 and 1:3,000 were also found unsuitable as, at these scales the outlines of the pipes were diffuse and unrecognisable. Finally, by using photographs of 1:15,000 scale and observing relief anomalies and vegetation changes (the ultrabasic rocks here showed thick elder and larch growth in contrast to sparsely covered tundra on carbonate rocks) a number of likely locations were selected for ground geophysical and geobotanical studies, and further pipes were thus discovered. The desirability, in such exploration, of using combined data from air photographs and aeromagnetic survey was stressed (Kobetz and Komarov, 1958).

FURTHER EXAMPLES OF APPLICATIONS TO MINERAL EXPLORATION

The wide range of application of air photographs to economic mineral survey may be emphasised by further examples. Thus, Stephens (1963) has discussed the problem of tracing on air photographs zones of graphitic gneiss in the Lilongwe-Salima area of Central Nyasaland. The gneiss occurs in regionally metamorphosed sediments. It was necessary to establish by field observations that parallel ridges and lineaments seen on photographs represented the strike of the metasedimentary foliation. Field work also established the parallelism of the graphitic beds with foliation. It was then possible to extrapolate between known occurrences of the graphitic gneiss and plot the extent of this on air photographs. Impregnations of iron pyrites in the gneiss resulted in more resistant ridges and variations in photographic tone, thus permitting assessment of the extent of pyritous areas.

The significance of vegetation patterns in photogeological interpretation has already been mentioned. A classic example of this was the discovery of the great magnetite orebody of Cerro Bolivar in Venezuela in 1947, to which a distinctive pattern (copei-tree) on air photographs largely contributed.

FUTURE DEVELOPMENTS

As an extension to the established use of air photographs, the application to mineral exploration of more sophisticated remote sensing systems is a future possibility. Certain types of economic mineral deposits show strong and unique fluorescent properties, which may be exploitable by low altitude twilight reconnaissance, using the appropriate sensor and a strong source of radiant energy. The possibility of using maser devices to excite spectral response in specific materials, e.g. fluorescent minerals, even from aircraft flight altitudes, has also been suggested.

Radar, having the capacity to penetrate vegetation and to record the metallic content of surface and, to some extent, of subsurface materials, may also prove useful as an adjunct to other forms of airborne mineral survey. The amplitude of radar re-radiation may be affected by the heavy metal content of ground surface materials; thus the possibility of detecting buried iron deposits may be inferred.

Another future possibility is thermal mapping from the air. Changes in infrared radiation, related to surface temperature characteristics and to emissivity of surfaces, may be translated into a strip thermal map. Long range detection of hot springs and gaseous emanations would seem to be among the practical applications of this system.

CONCLUSIONS

Although the application of photogeological studies to mineral exploration is widely accepted and practised, there is scope for more comprehensive planning to interknit photogeological work in mineral surveys right from the outset. Especially in less developed regions, planning should aim at continuous, cohesive stages of development, involving inter alia, photogeological reconnaissance and geophysical and geochemical surveys. In view of the present day elaboration and refinement of photogeological techniques, the need to employ specialist photogeologists is emphasised.

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USE OF AERIAL PHOTOGRAPHS IN MINERAL EXPLORATION IN INDIA

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INTRODUCTION

Aerial photographs are extensively used in several branches of learning that are concerned with the study of the surface features of the earth. A three-dimensional view of an area seen on stereo pairs and the exact reproduction of the surface features in terms of tonal differences, provide a wealth of information not obtainable on conventional topographic maps. Study of areas that are remote or inaccessible is greatly aided by aerial photographs.

Geologists have also used aerial photos to advantage in regional mapping, mineral exploration and engineering geology studies. Photogeology, which is concerned with obtaining geological information from aerial photos, has made rapid advances in recent years. The oil geologist initially contributed most towards development of photogeology, later followed by geologists engaged in mineral exploration and regional geological mapping. At the present time, photogeologic studies form an important part of the mineral exploration and mapping programme in several countries.

AIR PHOTO COVERAGE

Aerial photography was initiated in India during the early 1920's and aerial photo coverage on different scales (1.5", 2", and 2.5" to the mile) is now available for over half of the country. Within the next few years, new photo coverage for over 2.7 million sq. km. will be available for geological investigation. Full photo coverage for the entire country is also expected to be available in the near future.

For geological work, vertical air photographs taken from 12,000 or 16,000 ft. with a camera lens focal length 6" or 4 1/2" are used. Scale of photography is generally 2" = 1 mile or 4" = 1 mile. Photo prints in common use are 9 inch square with 60% overlap and 30% sidelap.

Although some sporadic attempts were made earlier, the Geological Survey of India commenced using aerial photos regularly in large scale mapping of mineral belts in 1950. The use of aerial photos in geological mapping has been increasing steadily ever since, and at present almost all mapping of mineral belts is carried out on aerial photos. In 1962-63 an area of 2,000 sq. km. was mapped on aerial photos of 1:32,000 and larger scales in connection with investigation of metalliferous deposits.

METHODS AND PROCEDURES

Aerial photos are generally used for obtaining preliminary geological information over vast areas to help locate target areas for detailed photogeologic studies or ground surveys. Photogeologic maps of selected areas are also prepared, and later checked in the field.

The Geological Survey of India makes use of aerial photographs in a slightly different way. Due to a long record of ancient mining and smelting it is not too difficult to locate suitable target areas for detailed exploration. The Survey, therefore, does not normally undertake photogeologic studies over large areas in order to select target areas.

In several of the mineralised areas, topographic maps of desired scale are not available and in such areas photos are used as base maps to plot geological information in the field. Much of the area where detailed mineral exploration is undertaken is in an Archaean terrain which does not yield much photogeologic information. Therefore, instead of preparing photogeologic maps, a combination of photogeologic interpretation and ground observation is carried on simultaneously in the field.

Photogeologic techniques such as measurement of dips and thickness of beds, and construction of geologic columns are not normally practised as such information is obtained by ground survey in India. The geological information plotted on the photos is transferred to base maps at the end of each working session.

Aerial photographs have proved useful in large scale mapping connected with mineral exploration in the following respects:

(a) Serving as base maps where topographic maps of desired scale and accuracy are not available.

(b) Obtaining geologic information that is sometimes tedious and time-consuming to obtain from topographic maps (e.g. faults, shear zones, lineaments, distinction of key horizons, joint patterns, axial traces and plunge of large folds etc.).
(c) Logistic purposes and location of outcrops, suitable traverse lines, camp sites, ancient mine openings and dumps, slag heaps etc.
(d) Speeding up of mapping progress by on the spot combination of photogeologic interpretation and ground checking.

TERRAIN CONDITIONS

The usefulness of aerial photographs is largely dependent on terrain conditions. Greater amounts of photogeologic information can be obtained from areas underlain by sedimentary rocks than from those underlain by igneous and metamorphic rocks. Although detailed mapping of mineral belts in India is carried out under different terrain conditions, most of it is confined to Archaean basement complex. Moreover, thick tropical vegetation, lack of optimum relief, thick cover of alluvium or deep weathering are factors which tend to decrease the amount of geological information obtainable from aerial photos. In consequence there are limitations to the use of aerial photos in India. Nevertheless, aerial photos have become indispensable for structure studies of the mineralised belts.

PHOTOGEOLOGIC INTERPRETATION

Some of the geological data that Indian geologists have obtained from aerial photos are mentioned below.

Lithology:

Mapping of certain calc-granulite layers and granitic rocks is rendered easy in the central Indian manganese ore belt. Since the ore horizon is stratigraphically controlled, rapid mapping of key horizons using aerial photos was of considerable help. In Rajasthan, where several base metal prospects are being explored, aerial photos provided considerable information due to the arid nature and the relief of the terrain. In these areas, rock units such as quartzite, phyllite and dolomite could be mapped fairly accurately on aerial photos due to their geomorphological, vegetational and tonal differences as observed on aerial photos. Outcrops of ultrabasic rocks, quartzites, grits and lavas were easily recognised and mapped on air photos in the chromite belt of Orissa.

Mapping along strike, tracing of key beds and study of facies change are easily and quickly accomplished in the steeply dipping sedimentary rocks of the lesser Himalayas. Several days of fruitless traversing can be avoided by quick location of outcrops in the vast sand covered areas of Western Rajasthan.

Detailed, large-scale mapping of coalfields was rendered easier and quicker by using photogeologic techniques. Geomorphic features, e.g. low areas, marshy ground, stream patterns; and cultural features, e.g. cultivated or barren areas and distribution of vegetation are easily recognised on photos. This helps in locating and tracing coal seams which do not commonly occur in surface outcrop.

Structure:

Recognition of structural features on aerial photos is simpler than mapping lithologies. Faults, fold axes and plunges of folds are sometimes more easily recognised on air photos than on the ground.

In the subhorizontal Mesozoic strata in Western Rajasthan, recognition of true dip direction is difficult but this can be easily determined from air photos due to vertical exaggeration. Several minor faults that could be missed on the ground are easily picked up due to tonal and vegetational contrasts on aerial photographs. Thus, speed and accuracy were obtained by using photos in the detailed mapping of this area in connection with oil exploration.

Tracing axial planes and determining plunge of folds was much simplified by aerial photos in several base-metal areas of Rajasthan. A large amount of structural data, regional fracture patterns, minor faults etc., was rapidly obtained from air photos in several mineralised areas, e.g. Singhbhum copper belt, Khetri copper belt, gold-bearing areas like Kolar Ramagiri, Wynad etc.

FUTURE DEVELOPMENTS

There will be wider applications of photogeology in mineral exploration in the future. New techniques are being evolved which should help to obtain a greater measure of geological data from aerial photographs.

Colour photography, radar reflection photography and photographs taken with a combination of filters are in the experimental stage and may perhaps become more common in the future. These special types of aerial photos will help distinguish lithologies, locate alteration haloes, and delineate structural features.

As the search for mineral deposits becomes more intensive and extends over geologically little known areas, aerial photos will play an increasingly important role in selecting the more favourable parts of vast unexplored regions. This will involve small scale, high altitude photographs from which broad structural trends, lineaments and lithologies can be observed. This is now practised by several oil companies but will extend gradually to exploration in other fields. Aerial photo studies in the Himalayan terrain will be of great help when adequate coverage becomes available.

Aerial photos are perhaps not utilised to the full extent possible in regional water resources studies. A large amount of basic data on aquifers, surface water features etc. could be obtained from them. Geologists engaged in this field would find it helpful to obtain basic data from aerial photographs. Geobotanical studies such as recognition of phreatophytes or other vegetation that reflects surface or subsurface moisture content would also help in water resources assessment.

The field geologist of the future will depend to a greater extent on data obtained from aerial photos. Hence, sound training in photogeologic techniques has assumed vital importance, particularly in under-developed countries. Training facilities are offered by the U.S.G.S., the Dutch International Centre and other organisations. Proposals to start a training centre in India are presently being examined.

Training in photogeology does not require very expensive equipment and most geologists could profit greatly by a short basic course. Facilities for photogeologic training of a large number of geologists from the under-developed countries should be instituted in order to expedite geological mapping and mineral exploration programmes. Photogeology has come of age and its importance in geologic investigations cannot be over emphasised.

THE DEVELOPMENT OF GEOCHEMISTRY IN THE BUREAU OF MINERAL RESOURCES, AUSTRALIA

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Geochemical prospecting was first introduced into Australia by Dr. V.P. Sokoloff of the United States Geological Survey in 1947 and has been a function of the Bureau on a continuing and growing basis since that time. Present efforts in this regard cannot be compared with those of the past because staff availability and experience, techniques, instrumentation and policy have all changed: it is sufficient to say that in the Bureau, geochemistry received its first major impetus during the uranium boom, and later in prospecting for copper, lead, and zinc, using standard dithizone and biquinoline methods. Surveys were carried out in a number of areas including Rum Jungle, South Alligator River, Tennant Creek, Mt. Isa-Cloncurry, North Queensland, and Captains Flat.

As a result of the phosphate discovery at Rum Jungle in 1961, it became abundantly clear that many more elements needed to be analysed to reduce the risk of missing deposits of minerals other than those being directly searched for; and also that provision needed to be made for a large increase in the number of samples handled per annum. About this time the Bureau changed over from largely wet to largely spectrographic analyses; and a decision was taken to reorganize and modernize the Laboratory instrumentation, data processing, methods of presentation of results, coordination and interpretation.

This reorganization has been underway for 3 years and is now nearly completed. Trial runs to test sample and data handling procedures, flow of samples through various work areas, and instrumentation are in progress. The emphasis is now on spectrographic techniques; but standard wet techniques will continue to be used where applicable.

Geochemistry is not confined to geochemical prospecting, and due attention has been given to other aspects, e.g., silicate analyses, age determination studies, adsorption phenomena, formation of minerals, etc. The scope of the new system is outlined in the attached flow sheet.

The main basic requirements that had to be satisfied were:

(1) For geochemical prospecting, the facilities must cope with a very large throughput of samples and be capable of multi-element studies for orientation work, and analyses must be cheap.

(2) The analytical scheme must be capable of high levels of accuracy where necessary, particularly where there is a petrological bias.

(3) Data processing techniques had to be developed to handle the expected volume of analytical information.

These requirements posed many problems. The basic equipment had been purchased and as it was clear that different techniques were necessary to attain the desired level of precision for different elements, a battery of equipment was necessary.

Table 1 lists the equipment that is now installed and summarizes the main functions and capacity of each instrument. The number of samples quoted is only an estimate as much of the equipment is still being calibrated and staff training is still in progress. A major problem has been, and to some extent still is, the acquisition of suitable standards.

The end-product, it is hoped, will be a facility for analysing silicate materials in quantity for up to 50 elements, and for the most part operated by non-professional assistants. The effective increase in staff required is negligible, although a more formal status for the current structure of the laboratory organization at the non-professional level is being sought.

It is too early to estimate when the whole system will be fully operative and working on a routine basis, although the Automatic X-ray line is now fully operational for analyses of igneous rocks (ultrabasic to acid), but to shorten the working-up period meaningful samples were obtained on which the trial runs could be carried out. Three main projects were therefore initiated and those were chosen to allow a full trial of the different lines, sampling procedures, and data processing system.

Table 1

Equipment available in B.M.R. Geological Laboratory for Geochemical Studies

Automatic X-ray Spectrograph	Manual X-ray Spectrograph	Direct-Reading Optical Spectrograph	Photographic Quartz Spectrograph	Atomic Absorption Spectro-photometer	Miscellaneous-Polarograph, Flame Photo-meter etc.	X-ray Diffract-ion	Optical Equip-ment	12" Nuclide Mass Spectrometer	Ancillary Equipment
Capacity Samples per annum									
5,000	5,000	20,000	8,000	10,000	Variable	3,000		Not yet known	
Note: Some samples are duplicated on different analytical lines									
Application on present analytical scheme									
Silicate and mineral analysis for up to 15 elements. Trace and minor element analysis. Petrological and mineralogical research.	One or two element assays, Sr/Rb ratios for age determination. Comprehensive qualitative analysis.	Comprehensive trace and minor element analysis for up to 33 elements per sample. Mineral-ogical research.	Trace element analysis for up to 10 elements. Qualitative analysis covering 50 elements. Geochemical prospecting and research.	Determination of total metal content or fraction-ation according to the nature of bonding. Geochemical prospecting and research.	Alkali metal determinations. Phosphate investigations. Research and miscellaneous work.	Mineral identi-fication.	General petro-logical and minera-graphic equip-ment.	Rb/Sr K/Ar, lead isotope determination for dating rocks and minerals.	A range of crushing and fine grinding equipment starting from 4" jaw crushers and including swing mills, roll mills, vibratory mills, mechanical mortar and pestle, balances, sizing, digesting and extraction equipment etc.

(1) Direct-Reading Optical Spectrograph.

In cooperation with Mt. Isa Mines Ltd., more than 5,000 samples were collected by auger drill on a surveyed grid over the Urquhart Shale and adjacent formations. Seventy selected samples were quantitatively analysed by a 3-metre grating spectrograph for 33 elements; they constitute the "standards" for the remainder. The mineralogy of the sediments is being studied by M.I.M. in an attempt to elucidate the broad trace element assemblages, and this information will be used in processing the results of the main analytical work through a computer and auto plotter.

Most of the calibration and development of instrumental techniques are being carried out by Bureau officers; but we have hired consultants to assist with the direct-reading optical spectrograph, and to further develop the techniques for analysis of specific elements such as Hg and Te by atomic absorption spectrometry.

(2) Atomic Absorption Spectrophotometer.

Kalgoorlie was chosen as a suitable area for developing aspects of this technique. Work is in progress on analytical levels for Hg using single beam equipment, so far with encouraging preliminary results. Other techniques will be used or tried for other elements, e.g. Ag by optical spectroscopy, As by the Gutzeit technique or by X-ray. Western Mining Corporation generously provided an excellent suite of samples for a trace element halo study at Kalgoorlie. Great Boulder and Lake View and Star Gold Mining Companies have agreed to cooperate in this project. Standards again present a problem.

(3) Automatic X-ray Spectrograph.

This equipment will be used for a variety of tasks, the first of which is silicate analyses of rocks. These currently cost £33 per analysis by wet methods and if the development of the W1 and G1 standards can be used as a guide, single analyses are at least suspect. It is hoped to achieve higher accuracy by X-ray, and, using an internal standard, a constant check can be kept on precision levels. Age determination samples are being used for the trial runs and so far these runs have been encouraging.

The equipment analyses four samples at a time (three unknowns and one standard), and a complete analysis (apart from FeO, which has to be done by other methods) can be carried out in an average time of 25 minutes. The operation is largely automatic and can be performed by a laboratory assistant under normal supervision; so there is reason to hope that the cost of silicate analyses can be reduced to a fraction of present costs. Such analyses will inevitably become far more common than they are at present. A computer has already been successfully used for calculating norms.

The geochemical aspects of petrology will undoubtedly assume increasing importance; and more instrument time is now available on the manual X-ray and optical equipment, which in turn will result in increased use of these lines by mineralogists and chemists. On the age determination side, the Bureau Nuclide machine is now operative and has added considerable additional capacity to the A.N.U. geochronological laboratory, with whom the Bureau works in close cooperation. Three Bureau geologists work full-time in this laboratory, and a fourth geologist and two assistants in the Bureau laboratory on sample preparation, petrology, indexing, etc., of age determination samples.

It is part of Bureau policy to promote and develop geochemical prospecting and other aspects of geochemistry in Australia by research into techniques and analytical procedures, giving advice and assistance to mining companies, sponsoring exploration projects, and carrying out original investigations of a detailed or regional character. Mining companies have shown a great deal of interest in our new facility, not only in the instruments but also in the data processing procedures. It is not our policy to undertake custom work (in fact we send many thousands of our own samples from routine surveys to A.M.D.L. for analysis each year), but it will be within our capacity, and in the public interest, to give specialist advice and carry out multi-element analyses on samples collected in orientation surveys. Companies are undertaking many more geochemical surveys: major programmes are under way at present by Pickands Mather, Electrolytic Zinc, New Consolidated Goldfields, C.R.A., Noranda, and Australian Selection Trust in particular. By undertaking orientation work we think we can make the best use of our multi-element analytical equipment, gather a lot of otherwise inaccessible information from companies, and build up a store of information which will be of considerable future value. Also, such assistance should help to ensure that metals of present or potential value are not overlooked.

Four aspects of geochemical prospecting are either under study or being considered for study.

(1) The problem of distinguishing anomalies caused by adsorbed metal ions and those caused by total metal content of stream sediment and soil samples. This is a very real problem in arid environments and its solution could affect the style of geochemical work carried out by mining companies, mostly in regard to analytical techniques.

(2) Trace element halos around known orebodies. These require very precise analytical work and this in itself necessitates a good deal of research, particularly with the more difficult elements such as Hg, Pt, Se, As, etc. This type of information is essential to the understanding of geochemical anomalies in any metalliferous province. There will never be a simple answer, and each province will require its own study on a number of elements.

(3) Orientation surveys. We wish to establish a routine for this type of work. The trace element halo studies form part of orientation work.

(4) Regional geochemical surveys. These require good geological control to be most effective; for instance, the sampling interval is dependent to a marked extent on source-rock type as well as on drainage characteristics. In 1964, four groups were engaged on regional sampling - two in Queensland, one in Papua, and one in Central Australia. Except for Papua the work is regarded as partly experimental. We are trying to find the best sampling techniques in a variety of environments, the optimum staff, best means of transport, sample registration, type of sample bag, etc. This information will allow us to estimate how many samples can be collected per annum; and to balance more effectively the field work against the capacity of the Laboratory and the Transit Room to handle the samples.

The ultimate aim of the regional work is the production of metallogenetic and trace element distribution maps at 1:250,000 and 1:50,000 scale to complement the geological and geophysical maps already being produced. We have not yet decided on the form such maps will take, and in fact cannot do so until a good deal more work has been done.

The main task at present is to solve the problems which still remain on the analytical side. Staff need further training in the use of data storage retrieval and processing and sampling techniques. In this regard, a number of Bureau officers have attended IBM courses in Fortran and the 870 Document Writer system, and a Record on geochemical sampling procedures has been compiled and distributed to Party Leaders. This Record is currently being reviewed to bring it up to date with changes in the Registered Number system and other aspects which have been modified as a result of the 1964 trial surveys.

Apart from research and planning and trial surveys to gear future work to the new analytical and data processing systems, the Bureau has continued with geochemical surveys, mainly in the Northern Territory. An intensive six-element geochemical survey at Rum Jungle using contractors and the B.M.R. Gemco auger drill to collect samples has recently been completed. A large part of the prospective area within the Hundred of Goyder has now been sampled and a number of anomalies outlined. Similar surveys using 3 inch auger drills have been carried out at McArthur River and Tennant Creek, and a detailed soil sampling and regional stream sediment survey on the Port Moresby - Rigo area in Papua. Except for the Papuan work, these surveys were routine and followed a pattern established by previous work. In previous years all the samples were analysed in the Bureau laboratory. In 1964 all were sent to A.M.D.L. except those from Papua. Sample intake in 1964 is about 25,000, and the eventual intake could be as high as 40,000, involving between 400,000 and 500,000 element analyses per annum.

A COMPARISON OF THREE AIRBORNE ELECTROMAGNETIC METHODS OF MINERAL PROSPECTING - RESULTS OF TEST SURVEYS IN EAST AFRICA

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INTRODUCTION

This account is a summary of a much longer paper under the same authorship which is to be published by Overseas Geological Surveys as the second of a series of occasional papers on Geophysical topics.[1] Only the main conclusions on three airborne systems of electromagnetic survey are presented here. For a discussion of the theoretical principles involved and a fuller account of both aerial and ground surveys, the reader is referred to the main paper.

The recent attainment of political independence by many underdeveloped countries, particularly in Africa and Asia, has led to the need for reasonably swift appraisals of the economic value of their natural resources and one aspect of this is the necessity for quick, efficient and economic methods of mineral exploration. One of the most efficient approaches is the use of airborne methods and there are now several different techniques which can be applied to the search for minerals. These are the magnetic, electromagnetic and radiometric techniques, and in the direct search for sulphide orebodies, the electromagnetic (EM) methods are most useful. In the EM method, a primary alternating magnetic field, normally produced by an alternating current in a transmitter coil, induces eddy currents in nearby conductive material. These currents give rise to a secondary magnetic field which is investigated by a receiver coil. The manner in which the secondary field changes as the coils are traversed across a conductor can, to a limited extent, be interpreted in terms of the geometry and conductivity of the conductive body. Sulphide bodies usually occur as steeply dipping lenses or sheets, and if sufficiently massive form good electrical conductors; this is particularly so for deposits of pyrite, pyrrhotite and chalcopyrite and airborne EM systems have been successfully employed in the direct search for

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[1] Makowiecki, L.Z., King, A.J. and Cratchley, C.R. "A comparison of selected geophysical methods in mineral exploration - Results of an aerial and ground survey in East Africa" (In the press.) Occasional paper No. 2 Geophysical Division, Overseas Geological Surveys.

these deposits, particularly in Scandinavia and Canada. Most of the newly independent countries are in tropical areas, however, where deep weathering is likely to create practical difficulties for conducting EM surveys because of: a) the greater depth of burial of conductive orebodies which leads to small responses, and b) the variable thickness and conductivity of the weathered zone itself which creates "noisy" records and thus obscures possibly important anomalies.

Because of these considerations and the claims made as to the efficiency of various methods in overcoming such difficulties, Overseas Geological Surveys commissioned three contractors to carry out surveys with three different EM systems over the same areas of known mineralisation in East Africa, so that a direct comparison could be made, particularly in terms of their responses to conductive surface layers and their effective depth penetration. Other naturally occurring features form electrical conductors, the main ones being fault zones, lithological contacts and graphite bands, and it is clearly desirable that some form of discrimination against these non-economic types of conductor should be attainable. It is also desirable to have a system in which the resolution and accuracy of location are high. The main points which the three chosen methods were tested on were therefore:

a) freedom from response due to conductive surface layers,
b) effective depth penetration (i.e. maximum depth to the top of a detectable conductor),
c) discrimination against non-economic types of conductor,
d) resolution and accuracy of location,
e) ease of operation.

THE METHODS EMPLOYED

The airborne EM systems used in the surveys were: 1) the Rotary field method, 2) the Rio-Mullard method, 3) the Afmag method.

1). Rotary field method

In this method an attempt to obtain greater depth penetration has been made by using two aircraft and so increasing the separation of the transmitter and receiver coils. The leading aircraft carries the receiving coils (one horizontal and one vertical) in a towed bird. The transmitting coils (mutually perpendicular and at 45° to the horizontal) are carried in the trailing aircraft and the axes of intersection of the two sets of coils must be kept colinear during flight. The coil separation is 800 feet, the operating frequency 800 c.p.s. and the flying height (coils) 240 feet above ground. The instrument records the in-phase (R) and quadrature components (Q) of the secondary magnetic field in percent of the primary field as a continuous trace during flight. Increased depth penetration and freedom from the effects of surface conductivity are claimed for the method. It is also theoretically possible to determine the direction of both strike and dip from an anomaly on a single flight line (Tornqvist, 1958; Hedstrom and Parasnis, 1958 and 1959).

2). Rio-Mullard method

The receiver and transmitter coils are mounted in pods at the wing tips, 82.5 feet apart with their axes horizontal and parallel to the fuselage. Variations in the relative coil geometry are minimised but the small coil separation leads to a small depth of penetration. To off-set this, the instrumental sensitivity is very high and instrumental noise has been reduced to a minimum. The operating frequency is 320 c.p.s. and the flying height 250 feet above ground. The in-phase (R) and quadrature (Q) components of the secondary field are recorded in parts per million (ppm) of the primary field (Boyd and Roberts, 1961).

3). Afmag method

This method utilises a receiver unit only in the aircraft. The source of energy is that provided by distant thunderstorm activity which creates a horizontally polarised alternating magnetic field of audio-frequency. In the vicinity of a conductive body, the direction of polarisation becomes tilted from the horizontal. The angle of tilt of the natural field is measured in degrees by two mutually perpendicular coils, with their axes at 45° to the horizontal and in a vertical plane which also contains the flight direction. The coils are mounted in a bird at the end of a 200 ft. cable. Recording is made at two frequencies - 90 and 340 c.p.s. and the flying height (coils) is 350 feet above ground. Because the transmitter - receiver separation is effectively infinite in this method, great depth penetration has been claimed (Ward, 1959).

The method suffers from the disadvantage that the Afmag field strength is only sufficiently high at certain periods of the day and for certain parts of the year. In East Africa, the optimum periods for recording are from about 2 pm to 7 pm and during the wet seasons.

The types of anomalies recorded by the different methods over a steeply dipping conductor are illustrated in fig. 7. A measure of conductivity of the body is given by the ratio of in-phase to quadrature (R/Q) response in the Rio-Mullard and Rotary Field methods and by the ratio of tilt angles measured at low frequency and high frequency (LF/HF) in the Afmag method. In both cases high ratios are indicative of good conductors. The LF/HF ratio is theoretically unity for an excellent conductor, but ratios greater than 1 can occur in areas of high surface conductivity where the HF response from a buried vertical conductor is attenuated by the surface layer.

In addition to these EM systems, readings of total magnetic field were recorded with a Gulf flux-gate magnetometer mounted in the rear of the aircraft carrying the Rio-Mullard equipment. A Lundberg vertical component magnetometer was carried with the Rotary field equipment.

THE AREAS SELECTED FOR THE SURVEYS

The areas chosen had to satisfy the following conditions: they should be typical of a tropical area; they should be areas of mineralisation in which the geology was fairly well known; the terrain should be rugged in order to test practical aspects of the flying and facilities should exist for local liaison and as a base for subsequent ground work. The two areas are shown in fig. 1 and lie close to Lake Victoria. The Geita area in Tanganyika is a known gold field with one producing mine in the northern part of the area and some small workings in the southern part. The Migori Gold belt in Kenya is a long narrow strip of gold-bearing rocks with a copper mine (Macalder) at its western end and a small gold mine at the eastern end. Small gold occurrences have been worked at various localities in the past.

GEOLOGY AND MINERALISATION

The rocks of the two areas are similar to one another, to those in other areas of gold-bearing rocks in East Africa and to the mineral bearing "greenstone" formations of Canada. Both comprise huge "rafts" of metasedimentary and metavolcanic rocks of Nyanzian (Pre-Cambrian) age enclosed in batholiths of granite. At Geita, the Nyanzian rocks occur in a northern and southern belt with a large area underlain by granite between them. The main formations are a series of metavolcanic rocks and schists and a banded ironstone suite which contains intercalated layers of tuff and porphyry, all with a regional E-W strike. The banded ironstone proper is responsible for the striking ridges in the northern part of the Geita area which are up to 1,000 feet above the surrounding country. All the rock units are strongly folded and steeply dipping. A similar series of steeply dipping rocks occurs in the Migori belt, although shales and greywackes are more common than at Geita. The regional strike is WNW-ESE, parallel to the trend of the belt itself. There the banded ironstone member is generally more cherty, contains less iron and is less resistant than at Geita, although it forms distinctive ridges at the eastern end of the Migori belt. Also of importance here is dioritic porphyrite, a large intrusive mass of post-Nyanzian age, which lies to the north of the narrow belt of Nyanzian rocks.

The intrusive rocks include granites of two ages, of which Shackleton (1946) considers the earlier to be responsible for mineralisation in the Migori area, and two ages of dolerite dykes. More recent deposits of Neogene age include alluvium which probably attains considerable thickness in the lower courses of rivers which flow into Lake Victoria, laterite and eluvial deposits. Pale sandy soils tend to be found over the granite and red, lateritic soils over the Nyanzian rocks.

The economic forms of mineralisation consist of the following:

a) auriferous sulphide replacement bodies (pyrite-pyrrhotite-chalcopyrite). These are known in the Northern Nyanzian belt at Geita. The Macalder orebody is also a sulphide replacement.

b) auriferous sulphide impregnations (pyrite-pyrrhotite)

c) quartz reefs which carry gold and some sulphide (pyrite-arsenopyrite).

The last two categories are the commonest forms of mineralisation, particularly in Migori and the Geita southern belt.

These deposits occur much more frequently in the more friable lithological horizons, particularly the banded ironstone, tuffs and shales.

THE GEOPHYSICAL SURVEYS

a). Aerial Surveys

The only significant difference in the operating conditions of the three surveys was the time of year. The Rotary method was flown during June, July and August, 1959, i.e. the dry season, when there is a minimum interference from electrical noise. The Mullard survey was carried out in December 1959-January 1960 when the level of storm activity was moderately high, and the Afmag survey was flown during the rainy season, February and March, 1960, with a high level of storm activity. The flight direction was perpendicular to the regional strike in both areas, i.e. N-S at Geita and NNE-SSW at Migori. Over most of the areas, flight line spacing was 1/4 mile, increasing to 1/2 mile over the section of less potential interest at Migori and to 2 miles over the large area of granite in the central belt of the Geita area. The Mullard and Afmag contractors employed strip film for subsequent location of flight line traces on aerial photograph mosaics. In the Rotary method, the path was plotted during flight by the navigator who also marked the control fiducials on the record. The lack of identifiable features meant that control was less than desirable and clearly this affected the accuracy of location of anomalies in all three methods.

Over most of the areas flown, the relief was sufficiently gentle to allow the aircraft to keep a constant height above ground within the tolerance limits. In the northern Nyanzian belt at Geita, however, the slopes of the banded ironstone hills reach 35° and the aircraft were not capable of achieving the required 20° angle of climb (to keep within the specified limits). The two Rotary field aircraft were at a serious disadvantage here as they had to break away from the flight path at the foot of the slope in order to turn and climb sufficiently to allow them to dive back on to course with enough speed to carry them up and over the hills. This led to breaks in the record at important points (i.e. near the granite-Nyanzian boundary), and loss of accuracy in location and in positioning of the two aircraft relative to one another.

The three contractors were required to provide all the original records, a photomosaic showing flight paths with fiducial points, and a map with the anomalies plotted in the form usually used by the particular company. No interpretations were called for but each company produced a report which included, with varying detail, a general assessment of the more important anomalies. Although taking note of the companies' assessments, the authors have continually referred to original records in comparing the three systems.

b). Ground Surveys

Ground surveys were carried out by the three authors at sites where more important aerial anomalies had been recorded. The instruments used were the EM gun, ground Afmag, vertical component magnetometer, gravity meter and SP equipment. Depth estimates were made of the conductive bodies located and a limited amount of subsequent pitting and drilling largely confirmed these estimates.

ASSESSMENT OF THE AIRBORNE METHODS

From a comparison between the aerial responses and the subsequent ground results, and from a consideration of the aerial results themselves, the three methods have been assessed as follows.

a). Response Due to Conductive Surface Layers

In the two areas investigated, flat-lying surface conductors are represented by lake bottom deposits, alluvium in river valleys and around the lake shore and the decomposed zone which overlies the solid rock from which it is derived. These features are considered fairly typical of tropical areas. The responses by the airborne methods over such features are illustrated in fig. 2 for three flight lines which were almost coincident. The Mullard trace is relatively little affected and the picking of vertical conductor type anomalies is not excluded. Afmag responses tend to be confined to the edges of flat lying conductors and so long as steeply dipping conductors beneath the surface layer are located away from the edges of the sheet, there should be no undue difficulty in detecting the anomalies. The Rotary responses, however, have been markedly affected and show a general "base shift" of both R and Q components together with strong fluctuations which are difficult to interpret as other than "geological noise".

Similar conclusions are drawn from figs. 3a, 3b, 3c, which show responses over part of the southern Nyanzian belt at Geita. There the surface conductor is probably the decomposed zone of Nyanzian rocks.

The extreme variations on the Rotary records, particularly the in-phase results, almost eliminate the possibility of picking out anomalies which might be caused by steeply dipping bodies, while the other two methods are relatively little affected. One important point, however, is that the Afmag anomaly recorded over a short horizontal conductor (such as a fairly narrow alluvial-filled valley) is indistinguishable from that due to a steeply dipping body so that confusion between the two could arise.

b). Effective Depth Penetration

The maximum depth to the top of a detectable, steeply-dipping conducting sheet is determined by two factors i) the noise level which determines the minimum recognisable anomaly and ii) the rate of decrease of anomaly amplitude with height. From the previous section it is clear that the noise level, at any rate in the areas studied, is largely determined by the presence and variability of surface conductive layers. Other contributors are instrumental noise, atmospheric noise and spurious signals caused by changes in the geometry of the coil system during flight. In the case of the Rotary Field system, the latter factor combined with the presence of high surface conductivity appears to produce the high noise levels observed on the records obtained over alluvium and over the southern Nyanzian belt at Geita. Even over the granite areas, the noise-level is about 4% in-phase (fig. 3a) which greatly exceeds that in the example given by Tornqvist (1958) over obviously non-conductive ground in Sweden. This noise-level of 4% means that the minimum recognisable anomaly is about 8% in-phase, corresponding to a conductor at about 400 feet below the aircraft (see fig. 4 which shows the results of a model experiment over a conductor of infinite strike length). For the normally employed flying height of 250 ft., a conductor at depth greater than 150 ft. below ground would not be detected. The Mullard method has a relatively low noise-level and even over highly conductive ground, variations due to this rarely exceed about 60 ppm. The normal noise-level is about 40 ppm, so that for a minimum recognisable anomaly of 80 ppm, fig. 5 indicates a maximum depth penetration of about 350 feet below the aircraft or 100 feet below ground for a normal flying height of 250 feet. (Note that the results in fig. 5 were obtained over a body of limited strike length; over one of infinite strike length, the penetration would exceed this figure.)

The depth penetration claimed for the Afmag method greatly exceeds that of the other two methods (Ward, 1959). Fig. 6 shows records taken during flights at different altitudes over a long linear sulphide body in Canada. Anomalies at both frequencies are clearly recognisable at 1,500 feet, equivalent to an orebody buried at a depth of 1,000 feet below ground. The amplitude is approximately inversely proportional to height as predicted by theory. For conductors approaching a more spherical shape, the fall-off should be governed by an inverse cube law and hence a conductive lens of about 1/4 mile in strike length would not be detectable at depth of greater than 1,000 feet below the aircraft. This has apparently been borne out by experimental evidence (Ward, 1959). It appears therefore that the Afmag method should be capable of detecting a conductor of reasonable size (greater than 1/4 mile in strike length) which occurs at a depth of about 600 feet below ground.

The only practical test of depth penetration achieved during these surveys is illustrated in fig. 7. The double conductive sulphide body was traced on the ground by EM methods and confirmed by drilling. At its extreme western end it lies at a depth of 100 feet. The Rotary method failed to show a significant anomaly at this point (Line 41) as did the Mullard method on line 45, a little to the west of the proved conductor. The Afmag record (Line 51) shows a significant anomaly. This confirms qualitatively the superior penetration of the Afmag method.

c). Discrimination Against Non-Economic Conductors

Non-economic conductors are of two main types: i) flat-lying surface deposits, ii) steeply-dipping geological conductors including graphite layers and electrolytic conductors contained in faults, shear zones and lithological contacts.

The effect of surface conductivity has been dealt with above. It causes noisy records, is most marked in the case of the Rotary field method and probably least marked in the case of the Rio-Mullard method. Possible confusion could also arise in all three methods between anomalies caused by short surface conductors or their edges, and anomalies caused by steeply dipping bodies. The Afmag method is possibly the worst offender in this respect.

Geological conductors have electrical properties which overlap those of sulphide bodies so that complete discrimination against these non-economic conductors is impossible to achieve. The only criteria which can be adopted are the conductivity and geological environment of the body. Geological conductors tend to have poorer conductivities than sulphide ore-bodies, they also tend to have greater strike length so that long linear bodies of poor conductivity can often be interpreted as geological. In this respect there is little to choose between the three methods although the in-phase/quadrature ratios obtained from the Mullard and Rotary methods probably give a better indication of conductivity than the LF/HF ratios of the Afmag method and consequently, the Afmag anomalies tend to be less diagnostic than the others. On the other hand, the Afmag method was particularly good at detecting long zones of relatively poor conductivity, most reasonably ascribed to faults which could have had a structural control on the mineralising fluids prior to deposition.

d). Resolution and Accuracy of Location

The relative resolution of the three methods was well shown at three of the sites investigated during the ground survey. Fig. 7 illustrates one of the sites and it is clear that the Mullard method has a marked ability to resolve closely spaced shallow conductors, in this case 400 feet apart. The limit on the differentiation of two parallel bands for the Rotary method is greater than 1,000 feet. The Afmag method was least able to discriminate between closely spaced conductors.

Accuracy of location is mainly dependent on the navigational accuracy which is entirely independent of the particular EM system adopted. However, the large coil separation in the Rotary method and the fairly great width of the Afmag anomaly with consequent doubt as to its exact centre lead to greater inaccuracies of location than does the Mullard system with its wing-tip mounted coils. Some idea of the relative accuracy of location is also illustrated in Fig. 7.

e). Ease of Operation

It is considered that the two-plane Rotary field method was least successful in coping with the sharp topography of the northern Nyanzian belt. The other two methods operated successfully in conditions which might have been considered unsuitable for airborne prospecting with fixed-wing aircraft.

The Afmag method could only be operated for a maximum period of about 5 hours during any one day when the natural field strength was sufficiently high and this might be classed a disadvantage, although in practice the number of daily flying hours logged by the other operating companies were rather similar to this figure.

CONCLUSIONS

The following conclusions regarding the three airborne methods have been drawn from the aerial results and the subsequent ground surveys and drilling carried out in the two areas described. They are considered to be applicable to most tropical areas.

1. The Rotary Field Method

This method, although theoretically capable of increased depth penetration by virtue of the large coil separation, and of producing anomalies which can be interpreted in terms of depth, conductivity and strike direction of a body, suffers from serious practical defects. The most important of these is the high noise level caused by surface conductivity, probably rendered more serious by relative movements of the transmitter and receiver coil systems (inevitable in a two plane system) which results in the effective depth penetration being drastically reduced. Flying in areas of marked topographic relief results in difficulties because of both inability to maintain co-axiality of the two coil systems and inability to keep within tolerance limits of constant ground clearance. The method is judged to be unsuitable for areas of marked topographic relief and areas underlain by highly conductive superficial deposits and weathered material which are common in the tropics. Over areas of flat topography and where conductive overburden is not a problem, the method should give more diagnostic information than either of the other two methods; such appears to be the case in parts of Scandinavia and may also be true in Canada.

2. The Rio-Mullard Method

Although limited in its depth penetration by a small coil separation, this method's high sensitivity and lack of response from surface conductors (due mainly to its fairly low operating frequency and the vertical disposition of the coils) resulted in the system achieving a penetration comparable with the Rotary field method in the two areas surveyed. The arrangement of the coils in a line perpendicular to the direction of flight results in a greater degree of resolution and greater accuracy of location. Discrimination against non-economic conductors appeared to be better in this method than in either of the other two. It would be most useful where ore deposits are likely to be at shallow depth and over areas of shallow conductive alluvium which does not exceed 100 feet in thickness.

3. The Afmag Method

This method has a definitely superior depth penetration which results from an effectively infinite "transmitter - receiver" spacing. At the same time, the large volume of ground "sampled" results in lack of resolution and discrimination and the possibility of missing small but perhaps important conductors. The method is particularly effective in delineating long, poorly conductive fault and shear zones and these can have an important bearing on the structural control of ore deposits.

The method should find its greatest application in areas of rugged topography and where ore deposits are likely to occur at depth. It would be important, however, to ensure that adequate natural field strengths exist in the areas of proposed surveys.

ACKNOWLEDGMENTS

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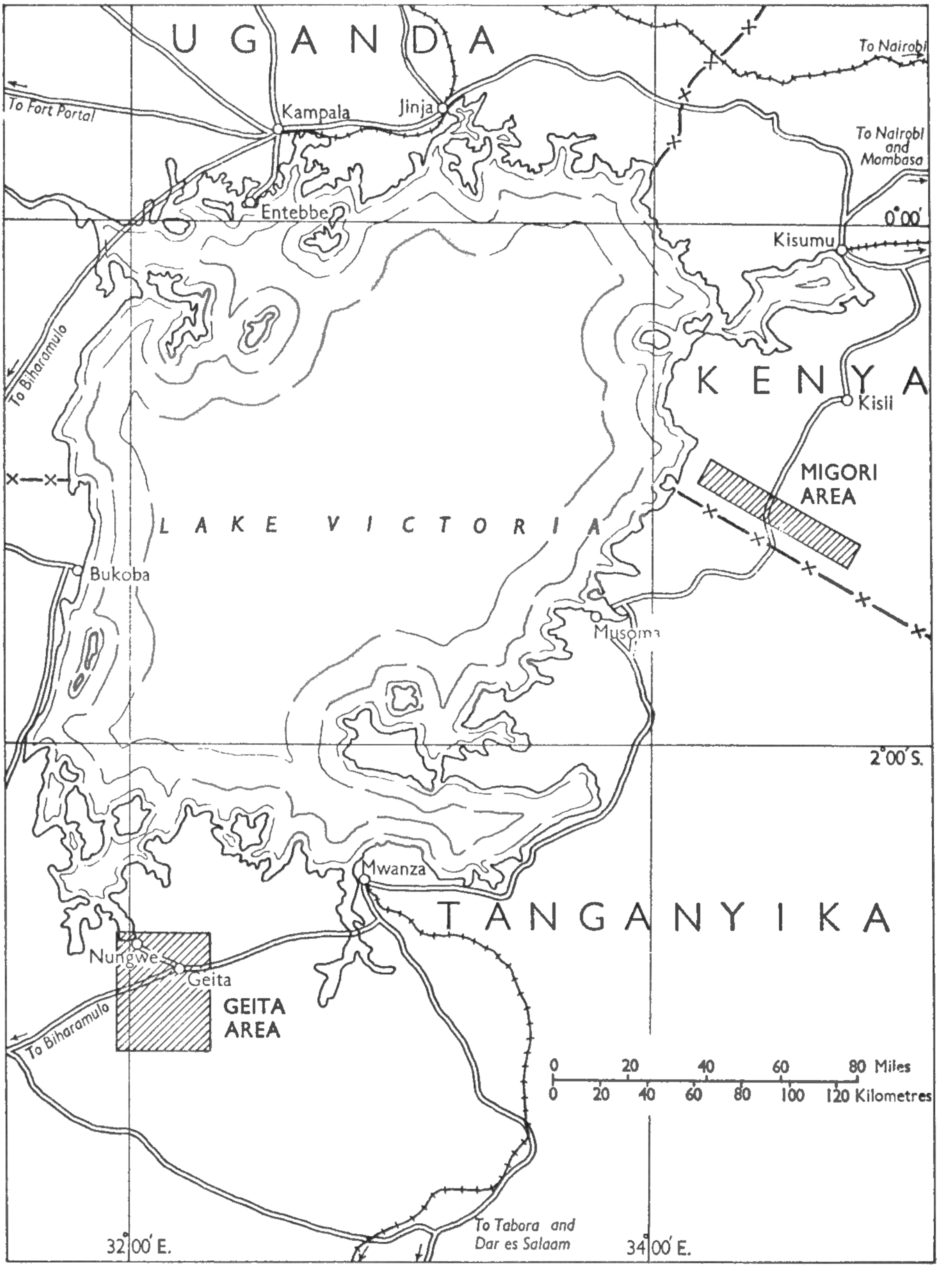

Fig.1 The Geita and Migori Test Areas

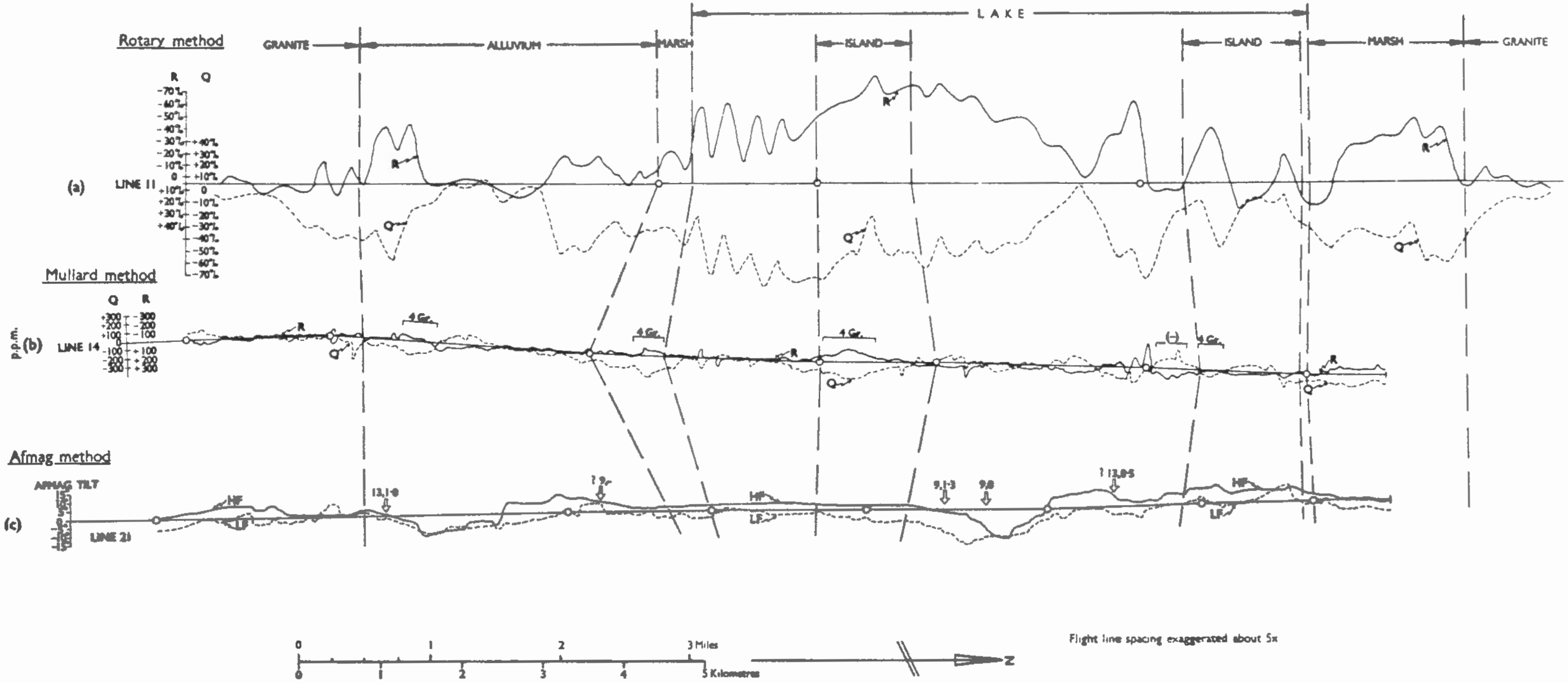

Fig. 2 Aerial Responses over lake, marsh, alluvium, Geita

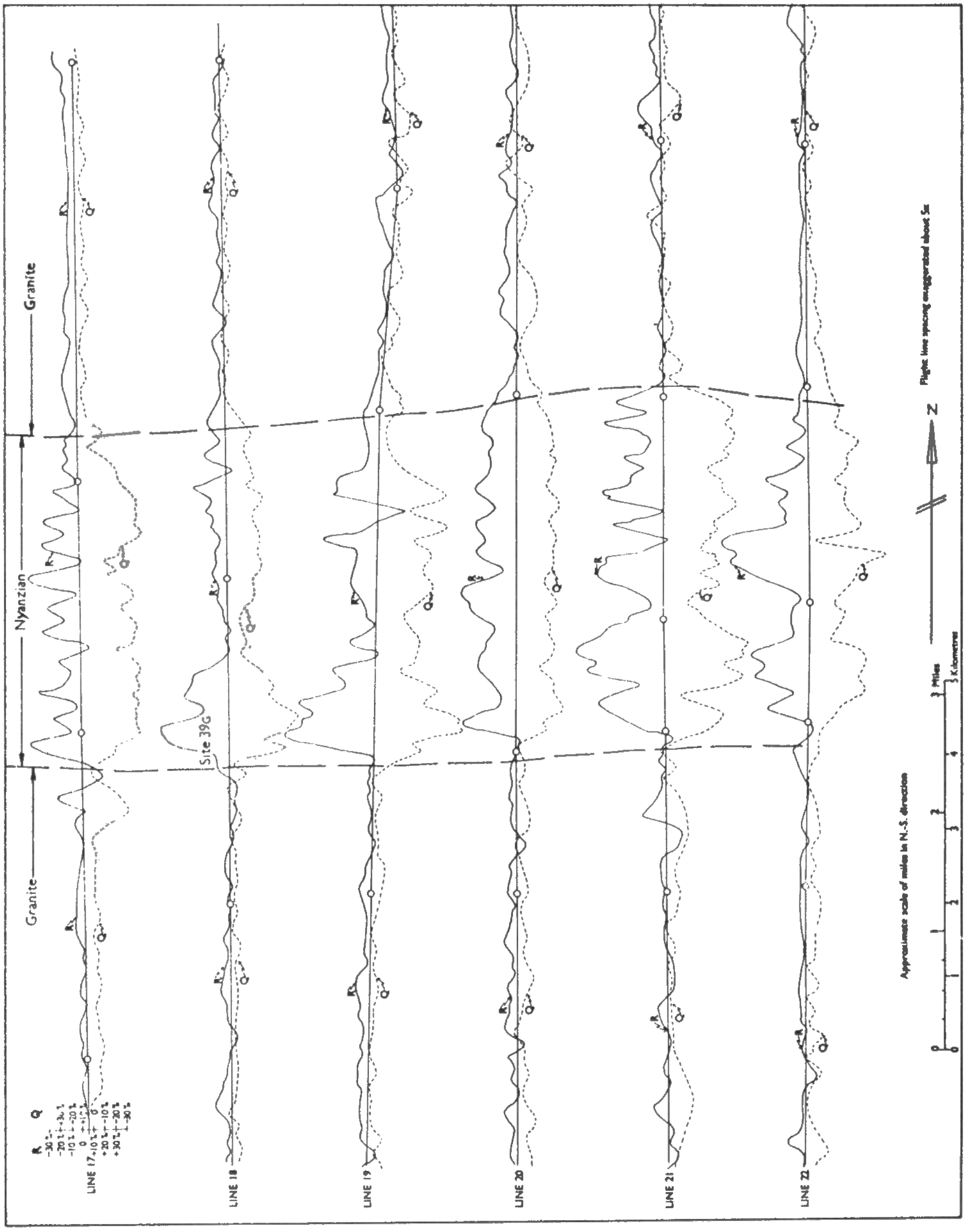

Fig. 3a Rotary Field responses over southern Nyanzian belt, Geita

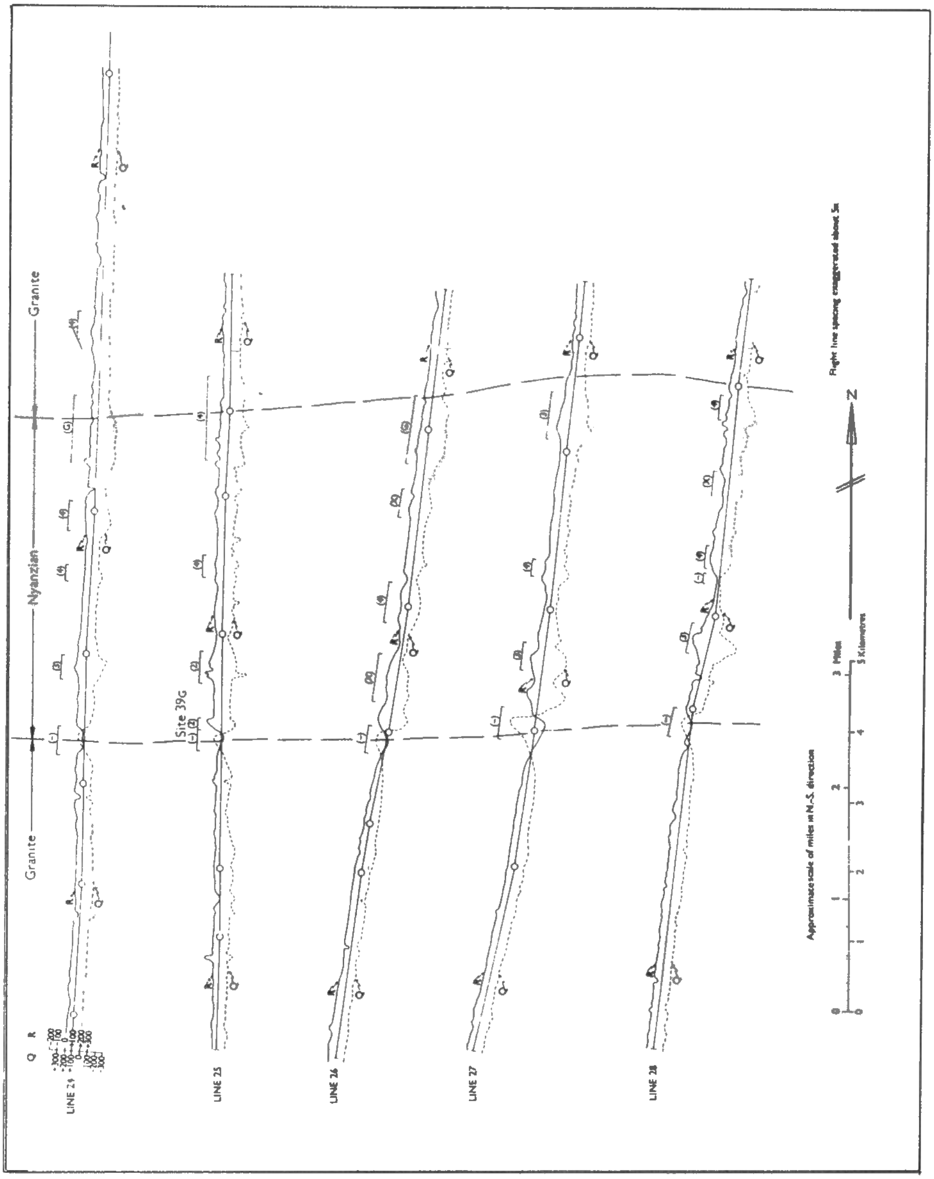

Fig. 3b Rio-Mullard responses over southern Nyanzian belt, Geita

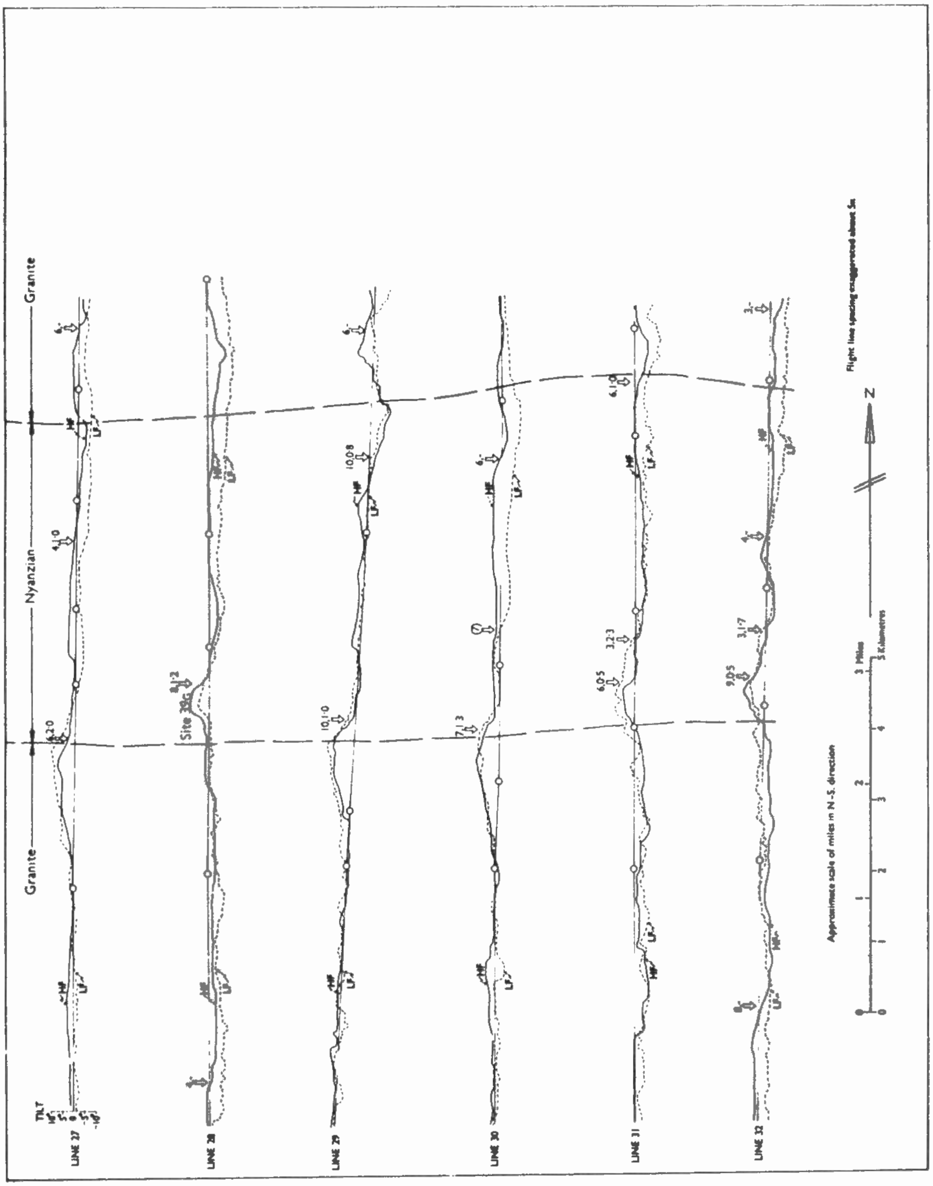

Fig. 3c Afmag responses over southern Nyanzian belt, Geita

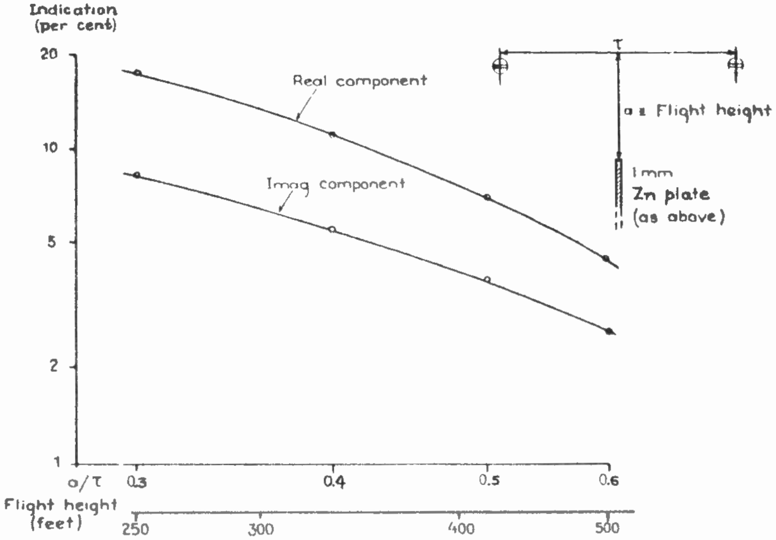

Fig. 4 Rotary Field Method. Decrease of anomaly amplitude with height (after Hedström and Parasnis, 1959)

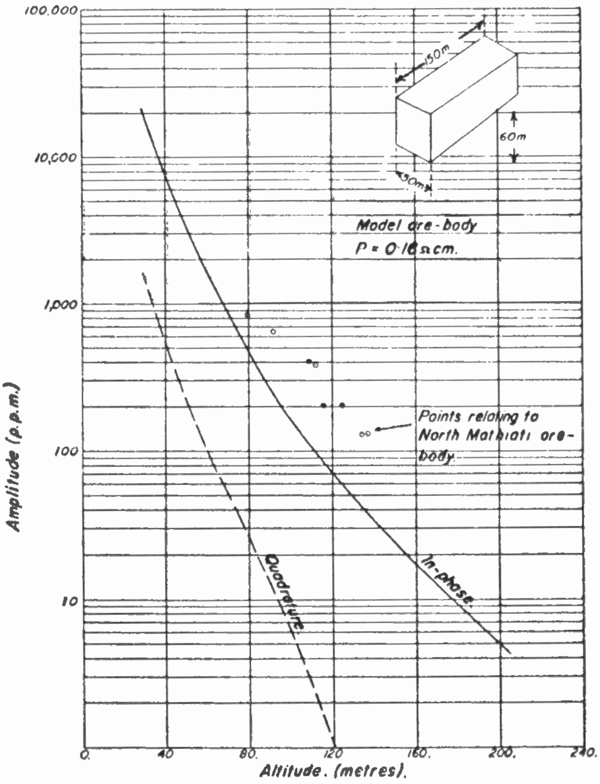

Fig. 5 Rio-Mullard Method. Decrease of anomaly amplitude with height (after Boyd and Roberts, 1961)

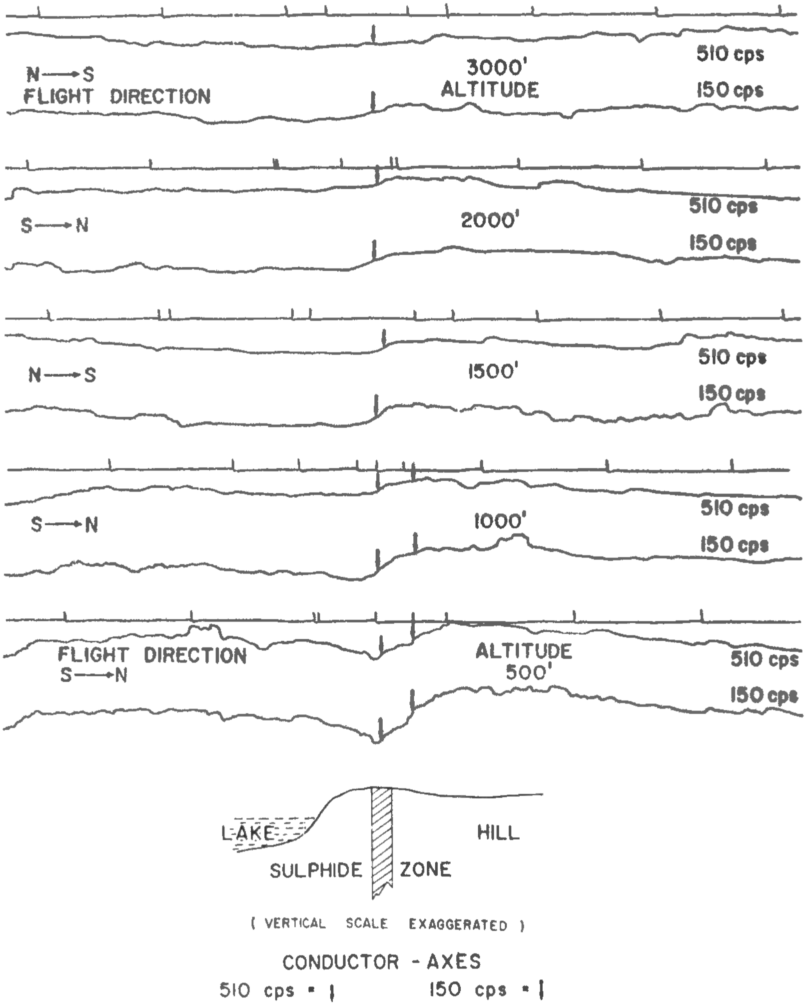

Fig. 6 Afmag Method. Decrease of anomaly amplitude with height (after Ward, 1959)

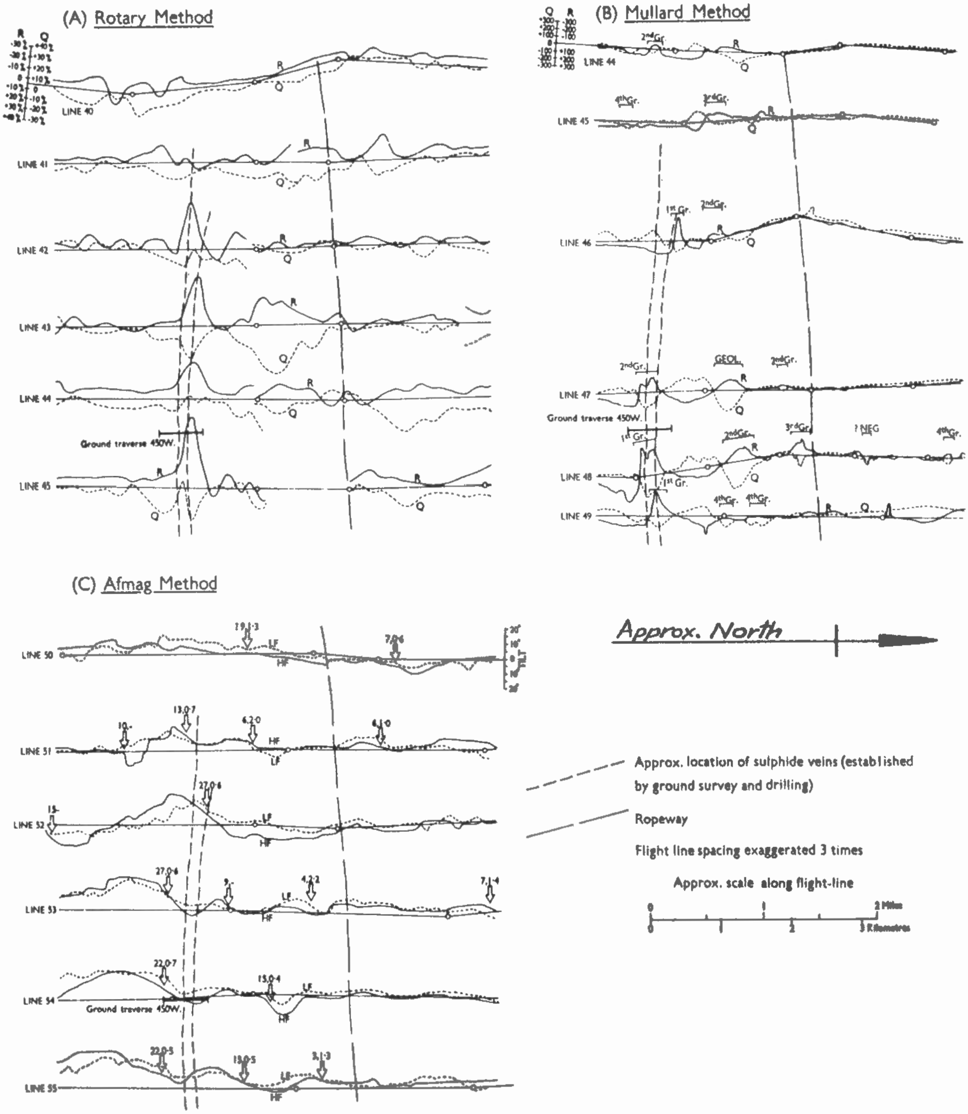

Fig. 7 Aerial Responses over Western Samena, Geita

THE INDUCED POLARIZATION AND THE INPUT METHODS IN GEOPHYSICAL EXPLORATION

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INTRODUCTION

Ten years ago "Induced Polarization" was not a common term in geophysical literature, much less a method of exploration. And now a new method 'INPUT' (Induced Pulse Transient System) has been introduced within the past four years. Both methods require a transmitter and a receiver. The ground has to be contacted in the induced polarization method, whereas the INPUT system uses loops and therefore is more adaptable to airborne techniques. Both methods were designed for the detection of sulphide mineralization but the techniques of achieving this end are different.

INDUCED POLARIZATION

The induced polarization method was developed to detect disseminated sulphides, such as porphyry copper type of deposits (Bleil, 1953; Wait, 1959). Self potential, resistivity and electromagnetic methods failed to detect these deposits because there is little or no continuity of the sulphide conductor throughout the rock due to the individual particles being separated from one another by the host rock. Normally, current conduction through rocks is by means of ions in the electrolytes present in the pores and interstices of the rock.

Electrode Polarization

When an ionic path is blocked by a sulphide particle, see Fig. 1(a), there is a build-up of charge across the interface. This is known as electrode polarization (Marshall et al., 1957, Madden and Marshall, 1958, 1959a, 1959b; Marshall and Madden, 1959). Energy is required to cause current to flow across the interface. This energy barrier can be considered to constitute an electrical impedance. Next to the surface is a "fixed layer" of charge, see Fig. 1(b). Adjacent to the fixed layer of adsorbed ions is a group of relatively mobile ions known as the diffuse layer.

The fixed layer is relatively stable whereas the diffuse layer thickness is a function of temperature, ion concentration of the electrolyte and valency of the ions.

There are two mechanisms by which current may be carried across an interface between an electrolyte and a sulphide: the faradaic and non-faradaic (Kumar, 1962). The faradaic current is carried across the fixed layer by ions resulting in an electrochemical reaction of oxidation and reduction, known as the "overvoltage effect" to electrochemists. This mechanism is not a simple one and in fact may not be represented by any combination of fixed capacitors and resistors; this phenomenon is referred to as the Warburg impedance, -W-, which is inversely proportional to the square root of the frequency. The non-faradaic current consists of charges that do not cross the interface; the current is carried by the charging and discharging of the fixed layer. The mechanism can be thought of as the current across a fixed capacitor.

Frequency Response

From the foregoing description of induced polarization in sulphides, it is evident that the response to passage of a current is frequency dependent. The plot in Fig. 2 shows diagrammatically how the apparent resistivity of the rocks containing metallic sulphides varies with frequency. At the same time, the method will respond to graphite, magnetite, serpentine, sericite and certain clay minerals resulting from rock alteration. On the other hand, the method is not affected by topography, and depth of detection is limited primarily by the size of the target.

Frequency and Pulse-Transient Method

There are two popular methods of measuring induced polarization, or chargeability effect. One of these, referred to as the "frequency method", involves the measurement of resistivity at two low frequencies, for example 0.3 cps and 2.5 cps or 0.3 and 5.0 cps. The change in the apparent resistivity at the two frequencies is a measure of the apparent chargeability. The parameters that are commonly used are:

$$\text{Metal Factor, M.F.} = \frac{\rho LF - \rho HF}{\rho LF \times \rho HF} \times 2\Pi \times 10^5$$

(Marshall & Madden, 1959)

$$\text{Frequency Effect, } f_e = \frac{\rho LF - \rho HF}{\rho HF} = \frac{\rho LF}{\rho HF} - 1$$

(Hallof, 1963)

$$\text{Percent Frequency Effect} = \frac{\rho LF - \rho HF}{\rho LF} \cdot \frac{100\%}{\log_{10} \frac{HF}{LF}}$$

(Keevil & Ward, 1962)

where ρ_{LF} = apparent resistivity at the lower frequency
ρ_{HF} = apparent resistivity at the higher frequency

The metal factor is a parameter that has been found to be more diagnostic in most cases than the frequency effect (Hallof, 1963a).

The other technique is known as the "pulse-transient" or "time domain" method (Seigel, 1962; Wait, 1959). A direct current is applied to the ground for a limited period through two current electrodes and the primary voltage, V_ρ is measured between two potential electrodes. Immediately after cessation of the current, the polarization potential V_ρ appears at these electrodes and decays with time. The chargeability, M, is expressed as the ratio of the area under the decay-time curve to the primary voltage, V_ρ. The integration is carried out electronically over a specified time interval. The cycle for the energizing current is on for one second and off for one second with the decaying voltage being integrated over a half or one second period. Then the polarity of the current is reversed so that polarization effects do not build up at the electrodes and the cycle is repeated (Fig. 3). Because the time-domain method uses square waves of current, an analysis of the wave shape shows that all the low frequencies above approximately 0.5 cps are present.

There are strong proponents of both methods, but either method is capable of producing excellent results.

Both methods for measuring the induced polarization of sulphides are done by applying a known current to the ground through a pair of electrodes and the resulting potential drop is measured across a second pair of electrodes. Any of the two, three, or four electrode configurations used for resistivity measurements may be employed in induced polarization surveys. The frequency method commonly uses the pole-dipole or the dipole-dipole method, known as the Eltran array, shown on the upper part of Fig. 4. The current is applied at two points distance 'x' apart and the potential is measured at two other co-linear points also spaced 'x' apart. The distance between the nearest current and potential electrodes is 'nx', where 'n' is a variable integer between 1 and 6. The distance used for 'x' in the field can vary between 25 and 1,000 feet. Values from 25 to 100 feet are normally used for the exploration for shallow bodies while larger values of 500 to 1,000 feet would be employed in reconnaissance surveys where deep sulphides might be anticipated. The choice depends on the assumed size, shape, and mineral content of the target. The depth of detection is increased by increasing both 'x' and 'n'. Similar considerations also apply to the two, three, and four electrode arrays.

In both the frequency and pulse-transient techniques, the D.C. resistivity is measured. The values for the apparent resistivity and the chargeability, M, in the pulse-transient method are usually plotted on a map and the values contoured. In the frequency method, a novel method of plotting the apparent resistivity and metal factor, M.F., is employed. The values of apparent resistivity and the apparent M.F. are plotted on separate graphs, portraying a two-dimensional array. The plotting method is demonstrated on the lower part of Fig. 4. The values for each value plotted at the intersection of 45° lines from the centre point of the current electrodes and the centre point of the potential electrodes. The apparent resistivity values are plotted above the centre line, and apparent M.F. below the line. Each horizontal row of values (n = 1, 2, 3, 4) represent a constant depth of penetration. As n is increased, depth of penetration is increased. These two-dimensional data plots are contoured. These contoured plots should not be considered a vertical section of the electrical properties of the ground but serve to indicate the apparent parameters at depth as the spacing of the electrodes is increased.

The word "apparent" is used because targets are usually covered by overburden and buried within the bedrock. Thus the chargeability measured at the surface, that is, the apparent chargeability, is usually smaller than the true chargeability of the body, due to the intermediate rock or overburden. This apparent chargeability is a function of the geometry of the body, its true chargeability, i.e. when the electrodes can be placed in direct contact with the body, and also of the resistivity contrast between the body and the country rock.

Depth of Penetration and Masking Effects

Induced polarization effects can be detected with frequencies of up to a thousand cycles per second approximately. The depth of penetration is proportional to $\sqrt{\frac{\rho}{f}}$ where ρ is the apparent resistivity and f is the frequency. At higher frequencies, the depth of penetration decreases, while the inductance of connecting leads causes effects that are larger than the induced polarization effects. For these reasons an upper limit of about 10 cycles per second is desirable. In areas where the upper layer has a very low resistivity, inductive effects in the electromagnetic method mask the secondary inductive effects from sulphide ores below. In such cases, induced polarization measurements made at two discrete frequencies below 5 cycles per second or by the transient method can "look through" the low resistive layer to detect sulphide mineralization below this horizon.

The transmitter power required to operate in areas under most geological conditions would be about 250 watts for overall spread length up to 1,000 feet, 1,250 watts up to 5,000 foot spreads and 2,500 watts or more for 10,000 foot spreads or greater.

Drill Hole Induced Polarization

The induced polarization method is adaptable for drill hole exploration (Wagg and Seigel, 1963). In the Noranda area of Quebec, Canada, most of the commercial orebodies could easily be missed with an 800 ft. drilling grid pattern. A drill hole log using the induced polarization method can effectively extend the "coverage" of the drill hole. Usually a massive sulphide body is surrounded by a zone of disseminated sulphides, thus effectively bringing the target closer to the drill hole. Wagg and Seigel have shown that some zones of fairly high percentages of sulphides do not respond to electromagnetic methods, but show up clearly when the induced polarization method is used.

Field Examples of Induced Polarization

An example of an induced polarization profile using the transient method is described by Faessler (1962), Fig. 5. The profile is across the western part of the Craigmont orebody in the Princeton, Merritt, Kamloops copper area of British Columbia, Canada. The orebody contains roughly 5 per cent sulphides and little or no magnetite. Due to its poor conductivity, the electromagnetic methods, both airborne and ground, show inconclusive evidence of the presence of sulphides. The upper trace is a plot of the apparent resistivity at electrode spacings of 100 and 200 feet. Over the ore it shows a slight decrease in resistivity which by itself would not be considered as being diagnostic. The lower trace is a plot of the chargeability which varies from a background of less than 1 millisecond to about 7 milliseconds on the 100 foot electrode spacing immediately over the ore. The 200 foot electrode spacing shows a double-peaked anomaly. The double peaks are due to the narrow width of the upper part of the body as compared to the electrode spacing.

Two examples of induced polarization over disseminated sulphide deposits using the frequency method are taken from McPhar Geophysics Limited, 1963, case history V and VI, Fig. 6 and 7 respectively. Note the method of plotting the apparent resistivity, $\rho_a/2\pi$, and apparent metal factor, $(MF)_a$. Both are from areas in the southwestern United States.

Case History V (Fig. 6) is from the San Juan Area, Graham County, Arizona, U.S.A. The area is completely covered by Gila Conglomerate of Tertiary Age. The results using a 500 ft. electrode spacing (x = 500 ft.) indicate that the source is shallow and broad in lateral extent. Because the anomaly is broad, the apparent metal factor measured must be nearly equal to the true metal factor within the source. The holes drilled to test the anomaly intersected disseminated mineralization (5 to 7% sulphides) under 150 to 300 ft. of conglomerates.

Case History VI (Fig. 7) is from the Cactus Area, Pinal County, Arizona. The Cactus Orebody is a zone of 3 to 5% sulphide mineralization occurring within the Pinal Schist just above the Cactus Thrust Fault. The mineralization extends to within 200 to 400 feet of the surface. The depth of mineralization is indicated by the fact that the induced polarization effects measured are greater for the larger values of n. Since this mineralization is much the same as that in Case V, the true induced polarization effects within the source must be of the same order of magnitude. The apparent induced polarization effects measured are much less because the depth to the top of the source is greater. The sulphide body is too small to be economically mined.

INPUT (INDUCED PULSE TRANSIENT SYSTEM)

Most present day electromagnetic systems use a transmitting coil through which a continuous oscillating current with a frequency chosen in the range between 300 and 5,000 cps is passed. The secondary response due to the eddy currents induced in the natural conductors in the ground are detected by means of a receiving coil. Because the transmitted electromagnetic fields are continuous, the detection of the secondary response from a conductor is done in the presence of the primary field which involves the elimination of the primary field from the receiver. This is done by supporting the transmitting and receiving coils in some fixed orientated relationship and electronically balancing out the primary component in the receiving coil. When the transmitted coil is mounted on an aircraft and the receiver coil is towed behind in a "bird", slight changes in orientation of the bird due to vibration and air turbulence will affect the coupling between the two coils. This misorientation produces spurious and unwanted signals in the receiver. The INPUT system has been developed, by Dr. A.R. Barringer, Selco Explorations of Canada, to achieve isolation in time between the transmitted and received signals (Barringer, 1962a, b; 1963a, b, c).

Half-sine Wave Pulses

The INPUT system (Barringer, 1963d) makes use of half sine-wave-shaped pulses of the order of 1.5 milliseconds duration (Fig. 8a). These pulses contain frequencies which lie substantially between about 40 and 10,000 cps with the energy reaching a maximum between 300 and 400 cps. The primary pulses have a repetition rate of 290 pulses per second and are generated in a large horizontal loop surrounding the aircraft. The system induces eddy currents in the conductive bodies lying beneath the aircraft. The receiver is towed in a bird behind the aircraft to detect the secondary transient fields radiated from these underlying conductive bodies, Fig. 8(c). The receiver amplifier is inactive during the pulse duration of 1.5 milliseconds, Fig. 8(b). Since the primary pulses are separated in time from the secondary transient responses, the method is loosely analogous to radar. Unlike radar, however, the delay is not caused by the finite propagation velocity of the electromagnetic waves, since this delay is minute compared with the delay involved in the decay of the secondary electromagnetic fields induced in the target. This time isolation principle is very desirable, as it is in radar, in removing interference between the transmitter and the receiver. The system is not affected by changes in the relative orientation between the transmitter and the receiver. For this reason orientation noise, which is caused by changes in coupling between the transmitter and receiver and which is the principal factor limiting sensitivity in other airborne electromagnetic systems, is completely eliminated. Thus very weak secondary fields can be detected without being obscured by powerful overriding primary fields as in the case of the usual continuous wave electromagnetic systems. Thus exceptional sensitivity and almost complete freedom from noise caused by air turbulence is one of the chief advantages of the INPUT system.

For recording the transient decay curve four successive sample points are positioned at delays of 200, 600, 1,000 and 1,400 microseconds after the termination of the primary pulse, Fig. 8(c). Each channel value is averaged over a few seconds and is recorded as continuous profiles on a chart recorder. When conductive bodies are absent the output of each channel is zero. When a conductor is traversed, the amplitudes on the four channels define the shape of the transient decay curve.

Advantages of the INPUT System

One of the main advantages of the INPUT system is its ability to penetrate conductive overburden and separate the effects of the overburden from the underlying conductors. Swamps, lake bottoms, etc. generally have time constants of less than 250 microseconds, while sulphide conductors show time constants of up to 1 millisecond and have an unusually long tail on the transient decay curve. The majority of overburden appears only on channel 1, leaving the other three channels unaffected. Recent results in the field and laboratory have pointed out the possibility that the INPUT system may be responding to induced polarization effects over certain classes of disseminated deposits.

Good conductors can be detected at flying height of 1,000 feet or more. Therefore at a normal survey height of 400 feet, a penetration of 200 to 500 feet may be obtained depending upon the overburden conductivity, and the size and conductivity of the mineralized bodies.

The INPUT Mark II system shows very negligible interference from major power transmission lines.

Field Example

An example of the INPUT system is taken from Barringer (1962a) which shows the response over Moak Lake nickel deposit in Manitoba (Fig. 9). The deposit is 150 feet beneath the surface. The right hand anomaly is significant in that it shows the response from a swamp and appears only on channel 1.

CONCLUSION

The induced polarization method is in common use today and has been applied to the detection of disseminated sulphides in many of the mining areas in the world. The method has been adapted for use in drill holes. Although it is not readily adaptable to airborne survey techniques, this possibility should not be precluded in view of the development of more sensitive magnetometers which can be used as receivers.

The INPUT system has completed many thousands of line miles of production survey. It is an excellent reconnaissance method for the detection of massive sulphides and possibly for disseminated sulphides. Since the method can detect sulphides beneath a highly conductive overburden, the potential extension of the use of this system to those parts of the world where adverse surface conditions provide a major barrier to other electromagnetic methods could be an important factor in sulphide mineral exploration. The method has been adapted for both ground and drill hole techniques.

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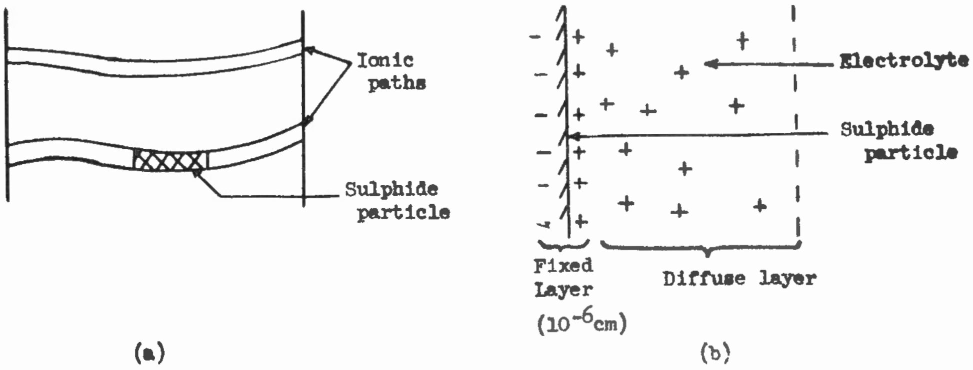

Fig. 1 (a) Section of conducting paths in rock (after Marshal and Madden, 1959).

(b) The electrical double layer at a sulphide particle interface (after Keevil and Ward, 1962).

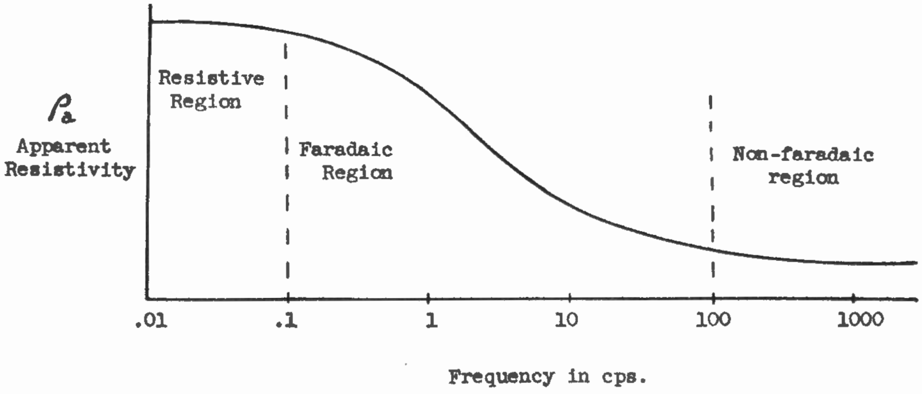

Fig. 2 Frequency dependence of induced polarization shown as change of apparent resistivity with frequency (modified after Kumar, 1962).

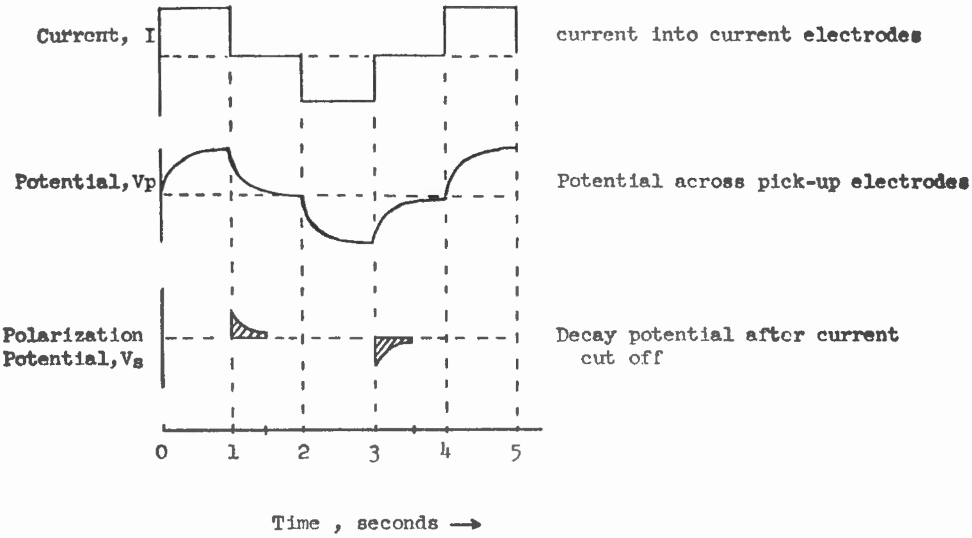

Fig. 3 Pulse-transient method, Wenner array

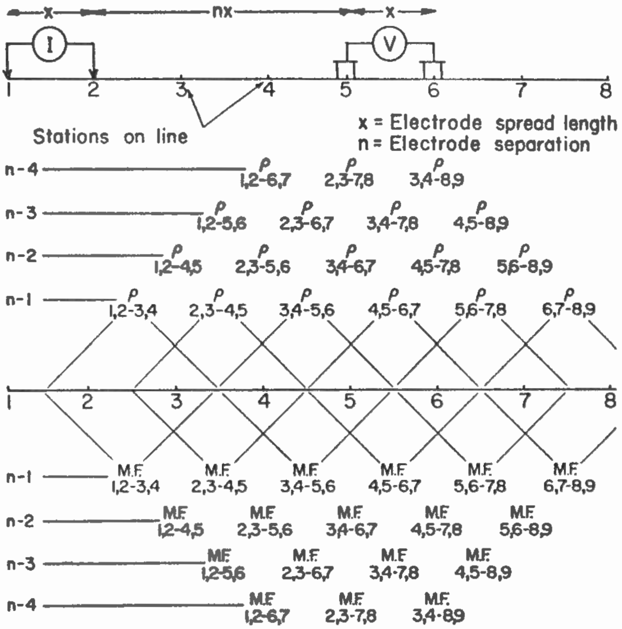

Fig. 4. Method used in plotting dipole-dipole induced polarization and resistivity results (after Hallof, 1961)

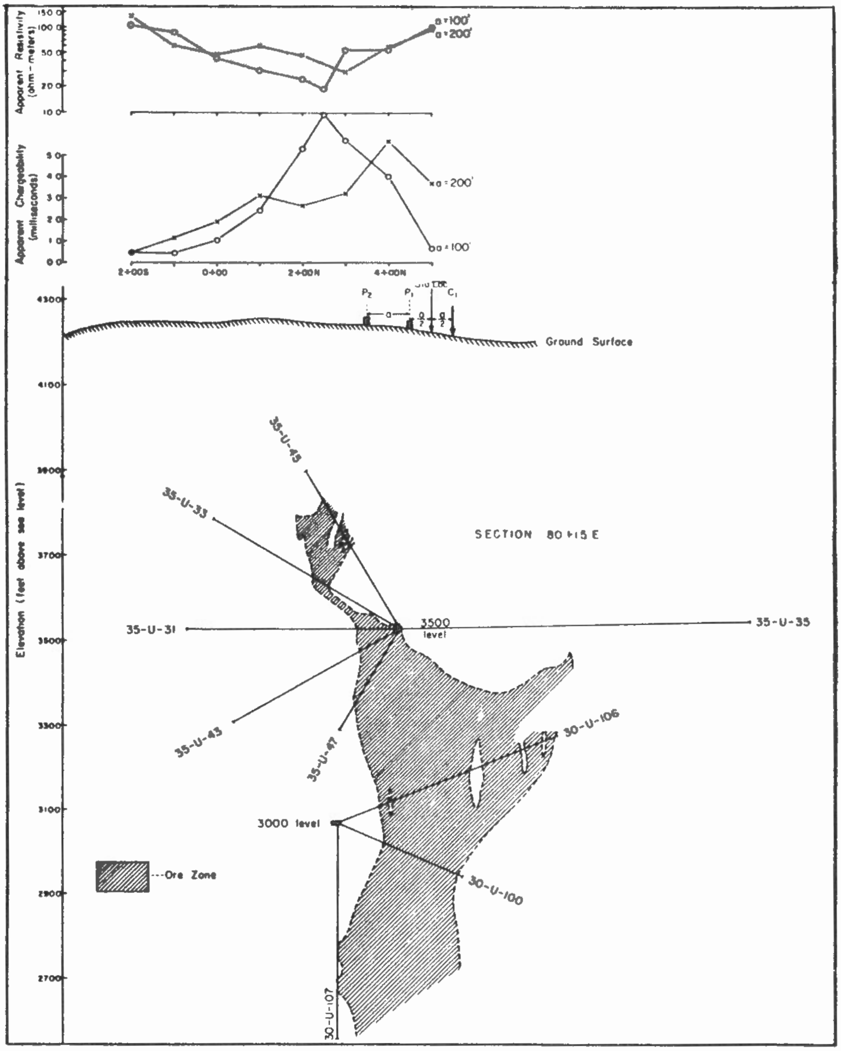

Figure 5. Induced polarization profile and cross section of sulphide ore zone. (Faessler, 1962)

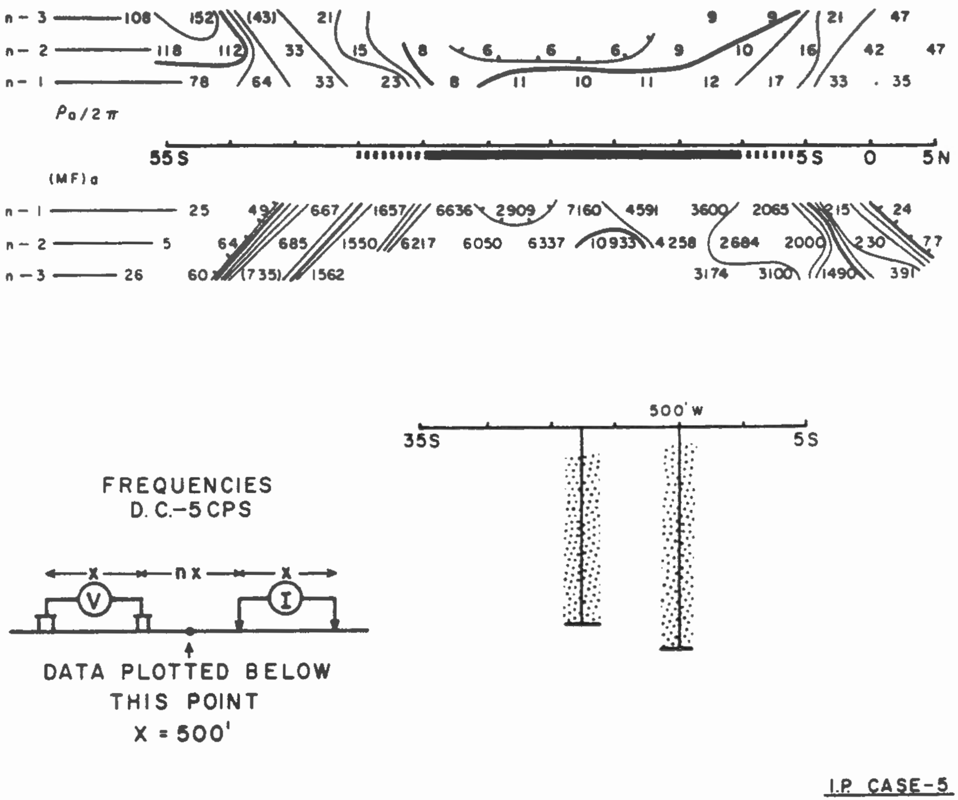

Fig. 6 Induced polarization and drilling results from San Juan Area, Graham City, Arizona (after McPhar Geophysics Limited, 1963).

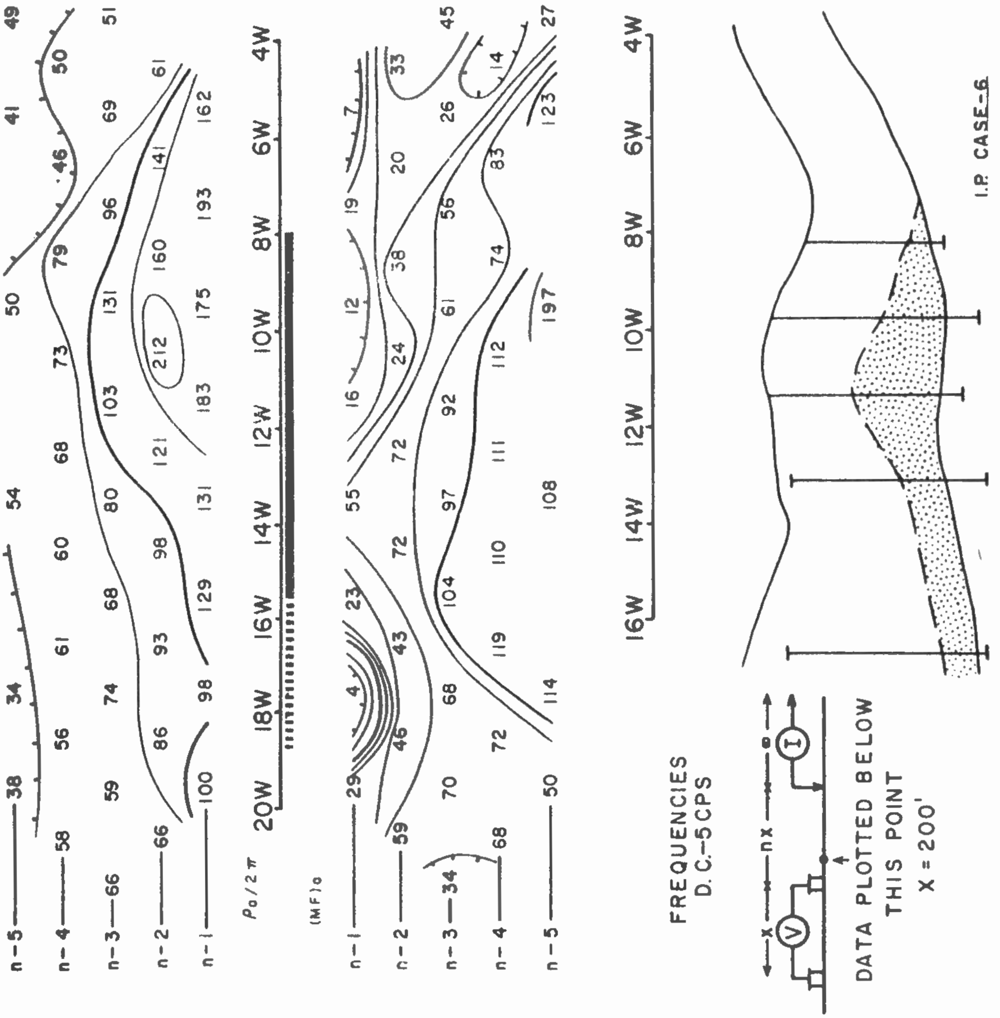

Fig. 7. Induced polarization and drilling results from Cactus Area, Pinal County, Arizona (after McPhar Geophysics Ltd., 1963)

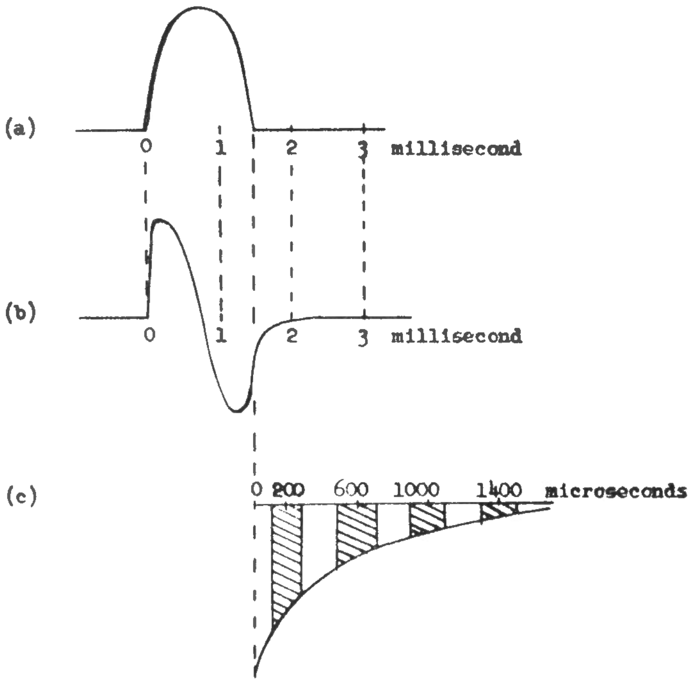

Figure 8. (a) INPUT current pulse waveform into transmitter loop.

(b) Differential of current pulse as detected in the receiving coil (amplifier inactive during this period).

(c) Transient signal amplified showing the four channels (modified after Barringer, 1963 a, b)

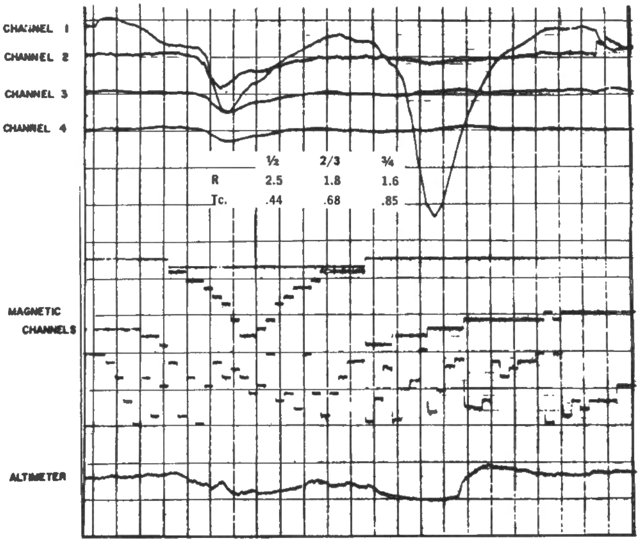

Figure 9. Left hand anomaly shows response over Moak Lake nickel deposit (150 ft. beneath surface) in Manitoba. Right hand anomaly shows response from swamp. The significant anomaly is recognized by its channel 3 and 4 response and magnetic correlation. Ration between channels and calculated time constants indicate departure from exponential decay (after Barringer, 1962a).

THE IMPORTANCE OF ORE DEPOSIT CLASSIFICATIONS TO THE EXPLORATION GEOLOGIST

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The writer is engaged in a metallogenic study of a part of the eastern Canadian Shield that contains a remarkable abundance and variety of ore deposits in diverse rocks of several Precambrian ages (Figure 1). This approach to ore deposit research differs from the more common approach of making very detailed studies of individual ore deposits and formulating hypotheses of origin that are in accord with a large volume of data. In the present study the emphasis is on comparisons of deposits, and decisions must be made regarding family relationships of many deposits for which we have relatively little data. The selection of an appropriate procedure for grouping, or classifying, deposits has been found to be a more crucial consideration than was initially realized. In order to show mineral deposits on a map, to describe deposits, or to evaluate possibilities of mineral discoveries in a given area, it is necessary to decide on some type of classification or order of presentation. Mineral deposits may be classified in many ways depending on the emphasis allocated to economic, chemical or mineralogical, physical, and theoretical factors. The type of classification used and the priority with which relevant factors are treated in arriving at a classification has a direct bearing on the type of information sought in the field, in the laboratory and in the literature.

Economic considerations are intrinsic factors in the recognition of any mineral deposit as a subject available or worthy of investigation and are therefore explicitly or implicitly involved in any mineral deposit classification. Classification according to commodity value and economic importance alone satisfies the interests of geographers, economists and others whose interest is focused on the metallic or non-metallic products that are or that may be profitably extracted from mineral deposits in various regions. It does not by itself provide much information of value to prospectors, geologists and engineers concerned with exploration or development. It is the simplest and least arbitrary method of classification and has been the most common one used by geologists in showing deposits on geological maps and in grouping them for orderly description in geological reports and economic geology textbooks. This procedure, however, tends to hide fundamental differences between various deposits of the same commodity. There may be greater differences, for example, between two copper deposits shown in the same way on a map and described together in the accompanying text than there is between one of these copper deposits and, let us say, some zinc deposits in the same area. Moreover, a different element may constitute the most valuable or even the sole product of two identical deposits located in different areas or exploited at different times.

Classifications of deposits according to their chemical or mineralogical composition can convey a great deal of information to persons familiar with the geochemistry and mineralogy of ore deposits. They are more descriptive than a commodity designation and can serve in many cases to distinguish between diverse deposits containing the same commodity - native copper and chalcopyrite deposits, for example. It may be difficult to avoid some confusion between such materials classifications and a commodity classification. In a special case, for example, the same deposit could be designated as a chalcopyrite-sphalerite deposit, a Zn-Cu deposit or a Cu-Zn deposit depending on whether it is classified according to the order of abundance of ore minerals, the order of abundance of ore metals, or the order of value of ore metals. Many deposits show wide variations in proportions of minerals present so it may be difficult to classify them mineralogically or to do so without making unwarranted distinctions between basically similar deposits.

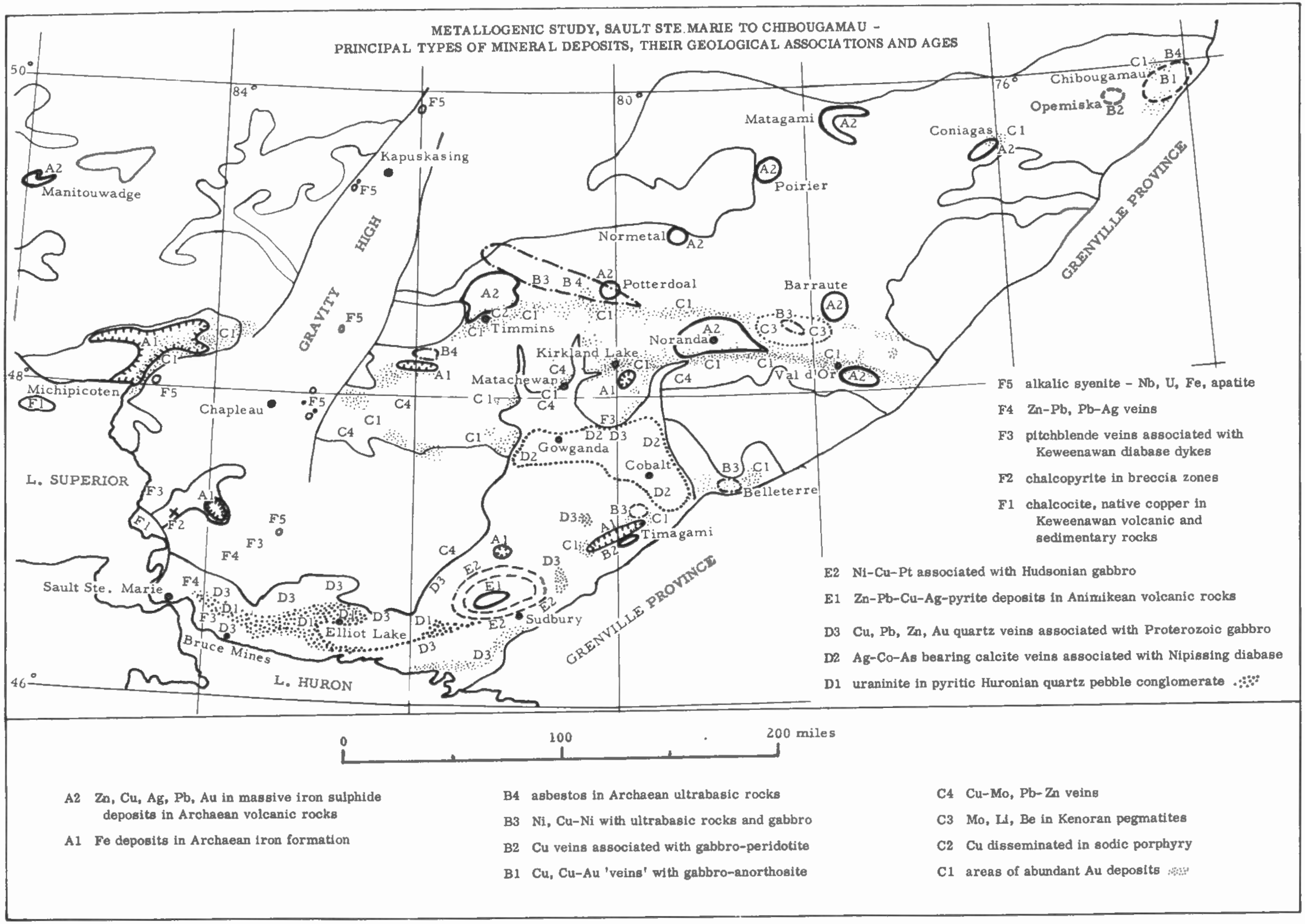
Physical factors, including shape, relationship to enclosing rock, fabric, and structural associations, are an essential part of any description of a mineral deposit. Terms such as massive, disseminated, breccia, saddle reef, and so on, are used to distinguish (or classify) different types of deposits in reports and, more rarely, in map legends. This type of designation conveys a great deal of useful information about an ore deposit. Its principal weakness as a primary parameter of classification is that a number of different physical features and relationships may be manifested among individuals in a group of mineralogically similar, co-genetic, coeval deposits and commonly even within the same deposit. It is interesting to note that bias can creep into usages of seemingly objective structural terms. The terms discordant and concordant, for example, have been widely used in recent years to summarize relationships of deposits to their enclosing strata while, supposedly, avoiding genetic connotations. In practice, however, those who believe a deposit to be syngenetic will emphasize its general concordant character while those who believe it to be epigenetic will describe it as 'discordant in detail'.

Geological associations obviously demand consideration as important parameters in the classification of mineral deposits. They constitute the definitive features of many types of deposits - e.g., pegmatitic deposits, uraniferous or cupriferous shale, red bed copper deposits. Other deposits, not so unequivocably indigenous to their host rocks, occur preferentially within or near a specific rock type or combination of rock types. Numerous base metal, precious metal and other deposits, however, show little obvious preference for particular host rocks and this may account for the fact that the conscious use of lithological associations as the primary factor in mineral deposit classification has been limited.

None of the four categories of information described above can be ignored in making compilations of mineral deposit information either for scientific purposes or for purposes of selecting exploration targets and exploration methods. The process of considering all of these factors together when making comparisons amongst a number of mineral deposits actually amounts to a classification of deposits whether this classification is formalized or not. There is not and probably cannot be any set formula for arriving at a formal or implied classification. Some geologists may attempt to follow a 'mechanistic' approach, others an approach involving trial and error tests of the degree of conformity of data to some idealized pattern or hypothesis.

The 'mechanistic' approach calls for filing of mineral deposit data under a cross indexing system, or on punch cards. Ideally, provision should be made not only for electronic sorting of such data cards but for possible processing of the data in digital computors programmed to give appropriate weight to various factors in arriving at a totally objective classification. We might further dream of future mineral deposits maps and mineral prognostication maps produced automatically from the output of digital computors. It must be pointed out, however, that data retrieved or answers obtained through such a system can be no better than the data originally collected or the human reasoning behind questions asked.

Many mineral deposits maps show deposits superimposed on a geological base and represented by various combinations of symbols, patterns, colours, abbreviations and numbers that convey information about the composition, structure and importance of individual deposits or groups of deposits. Mineral deposits maps of France by F. Permingeat and others of the Bureau de Recherches Geologiques et Minieres represent the most sophisticated and perhaps the ultimate development of this 'mechanistic' method of compiling mineral deposit information graphically. These are not



METALLOGENIC STUDY, SAULT STE MARIE TO CHIBOUGAMAU -
PRINCIPAL TYPES OF MINERAL DEPOSITS, THEIR GEOLOGICAL ASSOCIATIONS AND AGES

F5 alkalic syenite - Nb, U, Fe, apatite
F4 Zn-Pb, Pb-Ag veins
F3 pitchblende veins associated with Keweenawan diabase dykes
F2 chalcopyrite in breccia zones
F1 chalcocite, native copper in Keweenawan volcanic and sedimentary rocks

E2 Ni-Cu-Pt associated with Hudsonian gabbro
E1 Zn-Pb-Cu-Ag-pyrite deposits in Animikean volcanic rocks

D3 Cu, Pb, Zn, Au quartz veins associated with Proterozoic gabbro
D2 Ag-Co-As bearing calcite veins associated with Nipissing diabase
D1 uraninite in pyritic Huronian quartz pebble conglomerate

A2 Zn, Cu, Ag, Pb, Au in massive iron sulphide deposits in Archaean volcanic rocks
A1 Fe deposits in Archaean iron formation

B4 asbestos in Archaean ultrabasic rocks
B3 Ni, Cu-Ni with ultrabasic rocks and gabbro
B2 Cu veins associated with gabbro-peridotite
B1 Cu, Cu-Au 'veins' with gabbro-anorthosite

C4 Cu-Mo, Pb-Zn veins
C3 Mo, Li, Be in Kenoran pegmatites
C2 Cu disseminated in sodic porphyry
C1 areas of abundant Au deposits

metallogenic maps although they show basic data that can be used in interpretations of relationships between deposits and of factors important in their distribution. The reader is left with the task of making the actual interpretations from a complex array of codified information. An exploration geologist is likely to be interested in the following type of question: "Is this mineral occurrence one of an economically important class with a characteristic shape and restricted to one specific rock type?" The most probable answers to many such questions must have been known to the compiler or have become apparent to him as the result of his work. Mineral deposits maps can therefore be regarded as intermediate steps in the preparation of interpretative, or metallogenic, maps. Where publication is an objective, useful interpretations should be given even if this necessitates omission of some of the primary data.

Genetic classifications of mineral deposits, like genetic classifications of rocks, have generally been based on the presence of a few special or diagnostic features rather than on exhaustive analyses of all features that can be measured or described. Obvious features suggest possible processes of origin which themselves guide us in the search for additional features that will enable us to select and thoroughly test the most appropriate hypothesis. This general method has been a major instrument in the development of geological science. Genetic classifications of ore deposits must not be deprecated as academic. Exhaustive tests of hypotheses of origin provide us with the best possible insurance that we have learned the things we need to know about an ore deposit in order to exploit it efficiently and search most efficiently for others. Genetic terms, moreover, provide a most succinct way of conveying a great deal of information, albeit inferentially, about an ore deposit.. Consider, for example, the information about probable commodities, chemistry, mineralogy, structure, extent, and local and regional lithological associations that the term 'evaporite deposit' may conjure in the mind of a trained economic geologist who has never seen a deposit of this type. The same may be said of the expressions, placer deposit, laterite deposit, magmatic segregation, and many other genetic terms.

When we think of genetic classifications of ore deposits, most of us almost automatically turn mentally to Lindgren's classic treatment of deposits according to processes of concentration. His greatest contribution, perhaps, has been in influencing geologists towards thinking about ore deposits in dynamic rather than static terms, but his classification scheme is, in large part, still useful today. Its most dubious feature is its emphasis on certain mineralogical and textural features as indicators of temperature and pressure conditions attending the formation of epigenetic deposits and defining depths of formation or proximity to igneous source rocks. The terms mesothermal and hypothermal, in particular, do not appear to have proven to be useful generalizations.

The standard treatment of mineral deposits in geological reports exemplifies and helps perpetuate a weakness in our approach to ore deposits studies. General geology, stratigraphy, intrusive rocks, structure and metamorphism are treated in an order and manner that emphasize the geological history of the area under consideration. Descriptions and discussions of mineral deposits are isolated in a separate section at the end of the report that may seem almost like an appendix proffered as a bone to unfortunates who are more interested in ore, economic development and profits than in rocks and structures. This format is actually meant to emphasize the importance of ore deposits, of course, but a result has been the stultification of proper appreciation of the relationships between rocks and ores, between processes of rock formation and ore concentration and between geological history and metallogenic history of an area. An ore is a rock regardless of its rarity or value. Events and processes that produce the one also produce the other. Separate treatment of the two may be necessary because of comparative ignorance regarding some ore-forming processes or for other reasons but such ignorance or difficulties should not be tacitly sanctioned as insurmountable or unavoidable.

Russian geologists, Bilibin (1955) and others, have developed an empirical model of the sequence of formation of rocks and mineral deposits during the complete course of an idealized orogeny within and adjacent to a mobile belt. W.D. McCartney of the Geological Survey of Canada is studying the applicability of this scheme in the Appalachian region of Canada. Preliminary reports of this investigation have been given by McCartney and Potter (1962) and McCartney also has a paper in the present collection. The model can be more readily tested and is more likely to be useful in extensive young fold belts than in fragmentary remnants of Precambrian orogenic belts such as those within the writer's study area. The style and intensity of orogeny, moreover, may have differed in Archaean and even in Proterozoic time from that in Phanerozoic time from which the model has been taken. Volcanic rocks are much more abundant and true sedimentary rocks much rarer in Archaean than in Palaeozoic assemblages. Nickel deposits, massive zinc and copper-bearing massive sulphide deposits and gold deposits appear to be abnormally prolific in this and in other Precambrian areas whereas lead-zinc and certain other deposits appear to be comparatively rare. Nonetheless, the emphasis this hypothetical system places on spatial associations between ore deposits and rock assemblages characteristic of various tectonic stages commends it to the attention of exploration geologists working in Precambrian terrains as well as to those working in geologically younger terrains.

No specific recommendations for a system of mineral deposit classification are given in this paper. We should seek agreement and consistency in the way that we use descriptive and genetic terms but a universal system for using such terms in a classification does not seem necessary or desirable. Requirements vary with the size of the area of interest, the type of geological terrain, the abundance, variety and types of mineral deposits known or likely to be found in the area, and the way the user thinks about mineral deposits. The main object should be to develop a classification not as an end in itself but as a tool to help us consider separately those deposits that should be considered separately and to relate deposits that are basically, but not obviously, similar. An exploration geologist must distinguish between types of deposits that occur in different geological environments, that have different shapes, different size and different value potential, and that call for different geological, geophysical and geochemical exploration techniques and expenditures. For these purposes it may be convenient to think of some deposits primarily in terms of their genesis, others in terms of their lithological associations, age or stratigraphic position, and others in terms of a distinctive mineralogical association or a characteristic structural configuration. Ignoring asthetic considerations, there is no need to be consistent in our choice of factors for distinguishing diverse deposits. The important thing is that we find means to nurture our awareness that diversities amongst mineral deposits are as great as those amongst rocks.

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ORE GENESIS AND MANTLE CONVECTION

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The last decade has witnessed rapid developments in the application of physical and chemical techniqucs to geology. As the results from new techniques are made available it becomes increasingly clear that geological science is now at a more exciting stage in its development than at any previous time this century. Facilities now exist which can provide critical evidence on problems which hitherto were only subjects of speculation. Modern technology has provided the means to advance geology beyond the mere description of past events and now offers the opportunity to investigate processes deep within the crust. In these changed circumstances, where hypotheses can be tested much more rapidly and rigorously than hitherto, there would seem to be a place for increased scientific speculation, especially in those fields where there could be economic implications. The speculative hypothesis which is outlined here is an attempt to build upon existing information for the purposes of providing a model of ore-genesis which is compatible with available data. Mineral exploration programmes should be guided by some underlying philosophy of ore-genesis and this is taken as justification for including the present contribution in this series.

During the past few years a wealth of new data has been published concerning palaeomagnetism (Runcorn, 1962), crustal heat flow (Lee and MacDonald, 1963), physical structure and magnetic properties of the ocean floor (Heezen, 1962; Vacquier, 1962; Vine and Mathews, 1963) and major transcurrent faulting (Vacquier, 1962; Crowell, 1962; Wilson, 1962) phenomena which can be most reasonably interpreted in terms of large scale movements within the mantle (Runcorn, 1962; Bullard, 1964; Wilson, 1963). There has been equally important research pointing to the mantle origin of many igneous rocks, not only basalts (Faure and Hurley, 1963) and ultrabasics but carbonatites (Powell, 1962; Hamilton and Deans, 1963) and some granitic rocks (Moorbath et al., 1962; Hurley et al., 1963;Fairbairn et al., 1963; Lyustikh and Saltykovskii, 1961). Furthermore lead (Cannon et al., 1961) and sulphur isotope (Smitheringale and Jensen, 1963) studies have pointed to the mantle origin of many important ore deposits. It has long been recognised by petrologists that there is a relationship between tectonic environment and igneous rock-type (Turner and Verhoogen, 1960) and the occurrence of metalliferous ores. It is the writer's proposal that there is sufficient evidence available in these various fields to warrant a tentative hypothesis linking ore-genesis and petrogenesis to mantle convection. It is suggested that a wide range of crustal igneous rocks, and most large sulphide deposits are derived from convecting mantle material through a process that has operated over most of geological time. Most of the ideas in such a hypothesis have been put forward previously (Holmes, 1944; Wilson, 1963; Rubey, 1951; Spurr, 1923): such novelty as there is arises from the importance that is attached to the very long period of time that is available for the separation and differentiation of low melting point fractions from mantle material as it moves horizontally below the crust. Following from the development of the hypothesis it is suggested that pockets of metalliferous solution collect at the base of active orogenic belts and that the formation of orebodies at shallower levels in the crust depends upon the existence of suitable channel-ways.

Current experimental work being undertaken at the Geophysical Laboratory in Washington suggests that Earth's upper mantle is composed of garnet-peridotite (O'Hara and Yoder, 1963). A more empirical approach by Vinogradov (1961) has indicated that a chondritic composition would be in keeping with the known abundances of the elements. Recent work on Th/U ratios tends to confirm this (Lovering and Morgan, 1963; Lovering, 1964). Garnet-peridotite is not incompatible with the chemical composition of chondrites, but other phases capable of accommodating the volatile elements found in chondritic material must also be present. Present day views favour the theory that Earth formed from the gradual accretion of cold meteoric material (Elasser, 1963). Only subsequently did Earth become sufficiently heated for a nickel-iron 'core' to segregate from a silicate 'mantle'. Urey (1952) has argued that the growth of the core is a continuing process and it is from this that Runcorn (1962) has suggested that there have been periodic changes in the convectional motion of the mantle. The idea that there has been continuous convectional creep* throughout geological time carries with it the implication that there has been continuing geochemical evolution of both crust and core with respect to the mantle. Evidence to support the view that the continental crust has grown throughout geological time has been put forward by a number of authors including Wilson (1954) and Hurley et al. (1962). Evidence cited includes the apparent welding of successively newer orogenic belts onto older continental

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* The term 'creep' seems preferable to 'current' since the motion is within a predominantly solid body, and takes place extremely slowly.

nuclei (Engel, 1963); and the distribution of lead (Marshall, 1965; Gorai, 1960) and strontium isotope ratios (Hurley et al., 1962) in space and time, pointing to the periodic addition of new material from the mantle.

Interesting data collected by Smith (1961) concerning ultramafic intrusions in various parts of Canada can be interpreted in terms of changing mantle composition between Precambrian times and the present. Smith's conclusions which have an important bearing on the present hypothesis, relate to the Mg/Fe ratio of the mantle, and its Ca and S content. Chondrites, which exhibit a range of composition, contain elements not present in garnet peridotite (sensu stricto) which geological and geochemical evidence indicates must come out of the mantle. Recent investigation of Sr^{87}/Sr^{86} ratios by Powell et al. (1962) and Hamilton and Deans (1963) supports geological evidence that carbonatite magmas originate at subcrustal levels. Formation from limestone syntexis is ruled out and it is suggested that they are co-magmatic with alkaline rocks.

Basaltic eruptions in oceanic and continental regions are accompanied by the exhalation of large volumes of steam which is largely derived from the basalt source (Tolstikhin, 1961). The presence of a significant proportion of volatiles, particularly water, in mantle material appears to be well established and is an important factor in the arguments which follow. It should be noted that recent work by Gast et al. (1963) has pointed to the existence of measurable chemical heterogeneities in the mantle, which is again in keeping with the cold accretion hypothesis for the origin of this planet.

Bullard (1964) has recently provided a comprehensive survey of the evidence concerning continental drift, and concluded that the only plausible mechanism is thermal convection in the mantle with rising 'currents' beneath the oceans and descending 'currents' under continental margins. Where the descending limb is on the far side of a continent Bullard suggests the continent can be considered as moving on a conveyor belt without suffering any large stresses. It is evident that there is a well-defined relationship between Earth's superficial structural features and the direction of mantle creep. Whilst the strongest evidence for present day convection has been found from features such as the mid-Atlantic ridge with its discontinuous rifts it is reasonable to suspect any major rift structure as the site of present or past ascending 'currents' (Girdler, 1962; 1963). Thus the East African rift system and, on a smaller scale in the British Isles, the Midland Valley of Scotland must be considered as due to the same underlying phenomena at different periods in time. There is a common petrological link between rocks from these localities which is consistent with the circumstances that are considered to produce them.

It is a fact that magma is generated along rift belts and is intermittently expelled at the surface. If the correlation between rift belts and ascending mantle material is accepted then during its ascent some mantle material is hot enough for the reduction in pressure to permit partial melting to take place. As pointed out by Oxburgh (1964) melting may only occur within the outer shell of a convecting cell, since only this portion is likely to attain a sufficiently high level for pressure-temperature relations to permit any melting. Whether limited partial melting takes place in the outer portion of every cell, or whether it only occurs intermittently through the uneven distribution of hot-spots in the mantle cannot be determined at present. In either case the mechanism by which partial melting takes place is probably a form of zone-melting in so far as at any time only a small proportion of mantle material is within a zone where interstitial fractional melting can take place. Harris (1957) was the first to discuss this process in geological terms. Subsequently Vinogradov (1961) has reported the results of experimentally zone-melting chondrite, and has obtained a progressive partition into dunite and basalt fractions. Vinogradov has shown that the known abundances of the element in chondrite, dunite and basalt is compatible with such a partition process.

The liquid formed by partial melting must in the first instance be an intergranular film, but it seems reasonable to suppose that it would migrate under stress more rapidly than the solid phases with which it was in contact, and progressively coalesce to form larger droplets and pockets.

Yoder and Tilley (1962) have explained from known phase relationships how an 'eclogite' liquid envisaged by them as a fractional melting derivative of garnet-peridotite would at depth give rise to liquids of alkali-basalt type, in preference to tholeiitic-basalt liquids which would be formed at shallower depths. It is an important characteristic of alkali-basalts that they are prominently associated with the rift structures of the world, and from what is known of the conditions necessary for their production this is compatible with their being produced at great depth. Pockets of liquid forming at maximum depth in a vertically lineated column of ascending mantle would be relatively well placed for rapid expulsion whenever a temporary relaxation in horizontal stress permitted. A further important feature of alkali-basalts and their derivatives is that they possess a distinctly higher volatile content than do tholeiitic basalts (Turner and Verhoogen, 1960). Carbonatites, which are also a characteristic associate of rift regions, can only be taken to indicate that not only does partial melting at deep levels favour the production of volatile saturated silicate magmas, but that there are sufficient volatiles left over to form immiscible carbonate-rich magmas. The variety of magmas which can form in suitable circumstances is emphasized by the occurrence of sodium carbonate lava along the East African Rift in Kenya (Dawson, 1962). However, it is notable that rift belts show a marked lack of important sulphide deposits.

In so far as rare metals occur they are dispersed within host rocks, and only rarely in the case of some carbonatites are they in sufficient quantities to form economic concentrations. Thus the Palabora carbonatite in the Transvaal is being mined for its copper content (Anon. 1963), whilst other carbonatites have been worked for rare-earths, thorium and niobium. Although there is every reason to believe (by analogy with meteorites) that sulphides are thinly disseminated through parent mantle material there is apparently no mechanism whilst mantle material is ascending whereby a large volume of concentrated sulphide-bearing liquid can accumulate. Possible explanations for this will be considered below.

It is probable that only a small proportion of the interstitial liquid generated is able to escape to surface from the ascending mass. The bulk of it must continue upwards and then horizontally away from the rift belt. Under conditions of reduced pressure the composition of the silicate liquid will become modified to be tholeiitic rather than alkaline. The layer in which pressure-temperature conditions permit the existence of interstitial liquid most probably coincide with the low velocity layer originally postulated by Gutenberg, and shown by the more recent work of Lehmann (1961) to lie between 60 and 220 km beneath the oceans and somewhat deeper beneath the continents. As the mantle creeps horizontally the temperature at any given level must be falling slowly. Simultaneously the liquid fractions being more mobile and less dense than their environment must tend to migrate slowly upwards, individual droplets coalescing in the process. Thus the liquid must be moving horizontally and vertically into a progressively lower pressure-temperature environment. This would appear to provide an ideal setting for differentiation of liquids to take place. It can be envisaged that there is a layer (becoming gradually thinner towards the convectional downturn) containing an intersititial tholeiitic liquid whilst above this, as successive phases crystallise out, the residual silicate liquid becomes progressively more siliceous. Assuming a rate of movement of 3cm/yr, and a distance of 3,000 km from rift to downturn then 100 m.y. are available for differentiation to proceed to completion.

Recent work on the isotopic composition of lead (Cannon et al., 1961) and sulphur (Jensen, 1959) from a number of major metalliferous deposits in North, Central and South America favours their derivation from the mantle rather than the crust by virtue of the homogeneity of the results. Lead from a large proportion of relatively minor galena deposits in the British Isles shows very little variation in the Th/U ratio of the source material (Moorbath, 1962), much less than is shown by measurements on sequences of crustal igneous rocks (Darnley, in Press). It has been accepted earlier that concentrated silicate and sulphide liquids are immiscible. This is supported both by metallurgical experience and by examination of large basic masses such as the Bushveld, Insizwa, Sudbury (Hawley, 1962) and Skaergaard (Wager et al., 1957) complexes. It seems probable that at an early stage in the fractional melting of mantle material at least three liquids will exist, a predominantly silicate liquid, a predominantly sulphide liquid and a volatile-rich liquid such as produces carbonatites. Of these the sulphide liquid will obviously be the least abundant. It seems reasonable to follow Taylor (1963) in supposing that elements will be partitioned into the silicate and sulphide liquids according to their geochemical affinities and abundances in the mantle. Table I, based on Taylor's work shows how the partition of elements is envisaged as taking place.

TABLE I

DISTRIBUTION OF ELEMENTS BETWEEN SILICATE LIQUIDS AND SULPHIDE LIQUIDS

Element occurrence	Silicate liquids	Sulphide liquids
Abundant elements which enter principal minerals	Si Al Fe Mg Ca Na K O	Fe Cu Zn Pb S As (Co Ni)
Rare elements which enter late-stage minerals	Li Be B Cs Rb Cb Ta U F Sn W Th Rare Earths	Au Ag U Sb Hg Te Se (Bi)
Rare elements incorporated into structures of principal minerals	Ga Ge Cu Ni Co Zn Sr Ba Y Sc Cr Mn Pb Ti	Cd Tl In Ge Sn Ga Mn V (Co Ni)
Rare elements that form relatively early accessory minerals	Zr P Ti Cr S	Mo Bi

Consideration of density suggests that within horizontally creeping mantle sulphide liquid would tend to migrate downwards whilst volatile-rich liquid would tend to migrate upwards. Since silicate liquids must be present much in excess of sulphide, the coalescing of the former liquid must tend to engulf some of the latter in its path, thus providing the sulphides commonly encountered in basic rocks at the surface. It is only recently that the widespread occurrence of sphalerite in basic rocks has been noted, in addition to the usual Fe, Ni and Cu sulphides. This tends to support Taylor's view that the initial sulphide liquid carries the full range of thiophile elements. Sampson and Hriskevich (1962) recently formed the conclusion that the Nipissing diabase contained Co, As, S, Ni, Ag and Bi which gave rise to late stage mineralization.

However, economic sulphide deposits of the rarer metals are seldom associated with basic igneous rocks. On the contrary, their most prominent association as seen at the surface is with silica and carbonates, water, alkali elements and rarer volatile elements such as halogens and boron. This gives grounds for supposing that there may be an interaction between the dispersed droplets of sulphide-rich liquid and dispersed droplets of volatile-rich liquid within the mantle which gives rise to a volatile-rich* 'sulphide' liquid which is of relatively low density. Its rate of accumulation would necessarily be slow and not closely tied to the development of silicate rich liquids. Being largely composed of trace constituents from the mantle its composition might reasonably be supposed to show distinct variations in different areas. Insufficient time for formation of such a liquid could be the reason why major sulphide deposits are not found in the vicinity of ascending mantle 'currents'.

Recent work which provides evidence of the continuous generation of sialic material throughout geological time has been mentioned above. Hurley et al. (1962) suggest that in the case of North America the rate of continental growth as a result of this addition has averaged about 7,000 $km^2/m.y.$ The present hypothesis envisages (as have many others) that the mantle downturn coincides with active or potential geosynclinal development. The mantle downturn will be the most likely position for the gravitational separation of any slightly lower density material out of the mantle into the crust. Furthermore, liquids which have travelled along the full horizontal section of the convection circuit will have had the

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* 'sulphide' is written in parenthesis since it is virtually certain that sulphur and metals are carried in solution as complex ions.

maximum opportunity for the development of a differentiated product viz. a granitic liquid. This appears to provide a possible answer to the old problem of how the vast batholiths of orogenic regions could be the products of differentiation of the small amount of basic rocks either exposed or inferred from gravity measurements in such regions. It is appropriate to mention here that Moore (1959) and Moore et al. (1963) have drawn attention by their 'quartz-diorite line' to the geographic distribution of granitic rocks along the whole length of the western margin of North America. There is a progressive change from east to west which is apparently unrelated to superficial features of the crust or to age of the rocks, whether Cenozoic or Mesozoic. Such a feature could be related to the separation of liquids from successive layers of the mantle at the downturn. It is compatible with the theory that the most differentiated liquid would be at the highest level, and this material may reasonably be supposed to be the first to reach the crust. Discrete pockets of granitic liquid could be expected to accumulate at the downturn and subsequently rise at intervals through the plastic layers of the downbuckled crust being guided upwards by the fan-like distribution of major thrust planes. It is to be expected that a large proportion of sialic material separated from the mantle never penetrates through the crust but merely contributes to crustal thickening - especially in the vicinity of the geosynclinal belt where it must add to the heat flow. Gilluly (1963) has recently pointed out that plutonic activity in the Western United States has not been a necessary accompaniment of normal orogenic processes. This seems compatible with the processes outlined in so far as the level of penetration of plutons might reasonably be expected to vary considerably if they are derived from below the crust rather than generated within the crust as a result of the folding. However, it must be remembered that whilst work on Sr^{87}/Sr^{86} ratios has provided evidence which indicates that some granites are probably produced from the mantle it has also shown that some are not (Bottino, 1963). Thus there is no evidence to suppose that all granites are of subcrustal origin, or that varying degrees of mixing of subcrustal and anatectic granites does not occur (Hurley et al., 1963; Fairbairn et al., 1963).

By contrast with the volume of granitic material that may be supposed to separate from the mantle the volatile-rich 'sulphide' liquid must be of negligible proportions. It is suggested that the common occurrence of sulphide-ore deposits at the surface in the vicinity of, and post-dating granitic intrusions is a consequence of the relative volumetric importance of the parent liquids. The large mass and relatively low density of segregated granitic liquid must favour its gravitational ascent, but its progress must give rise to a wake of structural dislocations, and it is along such dislocations that the ore liquid could readily ascend to the base of the pluton. The overlying large mass of cooling granitic material would tend to insulate the 'ore liquid' and favour retention of its fluidity over long periods of time. This may well explain the spread of the ages of mineralization in various areas such as S.W. England, Portugal, The Erz Gebirge of Saxony, the Rhodesian-Katanga Copperbelt etc. over periods of 200 or 300 m.y. after apparently associated igneous rocks have been emplaced (Darnley, in press). Whatever the ultimate explanation it seems that pockets of ore-liquid are trapped at depth and remain available for intrusion whenever tectonic movements provide a suitable fissure system. It should be noted that many discordant sulphide deposits, by the inclusion of brecciated pre-existing material, give the appearance of forceful intrusion under explosive pressure.

The present hypothesis carries the implication that only granitic material of mantle origin is likely to be associated with important sulphide deposits. Support for this implication has been provided by Moorbath et al. (1962) in the case of a number of Tertiary acid intrusives from the S.W. United States which have associated Cu, Zn and Au, Ag deposits. The Sr^{87}/Sr^{86} ratio of the granitic source material is compatible with a mantle origin. Evidence that the link between granites and mineralization of comparable age is primarily spatial has been provided by the Pb isotope analyses of granite and associated galena mineralization at Balmat, New York. Doe (1962) concluded that the ores were not derived from the neighbouring igneous rocks. Murthy and Patterson (1961) summarised their study of lead from Butte, Montana with the statement that 'the available isotopic evidence constitutes a valid and serious argument against the suggestion that the ores were derived by differentiation and concentration in the late stage fluids of a [granitic] magma'. Whilst a loose spatial and temporal association with granitic intrusives is most typical of sulphide ores, it follows from the present hypothesis that any major planar feature within the crust is a potential channel-way. Thus recently described examples in the British Isles are provided by the Pb-Zn mineralization of Strontian, Argyllshire, which follows Permo-Carboniferous basic dykes (Gallagher, 1964) and by the Cu-Fe-U-Bi mineralization of Mesozoic age which adjoins a major Caledonian fault line along the Solway Firth in Kircudbrightshire. The exposed granite in the vicinity of each of these localities is Caledonian (pre-Devonian).

Metallogenetic provinces, (or metalliferous provinces as they were originally termed by Spurr) have been recognized for over 60 years. As a result of a study of a large number of ore deposits and mineral occurrences in the S.W. United States Burnham (1959) summarized his findings in the following words: (1) metallogenic belts are of vast extent (2) they are largely unrelated in time to the associated tectonic features (3) relatively small segments of them contain deposits that represent as many as four widely separated metallogenic epochs and (4) they are not uniquely associated with a particular kind of intrusive or wall rock, for the same kinds of rocks occur both within and outside the belts. These features seem more compatible with the type of mechanism that has been outlined than with any other that has been put forward. Burnham's demonstration of the existence of belts concentration of particular elements, with copper in the east and gold in the west is similar in pattern, but not in detail to the variation in granitic rock type demonstrated by Moore, and already referred to. Whilst deposits in the east are dominantly Cu with some Au and Ag, deposits in the west are Au and Ag with only rarely Cu. The ore liquids that separate in the east contain a wide range of metals, the liquids that approach the surface further west are apparently depleted in the more abundant metals.

It follows from the hypothesis that has been outlined that pockets of ore-liquid are continuously accumulating as a consequence of convectional creep of the mantle in the disturbed crustal region at the base of active orogenic belts. Age data previously referred to can reasonably be interpreted as indicating the persistence of these pockets over long periods of time (100-200 m.y.). It seems likely that a similar process has operated in the past in connection with each successive orogenic cycle, extending back in time to the period when present 'shield-areas' were forming. It is clear that much basic research needs to be undertaken before the hypothesis can be given any serious weight, but its implications could be of sufficient importance to warrant a systematic testing of its assumptions. Thus many more detailed isotopic and geochemical studies must be made to establish the degree of genetic connection between ore deposits and igneous rocks. Particular attention has to be given to regional studies embracing structural as well as petrogenetic considerations. Geochemical techniques need to be improved in order to provide new data on the composition of large volumes of crustal rocks. Geophysical techniques require substantial development to allow more detailed deductions to be made about the structure and composition of the lower levels of the crust. As an aid to immediate prospecting operations the hypothesis offers no more than a rationalized explanation of features that have long been used by experienced exploration geologists, e.g. the importance of deep seated crustal lineaments on the occurrence of ore, the association of ore with certain types of acid igneous rocks and the overall geochemical enrichment at the trace element level of metals that form orebodies in a district. These criteria can be expected to be refined as more research is undertaken.

Looking into the future, much more ambitious hopes may be entertained if the hypothesis can be established. At a recent Symposium in New York, Gaudin (Anon., 1964) suggested that where future metal requirements could not be met by extraction from sea water, then in-situ leaching of metals from subsurface rocks broken by atomic explosives might be necessary. In an equally speculative vein, the present hypothesis gives rise to the suggestion that it might eventually be possible to tap pockets of ore-forming fluid from very deep levels in the crust. Clearly the problems would be extreme, but no greater than are currently being accepted in attempting to put men on the moon.

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