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OF CANADA

PAPER 69-56

A collection of papers prepared for a
Study of the Earth Sciences in Canada,
commissioned by the Science Council of Canada.

Edited by C. H. Smith

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CONTENTS

Page

Introduction, by C.H. Smith 1

SECTION I GEOLOGY

Stratigraphy, by C.G. Wider 5
Sedimentology, by G.V. Middleton 10
Petroleum Geology, by S.J. Nelson *et al.* 15
Coal Geology, by P.A. Hacquebard and A.R. Cameron 36
Palaeontology, by G.V. Middleton 43
Palynology, by C.R. Stelck 49
Economic Geology, by R.A. Blais 54
Petrology, by J.J. Fawcett 69
Volcanology, by A.M. Goodwin and T.N. Irvine 75
Meteorite Crater Investigations, by M.R. Dence 79
Crystallography, by J.C. Rucklidge 84
Structural Geology, by H.R. Wynne-Edwards 90
Tectonics and Geotectonics, by R.J.W. Douglas 95
Tectonophysics, by J.T. Wilson 99
Rock Mechanics, by D.F. Coates 113
Hydrogeology, by P. Meyboom 119
Permafrost, by T.A. Harwood and R.J.E. Brown 124
Muskeg, by N.W. Radforth 134
Engineering and Environmental Geology, by J.S. Scott 141
Soil Mechanics, by P. La Rochelle 151

SECTION II GEOPHYSICS

Exploration Geophysics, by L.W. Morley 158
Remote Sensing and the Solid-Earth Sciences, by A.F. Gregory and L.W. Morley 170
Marine Geophysics, by D.I. Ross 180
Seismology and Physics of the Earth's Interior, by K. Whitham 187
Geomagnetism, by C.M. Carmichael 200
Magnetotellurics, by D. Rankin 213
Gravity, by J.G. Tanner and R.A. Gibb 218
Geodesy, by L.A. Gale and H. Klinkenberg 231
Geochronology and Stable Isotope Studies 234
Heat Flow, by A.M. Jessop 241

CONTENTS (cont'd)

Page

SECTION III GEOCHEMISTRY

Exploration Geochemistry, by R.W. Boyle 254
Basic Geochemistry (Organic and Inorganic), by R.W. Boyle 262
Physical Geochemistry, by G.M. Anderson 268
Biogeochemistry in Canada, by H.V. Warren and R.E. Delavault 276

SECTION IV GENERAL

History of Earth Science, by D.H. Hall 292
Computer Applications in the Earth Sciences, by C.F. Burk, Jr. and D.A. Sharp 304
"Hard Rock" Core Storage Laboratories, by D.R. Francis 313

INTRODUCTION

The background papers included in this volume encompass most disciplines of the earth sciences. They were prepared in the Spring of 1969, as an experiment to probe the views of Canadian earth scientists on the present importance and future goals of their respective disciplines, and to form a basis for evolving future science policy as it relates to the earth sciences.

Many of the papers were prepared by authors representing disciplinary subcommittees of the National Advisory Committee on Research in the Geological Sciences or the Associate Committee on Geodesy and Geophysics. In the absence of national committees experts were selected to represent certain disciplines. On completion, unsigned copies of each paper were sent to between 50 to 110 reviewers across Canada. The anonymous comments received were, in turn, supplied to each author for use in the completion of his manuscript. Of the forty papers initially prepared, thirty-seven were submitted for final publication.

Each paper follows a similar format which was prescribed when the article was requested. The papers have received minor editing after final submission and represent the views of the author concerned or the committee he represented. Only rarely do they solely reflect the opinions of the reviewers as these were many and varied.

The preparation of these papers was one of the means used to assemble data and views on the earth sciences in Canada for the Science Council's Special Study of Solid-Earth Sciences in Canada. The results of this study have been published by the Council[1, 2]. The papers included herein are published as additional reference material and as documentation of the current views of Canadian earth scientists in the development of earth sciences in Canada.

The Study Group of the Science Council charged with the Special Study (Prof. Roger A. Blais, Chairman) is deeply indebted to all the authors and greatly appreciative of their work which has added immeasureably to the success of the endeavour. We wish also to express our appreciation to the many reviewers who presented useful and valuable suggestions for improvement of the manuscripts.

Charles H. Smith,
Solid-Earth Sciences Study Group,
Science Council of Canada.

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[1] R.A. Blais, C.H. Smith, J.E. Blanchard, J.T. Cawley, D.R. Derry, Y.O. Fortier, G.G.L. Henderson, J.R. Mackay, J.S. Scott, H.O. Seigel, R.B. Toombs, H.D.B. Wilson; Earth Sciences Serving the Nation; Science Council of Canada Special Study, No. 11, 1970.

[2] Earth Sciences Serving the Nation — Recommendations; Science Council of Canada, Report No. 7, 1970.

Section I

GEOLOGY

STRATIGRAPHY

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DEFINITION

Stratigraphy is the study of rock masses - their geometry, spatial distribution, lithology, paleontology, vertical and lateral variation, and relationship to adjacent rocks from which their correlation, age, conditions, of formation and geologic history can be determined. Although stratigraphy is most commonly associated with bedded or layered sedimentary rocks, the principles and methods are applicable in some instances to layered igneous and metamorphic rocks. Fundamental concepts include uniformitarianism, superposition, original horizontality and continuity, faunal succession, cross-cutting relationships, and facies.

The activities of the stratigrapher include (1) the definition and description of both lithologic and paleontological successions, evaluation of their lateral continuity, and their correlation with type and reference sections; (2) the recognition, classification and naming of rock, time-rock, and time units; (3) correlation of successions on a local, regional and intercontinental scale by all available means, including lithology, paleontology, mineralogy, geochemistry, geophysics, isotope age determination; (4) determination of geological age - both relative and absolute; (5) application of the facies concept to establish contemporaneity of different lithologic and paleontologic successions; (6) the interpretative reconstruction of the physical, chemical, and biological history of a rock succession from its original to its present state. The interpretation should include considerations of paleogeography, paleoecology and paleoclimatology. Environmental models for deltas, coastal plains, reefs and piedmonts provide a useful basis for such interpretation. In essence, stratigraphy encompasses the fundamental goal of the science — the elucidation of geological history.

The hydrocarbon and industrial materials industries are almost wholly dependent on sound stratigraphic studies in exploration. The largest group of Canadian geologists is employed in the oil and natural gas industry for the prediction of reservoir rocks which occur as "stratigraphic traps". The distribution and movement of groundwater within Pleistocene glacial deposits is controlled primarily by textural variations which can be revealed by stratigraphic studies.

Concerning applications of stratigraphy in the mineral industry, stratigraphic procedures to prospect for stratiform sulphide deposits in volcanic rocks are well established. The search for many metals — copper, zinc, lead, barite, fluorite, gold, silver, iron, manganese, aluminum and uranium — is guided by concepts and methods of stratigraphy. The Geological Association of Canada has recently published a special symposium on the relationship of mineralization to Precambrian stratigraphy.

An understanding of geologic history provides a sound basis for the cultural appreciation of man's place on earth and in the universe. Stratigraphy, along with the other branches of geology, has an increasing role to play in the conservation of resources and the maintenance of a viable environment for man's continued existence on earth.

PRACTICAL APPLICATION

The data of stratigraphy are basic to an adequate geological inventory of the country. An understanding of the succession, distribution and disposition of rocks and their inherent properties such as mineral composition, texture fabric, porosity and permeability is fundamental in the search for mineral resources. More readily available and rapidly accessible data banks can aid geological interpretation and facilitate the search for economic mineral deposits.

HISTORY

Stratigraphy was born of the efforts of many European workers in the eighteenth century - prominent names include Smith, Guettard, and von Buch.

In Canada, one of the first annual reports of the Geological Survey of Canada, dated 1845, included a detailed description of the coal measures at Joggins, Nova Scotia. Logan's "Geology of Canada, 1863" contains numerous stratigraphic columns, and correlations were made with sections in New York State. Subsequent geologic mapping by federal and provincial governments, and to some degree by university faculty and students, has continued to provide stratigraphic data. In the last fifteen years, the large-scale field parties of the Geological Survey of Canada, supported by helicopters and fixed-winged aircraft, have revealed the basic stratigraphy of the Arctic Islands, the Cordillera, the Canadian Shield, Hudson Bay lowlands and selected areas of the Maritime Provinces.

Canadian geologists proposed the first stratigraphic interpretation of the Precambrian on the basis of commendable studies of the Canadian Shield. New general interpretations based on conventional stratigraphic studies and reinforced by radiometric dates have now been proposed and extend many earlier interpretations. The application of sophisticated stratigraphic, structural, petrographic and radiometric techniques should expand our comprehension in the search for economic mineral deposits.

Stratigraphic studies of Paleozoic and Mesozoic strata of the Interior Plains became more intense after 1947, the discovery year of the Leduc oil field. The search for hydrocarbons has subsequently revealed the potash deposits of Saskatchewan, in addition to other productive oil and gas fields. A large part of the basic data remains in government and company files, but several syntheses can be found in monumental publications of the Alberta Society of Petroleum Geologists and associated groups. Society publications worthy of note include (1) Lexicon of Geologic Names, 1960, (2) Oil Fields of Alberta, 1960, (3) Geology of the Arctic, 1961, (4) Geological History of Western Canada, 1964, (5) Devonian System, 1968, (5) Gas Fields of Alberta, 1969. Synoptic reports of comparable magnitude using similar methods of regional basin analysis do not exist for other parts of Canada. A general resumé of Canadian geology is found in "Geology and Economic Minerals of Canada" published by the Geological Survey of Canda, of which the 5th edition will be issued in 1970.

The application of the facies concept to Canadian geology has not been fully realized but notable studies have been made, such as those for the Upper Devonian of Alberta by H. R. Belyea. Many faunal successions could be considered as sequences of fossil communities controlled by environment. Possibilities of establishing successions resulting rom evolution exist in a number of invertebrate groups of the Mesozoic and Paleozoic. Meaningful results may be expected in the future because the task of describingthe faunas is just begun.

ACTIVITY

Steady progress in field studies and mapping is being made by the federal and provincial surveys. The increased detail on the 1969 version of the "Geological Map of Canada" issued by the Geological Survey is startling when compared with the 1962 version. Further detailed geological maps in areas of special interest on a scale of 1:50,000 are essential for practical and economic applications. The report of activities by C. W. Stearn in the 1966-67 report of the National Advisory Committee on Research in the Geological Sciences would suggest that research in stratigraphy, paleontology and sedimentology has been increasing during the last 6 years and represents about 10 per cent of all reported geological research; but probably an equivalent amount if not more, of activity by the petroleum exploration companies has not been reported. "Stratigraphic studies" are pursued at most Canadian universities but such research commonly falls within the restricted fields of sedimentology and paleontology. These activities, combined with Precambrian stratigraphic studies in the Canadian Shield, suggest that research in stratigraphy constitutes a major proportion of geological work in Canada.

Huge quantities of subsurface data come from drilling and subsequent geophysical logging, particularly in sedimentary basins. The governments of Saskatchewan and Ontario have available computerized banks of stratigraphic data on "tops" and rock types. Some companies in western Canada maintain their own data banks, and consulting firms provide information for a fee. The subsurface data for the Paleozoic of Ontario is available at moderate cost from the Ontario Department of Mines and Northern Affairs; the data bank was created by a unique co-operative effort of governments, industry and a university. Canada leads in the initiation of a national storage and retrieval system of geological data; the system, named SASFRAS, is "user-oriented" and banks of data, regardless of format, can be integrated.

TRAINING

A survey of university calendars indicates that stratigraphy and/or historical geology is taught as a basic course in all departments. However, such courses sometimes involve the memorization of a catalogue of formation and/or fossil names data which can be obtained from the literature. Students from geology departments with a "hard-rock" orientation have been almost traditionally deficient in their understanding of the stratigraphic principles of correlation, faunal succession, facies, classification, and nomenclature. The subject matter is sometimes combined with sedimentation, and then the principles can be overlooked by default because sedimentation has a more evident interest and practical application.

MAJOR OBJECTIVES AND FUTURE TRENDS

Future studies in stratigraphy should include the following:

(1) Increased application of stratigraphic principles to both the Precambrian and Pleistocene rocks of Canada. Radiometric dating establishes broad correlative units but detailed stratigraphic mapping is necessary to provide the basis for regional correlation and synthesis. Results thus far in the Huronian, the Labrador Trough, and sections of the Archean are indicative of the potential. Stratigraphic studies of the Pleistocene have been pursued on limited areas in southern and central Canada.

(2) Initial stratigraphic studies establish the vertical succession of rock units within an area, but imaginative, and even speculative, interpretations using a regional environmental model may indicate a contiguous unit of deposition, and thereby reveal a valuable paleogeographic relationship.

(3) Initiation of catalogues and lexicons of data for eastern Canada, the Canadian Shield, and northern Canada for the entire stratigraphic column; existing catalogues should be kept up to date. The data should be prepared in a form suitable for storage and retrieval by computers using a system compatible with other geological data files. Data in a form susceptible to machine computation can be subjected to trend and factor analysis and compared with such as geophysical, geochemical, and other data.

(4) More adequate description and redefinition of type and reference sections or areas. There are instances where correlations are given with type areas for which only the original, inadequate descriptions are available. Exposures of major boundaries - systems, series - should be located, defined and correlated with the same boundary in other parts of the world. Material from important reference localities should be stored and catalogued in a central library for study by all qualified geologists.

(5) Biostratigraphic studies in which the principal influence on the changing faunal and floral succession has been evolution, and not environment. Integrated lithological and paleontological studies can provide the basis for paleoecological and paleoclimatic reconstruction.

(6) More subsurface exploration of the stratigraphy of Canada's continental shelves and offshore deep parts of the ocean.

CONCLUSIONS

(1) Geology departments should examine their curriculum to insure that the principles of stratigraphy, as such are not overlooked. The traditional "hard-rock" departments have a particular responsibility to ensure that their students understand the principles and can apply the methods. Students of stratigraphy must be exposed to rocks in outcrop. At a more advanced level, students should become familiar with the fundamentals of automatic data processing and the potential of statistical techniques such as trend and factor analysis.

(2) Federal and provincial surveys should continue field studies with a trend toward detailed mapping once the large scale regional examinations are completed. A program of remapping should be initiated in order to apply newly-developed geological concepts and techniques. Application of the stratigraphic code should be universal from the Precambrian to the Pleistocene.

(3) Permanent local committees should be formed to organize, standardize, and synthesize the stratigraphic data for specific regions. Synoptic studies, comparable to those on the Devonian of western Canada, should be initiated for other systems - and in other parts of Canada.

A central committee should be created to co-ordinate activities. A central agency could provide counsel, expedite the use of computerized data banks for research, and provide liaison between institutions and organizations which require the data. Regular symposia such as the Biostratigraphy Seminar organized by geologists in Ontario and Quebec should be held to elucidate stratigraphy on a local, national and international basis.

(4) Knowledge of subsurface stratigraphy is largely limited to those areas explored by companies in the search for ores and hydrocarbons. Data from oil and gas drilling normally become public information after 1 year. A concerted effort should be made to collect and make available, in a similar fashion, the information from mining operations. Surface mapping allows limited interpretation at depth; some government-sponsored deep drilling should be done in these areas which have not yet been explored by industry, although industry could be encouraged to contribute. Arrangements of this type are used in the search for hydrocarbons in the Arctic.

(5) Encouragement should be given to multidisciplinary, integrated studies.

(6) Detailed lithofacies and, where possible, biofacies analysis of regional basins should be pursued in order to establish the sedimentologic and tectonic history. Interbasinal comparisons on a local scale (such as the Carboniferous of the Maritimes) or on a continental scale (such as the various basins which existed within the Canadian Shield during the Precambrian) will provide an understanding of continental behaviour during any one span of geologic time.

(7) Studies of igneous and metamorphic rocks, and stratiform ore deposits should be pursued with the objective of applying stratigraphic principles as are commonly used for sedimentary rocks. Sequences of volcanics especially within the Canadian Shield and the Cordilleran should be studied to determine the centre of effusion; time and duration of activity; sequence, volume, and type of material; relationships to adjacent sedimentary and other rocks; and the history subsequent to solidification. The stratigraphic studies of metamorphic rocks will be more complex because of regional and local metamorphic facies.

SEDIMENTOLOGY[1]

DEFINITION

Sedimentology is the study of consolidated and unconsolidated sediments and the processes by which they were formed. The term is more or less synonymous with Sedimentary Petrology but, to some extent, the latter term has become associated with studies of sedimentary rocks by petrographic methods (such as thin sections, heavy mineral and chemical analysis). For this reason many workers now prefer the term 'sedimentology', which suggests a broader field including theoretical and experimental studies and studies of Recent sediments, as well as studies of ancient sedimentary rocks.

Stratigraphy (q.v.) is a broader field than sedimentology but it does not include all of sedimentology. Stratigraphy is concerned with sequences of rocks, and thus all aspects of rocks which relate to their formation as part of a sequence are included in stratigraphy. But sedimentology additionally is concerned with general laws of sedimentation (settling, sediment transport, chemical equilibria in low-temperature aqueous systems, etc.), and with processes acting on Recent sediments, without necessarily being concerned with stratigraphic sequences. In practice the two fields are closely related and to a large extent interdependent, but different professional societies and journals have developed to serve the specific needs of sedimentologists.

Sedimentology is also closely related to geomorphology, the study of landforms. In Canada, geomorphology is often considered to be part of geography rather than geology, but the reverse is true in some other countries. There is a wide degree of overlap in the processes studied by the two disciplines, but the emphasis in sedimentology is on sediments rather than on landforms.

SIGNIFICANCE OF RESEARCH

Sedimentology seeks a scientific understanding of materials which cover 75 per cent of the continental surfaces and almost all of the floors of the ocean basins. The discipline has made significant contributions to basic knowledge of the earth and earth history.

Careful study of unconsolidated sediments and sedimentary rocks leads to their better economic utilization as construction materials and is essential for exploration and development of oil, gas and economic deposits of minerals which these rocks commonly contain. An important aspect of sedimentology is the study of changes in rock composition and texture resulting from consolidation, compaction and other diagenetic processes; these processes play an important role in the development of porosity and permeability and consequently in the development of resources such as groundwater, oil, gas, coal, potash, salt, lead-zinc, iron and uranium. The practical

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[1] Prepared by the Subcommittee on Stratigraphy, Paleontology and Sedimentation of the National Advisory Committee on Research in the Geological Sciences, G.V. Middleton, Chairman.

application of sedimentology to the oil industry is probably receiving adequate attention in Canada directly, or indirectly through the oil company research laboratories in the U.S.A. It is doubtful, however, if the application of sedimentology to the other mineral industries, engineering or to marine sciences have yet received sufficient attention.

The study of sediments in the oceans and lakes (especially the Great Lakes) is necessary for recreational, conservational, economic and other purposes of social or scientific value.

Knowledge of the basic processes of sedimentation has many scientific and practical applications (including many outside of geology), such as in waste disposal and pollution control, ecology, sedimentation in rivers and reservoirs, and sedimentation processes used in mining and chemical engineering.

HISTORICAL DEVELOPMENT

Sedimentology has several historical roots. The main trends have been as follows:

(i) Microscopic studies. Initiated by Sorby in the 19th century, reaching a 'classical' phase with the work of Lucien Cayeux in France (1900-1940), and continuing strongly at the present time. A strong Russian tradition exists, known in English-speaking countries mainly through the work of P.D. Krynine (1930-1960). In the last ten years much attention has been given to the petrography of carbonate rocks.

(ii) Textural studies, especially size and shape analysis. Leading exponents have been Wentworth (1922-1936) and Krumbein (1932-1941). A recent development has been petrophysics, which studies the relations between rock fabric, the enclosed fluids and the bulk physical properties of the rock, such as electrical resistivity.

(iii) Environmental studies. These have a long history because one of the main aims of sedimentology has always been environmental recognition. Early work was summarized by Twenhofel (1926) and there have been numerous modern descriptive studies of Recent environments of deposition and environmental reconstructions for ancient sediments.

(iv) Experimental physical studies. Most of these have been carried out by practising engineers or by independent investigators such as R.A. Bagnold (1930 to present).

(v) Paleocurrent studies. The importance of mapping vector properties of sedimentary rocks was recognized by Sorby in the 19th century, but the full development of these studies is a relatively recent phenomenon, associated mainly with the names of Kuenen in Holland and Pettijohn in the U.S.A.

(vi) Geochemical studies. There has recently been a rapid growth of interest in sedimentary geochemistry and diagenesis stemming from theoretical and experimental work on low temperature, aqueous systems by Garrels (1950 to present), from chemical oceanography, and from the need to understand diagenetic processes as they relate to the origin and occurrence of petroleum and other mineral deposits.

(vii) Studies of clays and shales. Much progress has been made in these studies since X-ray techniques revealed the crystalline nature of clays in the 1930s. Clay mineralogy is an interdisciplinary study with important applications in soil science, ceramics and geotechnics as well as in sedimentology.

Sedimentology evolved as a separate discipline partly in response to the stimulus of the oil industry. Early studies of heavy minerals were undertaken as a technique for correlating oil sands in the absence of fossils. More recently, oil companies have financed many studies of both Recent and ancient sediments in an attempt to discover how to predict those properties of sedimentary rocks, such as porosity and permeability, which control the occurrence of hydrocarbons.

The first professional society to promote sedimentology, the Society of Economic Paleontologists and Mineralogists was founded in 1927 as an offshoot from the American Association of Petroleum Geologists: the Journal of Sedimentary Petrology was first published by S.E.P.M. in 1931.

PRESENT LEVEL OF ACTIVITY

Conventional criteria such as growth of journals and membership of societies indicate that sedimentology is a young science which is still in a period of growth and expansion.

Canada, however, has lagged in the development of sedimentology, whether in government, industry or the universities. Only in 1966 was the topic 'sedimentation' considered sufficiently distinct from stratigraphy to be included in the title of the relevant subcommittee of the National Advisory Committee on Research in the Geological Sciences. The Geological Survey of Canada has not laid much stress on sedimentological studies, in spite of the example of a few pioneers, such as E.M. Kindle. In recent years, however, an increasing number of Survey publications have included descriptions and maps of sedimentary structures and detailed microscopic and geochemical studies of sedimentary rocks.

Provincial Surveys have generally also neglected sedimentology, except for the Alberta Research Council and the Saskatchewan Department of Mineral Resources, which have conducted sedimentological investigations relevant to the petroleum industry. Ontario Hydro has made petrographic studies of road constructional materials. Recently (1966) the Federal Geological Survey established an Institute for Sedimentary and Petroleum Geology in Calgary. Only in 1960 was a branch of Marine Geology founded and in 1963 it was incorporated in the Bedford Institute of Oceanography. In 1968, a section of Limnogeology was established at the Canada centre for Inland Waters at Burlington, Ontario.

Courses in sedimentology or sedimentary petrology, separate from those in stratigraphy, were taught in some Canadian universities at least as early as 1947. At present, teaching and research in sedimentology is carried out in almost all of the major universities.

In Canada, a leading role in the development of sedimentology has been played by the Alberta Society of Petroleum Geologists which sponsored the very successful Bulletin (1953), now the Bulletin of Canadian Petroleum Geology; and in the east by an informal group in Halifax which began publication in 1965 of Maritime Sediments. The national geological societies, including the Geological Association of Canada and the geology section of the Royal Society, have until recently done little to aid the growth of sedimentology.

NEED FOR INCREASED ACTIVITY

Accelerated growth of sedimentological research activities in industry, government (especially Federal Government) and universities should be encouraged. Expansion in the universities is already under way and will continue in response to the growing demand for well-trained sedimentalogists and pressures from the international academic community. The Federal Government has made important advances recently. Unfortunately, most of the research by companies operating in Canada is done at present in the U.S.A.

Many universities offer adequate undergraduate training in sedimentology but at present only a few support Ph.D. studies in this area. While most established universities can do so, few of the emerging universities can support graduate studies in sedimentation. It may be that a large number of centres of specialization is not required, but the existing centres should be better equipped and more adequately staffed.

Students trained in sedimentology should also be adequately trained in physics, chemistry and mathematics. An adequate doctorate program should include (besides courses in geology) provision for studies in oceanography, physical chemistry, fluid mechanics and statistics. Many universities in Canada are not yet meeting these minimum standards.

Students undertaking sedimentological research in physical geography are often less well trained in basic sciences than students in geology: for these students, further science training in graduate school is desirable.

FUTURE TRENDS

Future trends in sedimentology will include:

(1) comprehensive regional investigations of Recent and ancient sediments and sedimentary processes.
(2) physical experimental studies.
(3) geochemical studies (including studies of diagenesis).
(4) development of mathematical models.
(5) geotechnical studies (applications of soil and rock mechanics to sedimentary studies).

In general, there will be more emphasis on the analysis of processes and less on descriptive aspects of sedimentary rocks. For this reason, sedimentologists will be required to have a higher degree of preparation in the basic sciences than has been the case in the past.

Some of the techniques developed during the past few years will become part of the standard techniques used by every geologist in the routine investigation of sedimentary rocks. Examples include: (i) field recording of sedimentary structures and especially, paleocurrent indicators, (ii) standard petrographic techniques, especially as applied to carbonate rocks, (iii) clay mineralogic techniques, (iv) automated methods of data processing and analysis (e.g. trend analysis, factor analysis).

Certain practical applications will become increasingly important, such as in pollution studies, the search for metallic minerals and construction materials, in exploitation of oceans and lakes and in engineering investigations.

CONCLUSIONS

1. In view of the economic importance of sedimentary rocks, increased support should be given to research on the understanding of ancient sediments.

2. Research in Recent sediments, particularly Recent marine sediments, should be supported in Federal Government agencies and universities. It is particularly imperative that this work should be further developed on the west coast. Sedimentological studies of Recent and Pleistocene glacial sediments should also be encouraged.

3. Steps should be taken to encourage research in applied sedimentology by Industry in Canada: the results of such research should be made generally available. Research in applications of sedimentology to industry should not be left to company laboratories located outside Canada. The importance of stratiform deposits of metallic minerals warrants more research in sedimentology by mining companies than has been done in the past. Such research is particularly appropriate in Precambrian sequences, from which much of Canada's mineral wealth is derived.

4. Chemical sedimentology (and associated branches of chemical oceanography and limnology) should be further developed, especially in universities.

5. Funds should be made available for installation of experimental sedimentological equipment in a few institutions. An attempt should be made to foster the growth of interdisciplinary studies in the areas of (i) sediment transport and experimental physical sedimentology, (ii) soil mechanics and physical sedimentology, (iii) computer simulation of sedimentation processes.

PETROLEUM GEOLOGY

S. J. Nelson, University of Calgary
J. M. Andrichuk, Andrichuk and Edie Consulting
C. R. Evans, Imperial Oil Limited
C. R. Hemphill, Home Oil Company Limited
J. Hodgkinson, Atlantic Richfield Company
W. Kirker, Wintershall Oil of Canada
R. W. Macqueen, Geological Survey of Canada
M. S. Stanton, Chevron Standard Ltd
P. Verrall, Chevron Standard Ltd
J. W. Wonfor, Gulf Oil Canada Limited
U. F. Wissner, Mobil Oil Canada Limited

INTRODUCTION

Petroleum geology is a synthesis of disciplines pertaining to petroleum exploration. The most germane sciences are stratigraphy, palaeontology, structural geology, reservoir geology, logging, petroleum evaluation, geochemistry and geophysics - although geomorphology, photogeology and engineering geology often have extremely important roles.

The finding and delineation of oil and gas pools is usually taken as the aim and scope of petroleum geology, although it has become connected with the study of evaporite and potash deposits through their common association with oil-bearing and gas-bearing strata.

Although petroleum was discovered in Canada in 1857, it was not until 1947 that the significant Leduc discovery made the petroleum industry important to Canada's economy. The industry's growth since then has been impressive - from generating only 5 per cent of Alberta's total personal income in 1947, to producing 47 per cent of it in 1964 (as against agriculture's 31 per cent). This growth was also largely responsible for adding over one and a half million to the population of the Prairie Provinces during the past two decades (1).

As for the petroleum industry's importance to the rest of Canada, an economic study (2) has shown that oil companies buy $300 million worth of goods in eastern Canada every year. Significant discoveries off the east coast of Canada could thus change the economic climate of the Atlantic region dramatically.

Although the industry's administrative centre is in Calgary, the search for oil and gas has gone far beyond the boundaries of Alberta - to the Arctic and to the offshore regions of British Columbia and the Atlantic Provinces.

In 1964 (the last available record of the Alberta Bureau of Statistics), 826 geologists and 345 geophysicists worked in Alberta. These men were responsible for spending $161 million on geological and geophysical activities. In 1967 this figure increased to $273 million.

The industry has also established major scientific communities in western Canada. A great many scientists have been attracted to the west from abroad, and of these a fair number have been Canadians returning from employment in the United States. In 1961 Alberta, with only 7.6 per cent of the nation's labour force, had 42 per cent of its professional geologists and 30 per cent of its professional mining engineers. In 1967, 90 per cent of Canada's petroleum geologists were concentrated in the three western provinces.

The location in Calgary of the Alberta Oil and Gas Conservation Board and a regional office of the Geological Survey of Canada is an almost direct result of the industry's influence. The University of Calgary, too, would probably have grown much more slowly without the petroleum industry.

RESEARCH IN PETROLEUM GEOLOGY

This section reviews the various disciplines of petroleum geology and the research trends within them. The authors acknowledge their great debt to the late Dr. R. W. Landes, of Imperial Oil Limited, whose paper Geosciences in the Petroleum Industry (4) has provided much of the material for the review.

Stratigraphic and Facies Geology

Definitions

Stratigraphy has been defined as "that branch of geology which treats the formation, composition, sequence and correlation of the stratified rocks as parts of the earth's crust"(3). This is a very broad concept and obviously the aims of stratigraphy cannot be fulfilled without incorporating knowledge obtained from petrology, petrography, sedimentology, palaeontology, historical geology, biolocy, ecology, palaeoclimatology, geomorphology, structural geology, metamorphic geology, and geophysics.

Façies studies constitute an integral part of stratigraphy and involve the consideration of relationships between lithologic entities (lithofacies) and biologic assemblages (biofacies). Facies analyses are an important tool in petroleum geology, where they help define significant changes in depositional environment and the palaeoecology of biofacies, with a view to interpreting sedimentary history and predicting favourable reservoir trends.

Stratigraphic studies for petroleum exploration have evolved from essentially lithologic descriptions to actual interpretations of environment within relatively few years. Lithologic descriptions are still basic, but with more refined methods of examination and a more imaginative approach (based largely on the study of modern environment), the geologic history now unfolds much as a series of "landscapes". This imaginative approach is not a mere academic embellishment in the highly competitive oil industry -

it is a vital necessity. The days when major discoveries - and reputations - were made on obvious surface features are long since past.

Past Research

In an excellent recent paper (4), Landes reviewed the progress made in carbonate and clastic stratigraphy over the last 20 years. He traced the evolution of thinking in such fields as reef ecology and geometry, the mechanics of basin fill, transgressive-regressive sedimentation, and others. Landes' report is so lucid and pertinent that a summary of his comments on stratigraphy and facies is given below.

> Detailed examination of cuttings and cores from wells and samples from outcrops provides basic data for interpreting stratigraphic and facies conditions used by industry to determine areas favourable for oil production.
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> Discovery of oil in a Devonian reef in Alberta in 1947 gave considerable impetus to studies of carbonate rocks and associated evaporite and shale sequences, with emphasis on reef bearing facies. Stratigraphic and facies concepts are used routinely to reconstruct basin framework and depositional environments in ancient carbonate sequences. Moreover, much research has been done on lithology, ecology and morphology of carbonate banks and reefs presently forming in the Caribbean and Pacific areas. Principles learned from these studies have been applied to understanding ancient petroleum-bearing banks and reefs.
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> Reef distribution in any basin is complex and is related to structurally or depositionally controlled palaeotopographic shoals on the sea floor. Facies relations in the reef platform and characteristic distribution patterns of reef-derived carbonate muds and silts in stratigraphically equivalent shales are being used to outline areas considered favourable for reef development.
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> Reef to off-reef stratigraphic relationships are of great importance in exploration, particularly in areas where velocity differences between reefs and enclosing rocks are not significant and thus the effectiveness of the reflection seismograph is hindered.
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> The improved techniques in describing and interpreting carbonate rocks have increased effectiveness in predicting reefs and other porosity trends in bedded carbonate rocks. Terminology and classification of carbonate rocks have been standardized. Fossil studies have been highly refined for more precise correlation of stratigraphic units needed for analysis, and quantitative distribution of indicator fossils has been mapped for reconstruction of environmental conditions, although a tremendous amount of work remains to be done.
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> Despite the large reserves of oil in Cardium sandstone of the Pembina field, sandstones have received less attention than carbonate rocks in the last 15 years. With exploration moving actively into the Arctic

coastal area and the offshore Atlantic and Pacific, sandstone and shale studies assume great importance. There is a need to be able to predict at an early stage of exploration the three-dimensional distribution of porous sandstone bodies. Significant advances in mapping and understanding the geometry of clastic bodies or wedges have resulted from new technology and equipment of seismic surveys of the continental margins.

In conclusion, current facies investigations in petroleum exploration and production are directed toward methods of locating and predicting porosity distribution, and to determine the relationship of source rocks to reservoir rocks and the character and distribution of stratigraphic traps. Diagenetic and other chemical processes affecting sediments, including cementation, leaching and dolomitization of reservoir rocks, require further detailed research.

A further development of increasing importance in stratigraphic studies is the use of computer technology in problems ranging from the processing of simple but voluminous control data to the handling of complex multivariate parameters. In the first case, the computer relieves the stratigrapher of the tedious and time-consuming task of assembling, plotting and processing vast quantities of simple data. In the second case, it procides the means of integrating and analyzing the complex interrelationships of numerous different variables - a task which might otherwise prove impossible.

Future Research

Stratigraphic research should be oriented toward finding solutions or improving techniques in known areas of deficiency. Further directional control of effort in the oil industry will be dictated by specific problems as they arise in old or new petroliferous regions. The following list discusses a few of the areas in which further research is necessary.

1. Much more work should be done on the detailed ecology of bioclastic carbonates and reef environments, with increased attention on internal morphology and growth stages.

2. Increased research into sand-shale sedimentological mechanics and geometry is required as a result of the Alaskan Prudhoe Bay - Sag River discoveries, activity in the Mackenzie delta, and Panarctic activities and drilling in the Sverdrup Basin of the Queen Elizabeth Islands.

3. Further research is needed into the typological identification of stray sands. The early recognition of type of sand mass (beach, bar, channel, sheet, etc.) and its probable geometry relative to basin morphology is important for predicting trends.

4. The analysis of palaeostructure should be more widely studied, as its influence on subsequent sedimentation patterns - even for relatively minute changes in structural conditions - is often dramatic.

5. The earth's crust is a vital, mobile skin whose pulsation and fragmentation depend very largely on subcrustal forces. Basement structure and deep-seated geophysical studies reveal many features pertinent to Phanerozoic sedimentation and petroleum geology. The current emphasis on continental drift and sea-floor spreading is but one aspect of a wide spectrum of studies important to the stratigrapher.

6. The validity of facies studies depends on the accuracy of time datums. This in turn calls for continued massive effort in the fields of palaeontology and palynology. The development of reliable absolute or relative age dating techniques by some sort of time-dependent geochemical or radioactive parameter within the sedimentary section would be an enormous boon to facies studies - if such physical parameters actually exist.

7. Reservoir rocks are only as good as the net effect of postdepositional processes acting on them. The problems of diagenesis in general, and of dolomitization and silicification in particular, are perennial and important ones that will unquestionably receive much future research effort.

8. The entire subject of evaporites is receiving increased attention. Avid proponents for both a shallow-water and a deep-water origin for the same salt body can often be found among groups of geologists. When such a fundamental concept as this is still being heatedly debated, there is obviously ample scope for evaporite research.

9. The recent impetus in Canadian offshore activities will focus much more attention on the structure and stratigraphy of the continental shelves. If one accepts the modern concept of continental drift, part of the answer to local stratigraphic shelf problems may well lie thousands of miles across the Atlantic. Geophysical studies and a program of critically located deep offshore wells (such as the Joint Oceanographic Institutes Deep Earth Sampling (JOIDES) program) will help provide new answers.
   It is one thing to find oil in deep water, but quite another to solve the problems of deepwater completion techniques. A solution to this problem will naturally influence the direction and scope of offshore stratigraphic studies.

10. Remarkably little is yet known about source rocks, although much is assumed. The whole field of source rocks, formation waters, hydrodynamics, oil migration and petroleum geochemistry in general offers challenges for future research.

11. It is obvious that the effectiveness of stratigraphic studies will be enhanced by research and development related to new and improved methods and equipment in the fields of well logging and geophysics.

12. Continued research in the fields of infra-red photography, radar imagery, geochemical direct-detection, and other exotic methods will indirectly aid stratigraphic interpretation.

13. Detailed bathymetric charts for all our offshore waters are urgently needed for the conduct of offshore stratigraphy and for petroleum geology in general. Charts of this type will soon be available for the Scotia Shelf and Grand Banks, and should be expedited for other offshore areas.

14. Research in computer techniques, ranging from storage and access to the routine processing of vast quantities of data and the complex studies of multivariate factor analyses, will result in great advances.

Palaeontology

Definition

Palaeontology is the science of ancient life and embraces three main branches:

1. Palaeozoology, the science of ancient animals;
2. Palaeobotany, the science of ancient plants;
3. Palaeoecology, the science of the interrelationship between ancient living organisms and their natural environments.

Special disciplines within these branches, such as micropalaeontology and palynology, need no separate treatment. Their special status refers only to techniques which are dictated by the minute size of the subjects under study; it does not involve separate scientific principles. However, the small size and abundance of the fossils they deal with makes them of particular importance to the petroleum industry. They provide by far the greatest amount of palaeontologic subsurface information.

Evolution of life through geologic history, and environmental control of the habitat of life, are the scientific principles basic to applied palaeontology. Applied palaeontology provides a chronologic framework for biostratigraphic correlations and age-relationships between different rock units. It represents the most important tool for relative age determinations in potential petroleum-bearing strata. For the petroleum industry's needs it is an efficient and fast method, better and much cheaper than absolute age dating by radioactive methods, and it will keep this place in the future.

A clear understanding and definition of the species as the fundamental unit is of utmost importance for both purely scientific and applied palaeontology. Therefore, the reliability of age determinations as well as the discrimination of different depositional environments depends directly on the reliability of the palaeontologic identification.

Present and Future Research

Research in palaeontology appears largely confined to biostratigraphic applications. Yet these applications will have much greater potential if reassessed in the light of modern biologic and palaeobiologic knowledge.

Worldwide distribution of organisms in time and space throughout geologic history calls for a synthesis of the large amount of scattered information. Such a synthesis will greatly improve the successful application of our present knowledge and eliminate costly duplication of basic research efforts.

The established trend in geologic and biologic sciences toward quantification of data and away from the outdated mode of descriptive sciences demands reorientation in palaeontology.

Future research in palaeontology should be directed toward systematic, taxonomic studies employing modern concepts of population statistics. Microfossils (foraminifers, ostracods, conodonts, nannoplankton, spores and pollen, etc.) are the groups best suited for this purpose. Furthermore, they are, as already mentioned, of greatest importance to the petroleum industry.

A thorough, up-to-date, palaeobiologic knowledge represents the base on which we can build, expand and improve the potential of applied palaeontology. A palaeontology that fulfills the basic requirements for successful and economic application by practising palaeontologists and biostratigraphers is based on clear definition, reliability of taxonomic identification, and verification of the results by other workers.

Structural Geology

Definition

Structural geology is defined as the branch of geology which treats of the forms of rock masses, and in this limited sense it is an essentially geometric discipline applied to data made available from many other branches of geology.

More generally, geometric analyses are supplemented by a study of chronological development, constituting a problem in kinematics, and further by speculation on the forces that have deformed the rocks, involving a study in dynamics. Tectonics is the generic term applicable to these more extended aspects of structural geology.

Past Research

R. W. Landes has recently published an excellent review of the relationship of structural geology to petroleum occurrence which, because it is germane, is summarized briefly below.

> Landes begins with a discussion of the anticlinal theory of oil accumulation. He then discusses the relations between continental drift, palaeomagnetism, the geological character of the ocean floor, and the nature of sedimentary basins along the continental margins, where

large petroleum accumulations are bound to occur. He proceeds to discuss the rheologically plastic nature of large rock masses, "the paradox of solids that flow", and the bearing of this upon the patterns of nappes, folds and thrust faults seen on the flanks of orogenic belts. He then notes that considerable progress in elucidation of the nature of transcurrent faulting has been made, and remarks that rocks normally respond to stress in accordance with a few simple mechanical principles. These responses are similar in similar tectonic environments around the world, and form the basis for a significant subdiscipline, comparative structural geology, which allows rational classification of the forms associated with these various tectonic styles.

Future Research

The petroleum industry must certainly continue to be interested in all forms of structural geology research as well as in new research in the field of computer applications. Suggestions for emphasis are as follows:

1. Present industry activity in Canada's offshore areas will attach great significance to the relationship between continental drift and the development of sedimentary basins along the continental margins. Research into this subject will involve continuing study of magnetic, gravity, seismic and oceanographic data, and of the nature of the transition zone between simatic and sialic "crust". Seismic work, especially reflection seismic, will be of increasing importance in delineating structures within the marginal sedimentary prisms.

2. As more data become available, work will proceed from a purely geometric analysis of structures to a study of the mode of their development, as suggested by Currie (5) and others. The atlas "Geological History of Western Canada" (6) contains a number of implicit studies of this type (usually by serial isopaching and ancillary structure contouring), and others will undoubtedly be undertaken. These will be of great importance, particularly in the western Canada sedimentary basin from the United States border to the Arctic Ocean, in determining the timing of the development of structures throughout the Phanerozoic Eon and the consequent understanding of the mode of hydrocarbon migration into structural traps (or out of them). An additional benefit will be a clear understanding of the effect of structural development on contemporaneous sedimentation. Similar studies will be of great use in the Canadian Arctic, and to a lesser extent in the Pacific and Atlantic offshore areas.

3. In most parts of Canada a large amount of field work remains to be done to determine the nature of structures well enough for valid comparative studies. Such work will doubtless be undertaken either by the Geological Survey of Canada, industry or the universities. Possible subjects are the analytical comparison of the Mackenzie Mountains with, say, the Wyoming Rockies or (as has already been attempted by Bally, Gordy & Stewart) of part of the southern Canadian Cordillera with the Alps; or the Rockies with the folded Appalachians. Such comparisons commonly illuminate the nature

of each of the compared examples, and this kind of analogical reasoning will continue to improve our understanding of Canadian structures. The scale of objects involved in comparison may, of course, range down to that of individual folds or faults or even smaller structural features.

4. Computers will be used more and more for solving structural problems. Several different approaches will be used, including:

   (a) The fitting of structural data to formal mathematical surfaces (trend analysis).

   (b) Fourier analysis of structural data, combined with various filtering devices, to determine the nature of subtle structures not otherwise easily separable from the regional grain.

   (c) Computer "modelling" of hypothetical structures for comparison with actual field examples. Very little of this kind of work has as yet been undertaken but its potential is obviously great.

   (d) Continued improvement of the use of computers for retrieving and plotting structural data.

   (e) Development of methods of statistical analysis of structural data, by computer, to determine the nature of the structural elements involved.

Rock Mechanics

Research in rock mechanics will continue within the universities and institutions such as the Mining Research Centre in Ottawa, but relatively little will be done by the petroleum industry except perhaps with respect to the technology of fracturing formations in well bores. Suggestions have been made for using photoelastic models to elucidate the nature of stresses in three dimentions, and this seems a promising field. Other model studies, designed to throw light on the nature of such features as thrust terrains or evaporite diapirs, could be undertaken on the analog principle. These could contribute greatly to our understanding of such features as have similar analog studies on Gulf Coast salt domes. There is also a possibility of using dry holes for measuring areal variations in crustal strain down to approximately 10, 000 feet. This kind of study, however, would seem more suitable for an academic institution than for industry.

Structural Geometry

Several regional geological studies designed to shed light on structural problems have been mentioned by Dahlstrom (7). They include the following:

(a) Structural Compilation of Eastern Cordillera. This project is now proceeding under the aegis of the Geological Survey of Canada and the Alberta Society of Petroleum Geologists.

(b) Appalachian Ribbon Project. No work is being done at the moment, but this suggested analysis of a major mountain system certainly warrants more consideration.

(c) Study of continental margins by widely spaced reconnaissance seismic lines. Dahlstrom suggests that the federal government should consider undertaking this study. More recent information indicates that such a study is now under way. However, it could save considerable money and duplication of effort if industry were persuaded to release regional seismic data from offshore areas, after a reasonable length of time, for such a worthy purpose.

In addition to the above studies, the Geological Survey, universities and industry are all engaged in surface-mapping projects involving the recording of structural geometry. These less exotic labours are certainly still worth encouraging, since they will continue to supply much of the basic data required for future synthesis.

Reservoir Geology

In the past, the goal of the reservoir geologist has been to guide development drilling in oil or gas fields to locations where structural elevation and reservoir characteristics are favourable, and thereby delineate a field or pool with the fewest dry holes.

With the advent of computer technology, reservoir engineers have lately come to need much more detailed knowledge of the associated rocks. Maximum ultimate recovery from any reservoir must be based on sound geological knowledge of the conditions that resulted in the formation of the reservoir, including structural deformation, organic activity, diagenesis, hydrodynamics, sorting, facies changes, and other factors.

Although it was recognized early that a multiplicity of factors affected petroleum recovery, the difficulty of handling so many variables forced the engineer to base his calculations on simplified models. High-speed computers allow consideration of the effects of an infinite number of variables, and their use will result in improved primary, secondary and possibly tertiary recovery from reservoirs.

Increased understanding of facies distribution in both sandstones and carbonates has permitted more detailed geological studies of petroleum reservoirs. This is particularly true where enough diamond drill cores are available. Insofar as such cores provide the basis for useful future research in several disciplines, they should be acquired on a more systematic basis. In addition, further research should be directed toward techniques of continuous coring.

Heterogeneous conditions within a reservoir may cause fluids to move through it in a preferred direction. It may be possible to predict such behaviour through detailed geologic studies. This, in turn, could cause radical changes in the design of a secondary-recovery project, with subsequent savings and increased ultimate recovery.

Considerable research could be done on relating porosity and permeability values to depth of burial, pore geometry and capillary pressure for known reservoirs in western Canada.

The fact that water and gas injection are the most common means of increasing reservoir energy has not precluded a proliferation of other methods for augmenting natural reservoir energy, such as steam injection, underground combustion, L. P. G. injection, or water and chemical additives. Examples of the benefits of research in this area can be seen in the fields producing from the Swan Hills formation, which have been subjected to pressure-maintenance and secondary-recovery schemes. Most of these involve water-flood techniques and have increased the ultimate recoverable oil by some 1.4 billion barrels. The pinnacle-reef structures of the Rainbow area lend themselves to vertical-displacement miscible-flood projects which are expected to increase recovery percentages up to 96 per cent of the oil in place.

In many cases, the original condition of the reservoir does not permit hydrocarbons to move freely into the well bore. This may be due to damage at the interface or to the poor natural permeability of the rock. One means for artificially increasing the permeability is hydraulic fracturing. Since it was first tested in 1947, the process known as Hydrofrac is credited with increasing North America's economically recoverable oil reserves by 8 billion barrels.

Although sand reservoirs account for a much smaller percentage of western Canadian oil and gas reserves, there is still much room for research to improve recoveries from these pools. In many cases, particularly with sand reservoirs, the manner in which the potentially productive zone is penetrated can make the difference between a producing well and a dry hole. New drilling fluids and completion techniques could still be devised to improve this situation, but they must be related to the physical and chemical properties of the rock.

Historically, much of the research relating to reservoirs and reservoir fluids has been conducted in foreign countries. The Canadian oil industry should now be important enough to warrant government funds and encouragement for basic research which will benefit the whole of Canada.

The reservoir geologists will still need to keep in close touch with the numerous other disciplines to help the growing trend toward more realistic reservoir models and increased efficiency of petroleum production.

Logging

There has been an immense development in wireline-logging technology since the first electrical measurements in boreholes were made at Pechelbrounn, France, in September 1927. The original experimental equipment was developed into a commercial enterprise by the Schlumberger brothers, and since then many millions of dollars have been spent to develop more refined devices for measuring specific rock properties.

The original use of primitive wireline devices was primarily for correlation, but with the advent of spontaneous potential, micro-, gamma-, neutron-, sonic-, borehole-compensated density and other logs, it is now possible to provide considerable help to engineers in making quantitative reservoir calculations.

Today, because of the complexity of the wireline tools and their importance to reservoir evaluation, most companies have a full-time log specialist or petrophysicist to interpret logs and plan the logging programs that are best suited to the drilling fluid and other conditions of a particular well. This is an important consideration when one reflects that it is a one-time opportunity to obtain a monumental amount of information from a particular hole. Generally speaking, it is now customary to run a suite of logs designed to complement each other and provide the maximum information for each possible reservoir penetrated by the bit.

It is possible to compute extremely accurate porosity values from sonic logs, once preliminary information on the rock type has been established. As research continues, it may one day be possible to make some reliable estimates of the degree of permeability.

Digitizing of logs and use of electronic computers permit development of models designed to relate log responses of several devices directly to lithology or other specific elements in various rock, and hence to the construction of a computerized litholog. The resulting consistency of such a stratigraphic correlation may help in deducing such complicated factors as depositional environments.

The development of synthetic seismograms from sonic logs has permitted much better velocity control for the geophysicists, and a resultant improvement in seismic interpretations.

New methods of manipulating the data now contained in the large library of Canadian well logs could result in the discovery of hitherto unsuspected hydrocarbon accumulations.

Obviously, the advent of the electronic computer will have many direct benefits on wireline logging, from speeding up the development of new downhole measuring devices to improving the interpretation of both old and new recordings through digitization and sophisticated computer programs.

It is this continuing improvement in information manipulation and transmittal that permits formal mathematical analysis and reappraisal of many geological concepts that can now be attacked with a wide range of mathematical and statistical techniques.

The value of wireline logging to the oil and gas industry, and its continued development, cannot be overemphasized. In many cases there are numerous side effects beneficial to other interests, such as neutron devices for testing road beds, and wireline devices that can be applied to mineral exploration.

Petroleum-Potential Evaluation

Petroleum-potential evaluation is the estimate of ultimate reserves of oil and gas and related substances in part or all of a sedimentary basin (8, p. 634). With this estimate should be included depth, area of production, and profitability. The petroleum-potential evaluation must, therefore, encompass the disciplines of geology, geophysics, geography and economics. Governments can assist in this by allowing a favourable economic climate that will give operations the incentive for exploration and development.

The determination of ultimate reserves (by the volumetric method) depends on co-ordination and evaluation of data from the geological fields noted above, and from magnetics, gravity, seismic reflection and refraction. The information analyzed from the above studies helps to determine the area and configuration of a basin, the volume and types of sediments within it, the presence or absence of source beds and their potential, the types of traps, the ages and types of structures, and unconformities. These data, when compared with those from similar basins having production, provide yardsticks to estimate ultimate reserves. Geochemical data have also been used to estimate the volume of oil generated, the amount that migrated, and the amount that was trapped. Extrapolation of statistics and probability theory can also be applied to petroleum-potential evaluation.

The information required for such studies comes from many sources in industry, universities, and government agencies. Each of these can add materially to the data required to appraise properly the potential of a basin.

To make this appraisal possible, we believe that government agencies should be mission-oriented to the needs of the country and industry, and that they should be ahead of industry in mapping the country - particularly on regional projects. Such projects as "Operation Franklin" of the Geological Survey of Canada are to be highly commended, as they give industry the necessary information to enter into the Arctic Islands exploration. Further, we feel that basic data should be made available to industry within a reasonable time, so that industry can make maximum use of it. In this regard, the national system for geoscience data, when operative, will be valuable to industry, and both industry and government should consider establishing regional clearing houses for data.

Geochemistry

Research to date has shown that organic and inorganic geochemistry can play an important role in defining and evaluating the four prerequisites of a petroleum deposit - source, reservoir, trap, and preservation.

Evaluation of source involves measuring the concentration of dispersed hydrocarbons, and estimating the efficiency of the primary migration and accumulation processes. Definition of source regions can be important, particularly if unconformities are involved. This can be accomplished by the analysis and correlation of chemical and isotopic properties of oils and sediment extracts.

The effectiveness of petroleum reservoirs is in many cases greatly influenced by processes such as leaching, cementation, and dolomitization which alter both the pore volume and the pore geometry. An understanding of the timing and controls of these chemical processes is important in evaluating discovered deposits and predicting areas of favourable reservoir development.

In order to be of value, traps must be timely, they must be efficient and, of course, they must be discovered. The timing of trap development can usually be deduced if geological and geophysical information are available. However, the relative timing of petroleum migration presents a real challenge to the geochemist. Similarly, the relative efficiency of the seal provided by different rock types at various stages of compaction is poorly understood. With improvements in analytical techniques and a better understanding of origin and migration, geochemistry is presently playing a small but increasing role in locating petroleum deposits. Analyses of near-surface sediments and subsurface brines now provide a useful complement to other types of geological and geophysical information in many parts of the world. In some cases, such analyses have played a prominent role in discovering oil and gas fields.

The physical and chemical preservation of petroleum in an environment which results in a producible product is the final prerequisite of an economic deposit. Physical processes such as erosion and faulting of a trap are obvious and predictable destructive agencies. Chemically destructive processes, such as thermal and bacterial alteration and water-washing, are also extremely important but not at all obvious or predictable without the extensive use of geochemistry. In addition to delineating high-risk areas, an understanding of these processes also helps to predict the type of petroleum accumulations that are likely in more favourable regions.

The petroleum industry needs additional research in geochemistry. In organic geochemistry, we require a better understanding of migration, in order to predict the timing of oil accumulation, the chemical or chromatographic effects on oil composition caused by migration through various types of rocks and, most important, the factors that control the efficiency of primary migration and accumulation. Canadian conditions of glacial drift, muskeg and permafrost present a special challenge to geochemical prospecting. Inorganic geochemistry can contribute to a better understanding of diagenetic processes that affect reservoirs. More knowledge is also needed of the interactions between organic components and inorganic components such as clays, brines, sulphur and uranium.

Historically, most of the research in petroleum geochemistry has been done by the major oil companies. More recently, interest in space research and oceanography has stimulated interest in organic geochemistry, and research in this area is now being conducted at a number of institutes and universities in the United States. In Canada, research on the organic geochemistry of petroleum is being carried out by at least one major oil company, by the Research Council of Alberta and, to a lesser extent, by the Geological Survey and Mines Branch of the Department of Energy, Mines and Resources. Some related work has been done by the Bedford Institute of Oceanography.

Although the level of government-sponsored research in petroleum geochemistry is low it is effective and could be made more effective by increased communication between government and industry scientists. It is, however, particularly disturbing that no Canadian university includes in its geological curriculum a course in petroleum geochemistry.

Exploration Geophysics

The three principal geophysical methods used in exploring for petroleum are gravitational, seismic, and magnetic surveys.

The gravity method usually requires instruments that measure to one part in ten million of the earth's field. Modern gravity meters can detect changes in this field in the order of one part in a hundred million. Airborne magnetic instruments can measure the magnetic field to within $\pm 10^{-5}$ oersted, and there are modern instruments with at least ten times this sensitivity under operating conditions. Although they lack the high resolving power of reflection-seismic methods, gravity and magnetic methods have been used regularly in the Canadian oil industry for rapid and often highly successful regional studies of basins and major structural trends. No interpretation of any given gravity or magnetic condition can be made unique unless it is tied to control provided by geological information and drilling data. However, the maximum thickness of sediments corresponding to gravity and magnetic anomalies can be closely determined without extra geological control, and these methods are at present widely used in interpretation.

Reflection-seismic surveys, which resolve considerable structural information, have been used successfully in Canada to delineate the complex folds and overthrusts of the western margin of the western Canada basin. Drilling based on this work has discovered and developed large natural-gas reserves and some oil. The reflection seismograph has also been used successfully in western Canada to locate reefs. Suggestions of reef presence are obtained from a variety of information, including isochron and character changes, the continuity and lack of continuity of reflections, and indications of dip. The successful use of the reflection seismograph in the search for productive porosity in reefs accounts for a substantial part of the known petroleum resources of western Canada. These include the Leduc field and many other reef fields in the same geological configuration, the Windfall group of productive reefs and, more recently, the Rainbow and Zama reef swarms. The delineation of productive areas at or near unconformities is difficult, but again the reflection seismograph has proved of great value in many areas, including the Souris Valley of Saskatchewan and the Mississippian productive area of central Alberta.

Reflection-seismic methods have been in effective use as an exploration tool for less than 40 years, and the technology of these methods has recently shown a rapid acceleration. Efforts to control the form of transmitted seismic energy have resulted in the development of new sources for generating elastic waves. Mathematical developments such as the statistical theory of communication provide the means for analyzing signal and noise. Modern filter theories offer an approach to solving the problem of recognizing significant events in the presence of noise. In order to utilize these developments to the best advantage, the primary information is recorded in the field in digital form, to take advantage of the greater available dynamic range.

An important problem in applying these new techniques is the development of economic methods for processing the vast quantity of data obtained per unit of coverage. A seismic record usually contains 24 channels, and if the data were sampled every thousandth of a second for three seconds, a total of 72,000 numbers would be recorded. A mile of line may have nine records, or 648,000 sample points. It is only recently, with the advent of large digital computers, that the mass-production capability has been available to apply these techniques routinely. The total seismic exploration system, using digital technology and digital computers, provides a revolutionary extension of the reflection seismic method which should markedly improve its application to structural and stratigraphic geology and, hence, to petroleum exploration.

CONCLUSIONS

The following conclusions concern communication, incentives, and agency assistance. Conclusions 1 to 6 are proposed to increase the research potential of the Canadian earth science community and prevent duplication of effort. Conclusions 7 to 11 are concerned with personal, financial and academic incentives. Conclusion 7 is considered particularly important in its possible impact on Canadian research growth. Conclusions 12 and 13, particularly if combined with conclusion 2, could save industry a great deal of time and money, and increase the amount of directed and original research.

1. The federal government has proposed the establishment of a Canadian Geoscience Data Institute to implement a national system for storage and retrieval of geoscience data. The system would provide industry with large volumes of computer-processable data recorded according to national standards. It would then be possible for individual companies to integrate, in a useful and efficient manner, the data supplied by the various provincial and federal agencies, universities and others. At present these sources each use different standards. The Institute would also publish a national index to the sources of all public geoscience data in Canada, whether computer-processable or

not, and lead to more efficient use of our existing information resources. We believe the Institute would fill an important need and lead to significant advances by industry. The provinces should support it wholeheartedly. In this regard, the first and very worthwhile step would be to consider adoption of some basic definitions regarding data to be tabulated.

2. A great deal of the scientific information compiled by the Geological Survey of Canada does not become available until several years after it was collected; the result is that it is less valuable when it appears. Accordingly, more rapid publication and accessibility to raw data after a reasonable length of time is recommended. We recognize that in a number of cases within the past few years publication of results has been effected with a minimum of delay. As well, the recently implemented "open file" approach to much data that is unpublished has narrowed the time gap between obtaining and disseminating data.

3. There should be better liaison and greater interchange of information among government, industry and universities with regard to geophysical equipment and related techniques. Examples have been noted where a university group has been using outmoded equipment, at the same time that industry is using more advanced equipment.

4. There should be periodic exchanges of government, university and industry personnel in the geophysical and geological disciplines. This conclusion is related to 3, above. Such interchanges would serve to broaden industry, university and government personnel and create a more co-operative and mutually beneficial climate of scientific research.

5. Greater liaison should be encouraged between universities and industry in developing earth science curricula. While we recognize the great potential contribution of basic research conducted in universities, we feel that the greatest contribution universities can make to the earth sciences lies in providing graduates trained in the necessary basic sciences. Petroleum technology is advancing so rapidly that constant liaison is needed to ensure that the requirements of industry are met. As an example, we might quote petroleum geochemistry: this science is now a major tool in oil exploration, but no Canadian university offers instruction in it at any level of its earth science training program.

6. The federal government should reappraise the responsibilities of its various agencies. Members of the Alberta Society of Petroleum Geologists, as representatives of their various companies, have noted that some duplication and lack of communication exists between the individual federal agencies which deal with regulations governing exploration and exploration data. It should be emphasized strongly that co-operation by individual federal agencies with members of industry is excellent. But it is also apparent that co-operation and communication between such agencies as the Geological Survey of

Canada, the Resources Administration Division and the Bedford Institute of Oceanography, of the Department of Energy, Mines and Resources, and the Department of Indian Affairs and Northern Development, to name the more prominent, is not in the same category as that between the individual agencies and members of industry. Misunderstandings as to the method of determining the use and dissemination of data obtained under regulations administered by the Department of Indian Affairs and Northern Development and the Resources Administration Division of the Department of Energy, Mines and Resources is common with the Geological Survey of Canada and other agencies. It is in the area of collection and dissemination of data that we are primarily concerned. In addition, we cannot see the merit of the present division of responsibilities between the Department of Indian Affairs and Northern Development and the Department of Energy, Mines and Resources in the administration of the mineral wealth of that part of Canada not administered by the provinces. It is clear that one agency could do the job as well as, or better than, two. From the standpoint of the Alberta Society of Petroleum Geologists, it would appear that the Department of Energy, Mines and Resources, with its vast store of knowledge of the natural resources of the whole of Canada, is the logical department to administer the resources on federal lands. If the twofold division is allowed to persist, it is imperative that the regulations dealing with administration of resources be identical in both agencies.

7. Research incentives should apply to total yearly budget, not increments. The establishment of research centres by some of the larger oil companies in Calgary has done much to foster the spirit of scientific endeavour and to develop new techniques of oil finding. In spite of this, the Industrial Research and Development Incentives Act (IRDIA) allows a 25 per cent tax-free grant only to research expenditures that exceed the average of the preceding five years.
The Act encourages oil companies either to continually expand their research centres or not have any at all. In the latter case, growth of alternative research centres in the United States is encouraged, to the detriment of Canadian scientific endeavour. The present Act, then, while admirably providing incentives for expansion, does penalize the good corporate citizens who have maintained research facilities in Canada over the years.
It is accordingly recommended that tax relief be calculated on the total yearly research budget. This may encourage other companies to develop research centres in Canada.
At the risk of appearing contradictory, we feel the federal government's proposed tax on "imported research" is harmful to the spirit of scientific endeavour. Legislation that deters the free flow of scientific information in Canada is certainly not serving our social and economic development. Although these regulations may claim to encourage the establishment of research facilities in Canada, their long-term effect will be the opposite. Information is the lifeblood of research. We are already separated from the world's major information sources by geography; these taxes will make Canada an even less desirable place in which to establish research facilities.

The Industrial Research and Development Incentives Act, Section 2(2)(d), defines scientific research and development for which grants are available, but specifically excludes "activities with respect to ... prospecting, exploring or drilling for or producing minerals, petroleum or natural gas." We feel that this discrimination has the effect of excluding geological and geophysical research projects of importance to the petroleum industry, and accordingly recommend that this section of the Act be clarified so that any activities that satisfy the basic definition of scientific research and development are acceptable. In this regard, the definitions of scientific activities provided by the Study Group on Solid-Earth Sciences of the Science Council appear to be more appropriate. If they are not acceptable in the context of IRDIA, which places emphasis on research in secondary industries, then consideration might be given to a separate incentive plan for research in the mining and petroleum industries.

8. The Government should encourage the development of coring techniques, lightweight drilling equipment, and better logging methods.

   (a) The research value of subsurface borehole cores cannot be overestimated: our greatly increased knowledge of the Swan Hills and Leduc reefs comes in large part from careful core studies. The cost of obtaining such cores is high, but could be reduced by research on coring techniques and instrumentation, thus encouraging the collection of more cores. Tax incentives for this type of research would have much the same effect.

   (b) Costs of drilling in remote areas are extremely high. Research toward the development of lighter-weight and more portable drilling equipment could appreciably reduce such costs which, in turn, could significantly increase the level of exploratory drilling in remote northern regions.

   (c) The drilling of a well, whether it is productive or not, represents a non-recurring opportunity to gather factual information on the subsurface rocks at a particular location in a sedimentary basin. Next to coring and cuttings, downhole logging devices provide the maximum amount of such information.

   Foreign companies do considerable research to develop new devices for measuring various rock parameters in a borehole. However, there are many avenues to be explored and improvements to be made on existing devices. Any research that can be done to make new and better tools more easily available will be of inestimable value to all.

9. Palaeontological studies in the petroleum industry provide the framework in which the age of source and reservoir rocks may be accurately determined, and basin-wide correlations, facies patterns, and perhaps new reservoirs, may be delineated. Micropalaeontological research is invaluable in this regard, especially in new-venture areas, and will become even more important in future.

There are two great palaeontological needs in Canada:

(a) Palaeontologists outside the government have no publishing medium in Canada. The Canadian Journal of Earth Sciences will only reluctantly accept the standard palaeontologic article, but will not publish fossil plates which are the basic data of the science. The Bulletin of Canadian Petroleum Geology, for economic reasons, has curtailed such publications. Canadian palaeontologists are turning more and more to the Journal of Palaeontology in the United States, and even this is having financial difficulties. A great need exists for financial help. Subsidies will permit existing Canadian journals to accept palaeontological articles. Establishment of a Canadian Journal of Palaeontology is desirable, unless the Bulletin of Canadian Petroleum Geology and the Canadian Journal of Earth Sciences are willing to change their policy and accept palaeontological papers.

(b) There is a need for field guidebooks showing the fossils of each stratigraphic interval in the western and northern Canada sedimentary basins. These guidebooks should be prepared along the lines of the Geological Survey of Canada's Illustrations of Canadian Fossils, but indicate relative abundance and importance of particular fossils.

10. Industry geologists should be encouraged to apply for research grants from government. The research of industry geologists often leads them into many worthwhile geological studies which frequently are dropped because they are not of immediate economic importance. It would benefit companies, geologists and science if grants were available for research on relatively non-operational topics, with the hope of eventual publication. Along these lines, the Geological Survey's Institute of Sedimentary and Petroleum Geology in Calgary has proposed a program to encourage members of industry to work at the Institute as research associates for periods from several months to a year. Such a program should be encouraged.

11. Some uniformity in the standard of geological training is desirable across Canada. The method we suggest may achieve this and perhaps also result in raising standards.
It is suggested that a central committee should be set up which would give a written examination in geology to every student about to graduate with his bachelor's degree. Results of this examination would be tabulated yearly for comparison among geology departments across Canada.
The central committee should consist of two groups: the first concerned with only administration and objective tabulation of marks; the second to set up and mark examinations. We feel the first group should consist of officers of the Geological Survey of Canada because of that organization's permanence. The second group should be outside the government and consist of university and industry geologists.

The universities across Canada should agree that their students all write a graduating examination at the same time. The examination should cover general geological subjects and be such that an evaluation of the candidate's grasp of principles and his geological background can be made. The results of these examinations should be kept confidential, tabulated yearly, and made available to the organizations concerned with obtaining geologists.
We feel that the suggested committee would accomplish a real purpose in that it would raise standards across Canada. All this can be accomplished without violating the most precious and necessary of academic prerogatives - academic freedom!

12. Co-ordinated subsurface and surface geological and geophysical studies in large areas by the Geological Survey of Canada and other government agencies are needed. In parts of western and northern Canada there is a lack of synthesized regional geologic and geophysical data, especially integrated surface-subsurface studies. Such studies by the Geological Survey and the provincial agencies should be given full and enthusiastic support.

13. More detailed field mapping is necessary, because of its great importance particularly in finding and delineating features of economic significance. The Geological Survey of Canada and other government agencies should be encouraged to embark on expanded geological and related mapping programs, and to improve the quality of map presentation.

REFERENCES

Bally, A.W., Gordy, P.L. and Stewart, G.A.: Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains; Bull. Can. Petrol. Geol., 1966, vol. 14, No. 3, pp. 337-381.

Booth, H.: Impact of Canadian oil and gas industry on the Canadian economy.

Dahlstrom, C.D.A.: Review of application of structural studies to petroleum geology; Natl. Adv. Comm. Res. Geol. Sci., 1969.

Hanson, J.E.: Regional employment and income effects of the petroleum industry in Alberta; 1966.

Howell, V.J. et al.: Dictionary of geological terms; Am. Geol. Inst.

Landes, R.W.: Geosciences in the petroleum industry; Roy. Soc. Can., Spec. Publ. No. 11, 1968, pp. 135-142.

Levorsen, A.I.: Geology of petroleum, second edition; 1967, p. 634.

McCrossan, R.G., Glaister, R.P., Austin, G.H., Nelson, S.J. et al.: Geological history of western Canada; Alberta Society of Petroleum Geologists, 1964.

COAL GEOLOGY

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DEFINITION

Coal geology is concerned with the collection, organization and assessment of geological data for the purpose of estimating coal reserves, for describing various types of coal and defining their extent, and for mine planning and exploitation. To accomplish these objectives, coal geology relies most heavily on standard stratigraphic and structural techniques along with petrographic methods and palynology (study of fossil spores and pollen). It is concerned not only with the coal seams in a given section but with the adjacent rocks as well. Some of these may be valuable in themselves, e. g. underclays, while others may be important in that they influence mining conditions.

Coal geology also includes studies of an organic geochemical nature relating to the origin of various coal types, to metamorphism in coal, and to origin and distribution of such constituents as sulphur.

Coal petrography describes the composition of coals. Such data are useful for seam correlation and also have a technological application in that the petrographic components react differently in industrial processes. Palynology is used largely for correlation and age dating of seams and may have use also in determining degree of organic metamorphism. Palynology is extensively used for similar purposes in oil and gas exploration and in more or less routine stratigraphy and geological mapping. Coal geology overlaps a number of disciplines, especially mining engineering and fuel technology, and in its use of paynology it overlaps the fields of paleontology and botany.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Coal is the most abundant fossil fuel and Canada is blessed with vast reserves. It is also a major accumulation of carbon, and hence a potential source for carbon-containing chemicals. In order to effectively produce from this resource, regardless of the purpose, it is necessary to have detailed information on the reserves available and on the structure within individual fields. Such information is essential in order to determine first the economic feasibility of a given area and, second, to assist in mine planning. These efforts belong in the province of the coal geologist in consultation with mining engineers. In developing such information, the value of such exploration tools as geophysical methods should be investigated.

To develop fully information on reserves, it is necessary to obtain basic information on coal composition. Composition influences utilization and technological advances in the field of utilization are increasingly intolerant of variations in coal quality and composition. Such variations, to a large extent, have a geological origin and research and development are necessary in order to describe their nature and extent in given coal seams and to define and understand their effect in industrial uses. Thus it might be possible to delineate certain coal seams or parts of seams as being particularly suitable for a given industrial process whether that process be coking, combustion or a non-energy use. This work should be done in conjunction with fuel technologists, chemists, and coal preparation experts.

PRACTICAL APPLICATIONS

1. To outline coal reserves by finding continuity of the seams and determining the stratigraphy and structure of the coal basins (through field and coal mine geology, coal petrography and palynology).

2. To aid in evaluation of the coking characteristics of virgin deposits by detailed petrographic studies. These should be combined with chemical analyses and coking tests and should be carried out in co-operation with fuel technologists, particularly experts in carbonization.

3. To aid in the search for oil and gas by using rank data from coal and dispersed carbonaceous materials including those found in rocks outside the coal facies. Rank determination on fossil spores and pollen may also be of much value to this type of study.

4. To advise in mine planning and to assist in matters of roof control, subsidence, bumps, outbursts and water problems. Included in such studies should be the development of basic structural data on stresses, competence, fractures and fault systems in coal and the enclosing rocks. In the course of such studies, information should be provided on the occurrence of non-coal lithologies such as clays and sandstones which might have value in the ceramics industry or as a building material.

5. To advise on coal cleaning, preparation and blending. In this endeavour petrography can be useful in describing the organic entities and mineral matter in a given coal seam. Such information should be integrated with physical data such as obtained from washability and grindability tests to define the behaviour of various coal types.

6. To assist in determining the most suitable coal types for conversion to liquids and gases. Petrography in combination with other analytical techniques can play a role in such studies. Although this area of utilization is not economically attractive now in Canada, in view of our oil and natural gas reserves, it should not be neglected completely. Future patterns of energy supply and demand combined with research might alter the economics to a more favourable position and the background information should be available to allow coal to take advantage of the situation.

7. To assist in any research which might promise a future non-energy use for coal. In this area, petrography could be a useful supplement to chemical and engineering studies.

HISTORICAL DEVELOPMENT

Coal geology started with evaluation of coal reserves by conventional geological procedures (determination of coalfield boundaries, determination of structure within coalfields, descriptions of the coal-enclosing strata, calculation of reserves of mineable coal). Somewhat later this led to more detailed studies of the coals themselves, including analyses of their chemical and petrographic compositions, the tracing of lateral and vertical changes in coal seams, and studies of the mineral matter in coal. For at least some time, coal geology probably lagged behind other branches of geology in Canada, because the then readily exploitable and marketable reserves of coal presented few geological problems.

In Canada there are several stages in the evolution of coal geology:

1. Early workers provided initial information on coals during routine mapping;
2. Later, more detailed work was done on individual fields with efforts to calculate reserves;
3. These detailed studies were combined with paleobotany to date the coals and to establish age relationships with coals from other parts of the world;
4. Establishment in the Geological Survey of Canada of a Coal Research Section in 1948 saw the beginning of a systematic detailed study of Canadian coals with strong emphasis on petrography and palynology.

The knowledge on individual Canadian coals and coalfields is at various stages. For example, the coals from the Maritime Provinces have been, in general, the most intensively studied with a great amount of data presently available including stratigraphy, structure, petrography, paleobotany and palynology. On the other hand, knowledge on some coals, particularly those from remote areas such as the Yukon and parts of Alberta and British Columbia, has advanced little more than the first stage cited above.

PRESENT LEVEL OF ACTIVITY

Present activity of coal geology in Canada is largely confined to the Geological Survey of Canada, with some work being done by the Research Council of Alberta, and Mines Departments in British Columbia, New Brunswick, and Nova Scotia. In addition, industrial coal petrology is carried out by the Mines Branch in Ottawa. Also, considerable exploration relative to proving of reserves prior to mining has been under way for several years by private industry in British Columbia and Alberta. Present and recent activities are listed below:

1. Field work by government agencies has continued and the resulting data have been collated with existing information to permit more accurate estimation of Canada's coal reserves. Such data have been organized and made available to industry to assist in coal exploration and development.

2. Detailed structural analyses have been carried out or are in progress in some fields such as Canmore to assist in correlation, mine planning, and interpretation of tectonic events.

3. Field studies, assisted by extensive drilling, to determine reserves of strippable coal in Alberta and British Columbia.

4. Petrographic studies of Canadian coals in order to determine composition and relate such data to environments of deposition, seam correlations and coal utilization; the latter in conjunction with evaluation by other methods.

5. Rank studies on coal and carbonaceous matter in order to determine variations in the degree of organic metamorphism. These studies are of significance for petroleum exploration and also for coal utilization (i. e. carbonization).

6. Palynological studies for correlation, age determination and environmental interpretation. Much of the present-day palynology is carried out on non-coal-bearing rocks. Where coal seams do occur, petrography and palynology have been used together for seam correlation and depositional studies.

7. Investigation of uranium content in Canadian lignites, mainly through field surveys using a scintillometer.

NEED FOR INCREASED ACTIVITY

1. More field work, especially in western Canada, to evaluate reserves of coking coals. This should include stratigraphic and structural studies to define the effects of tectonics on coal deposits. Such information could reduce uncertainty in future exploration and mine planning.

2. Rank studies including such studies on fossil spores and pollen. There are two aspects to rank studies. The first pertains to the metamorphism of coal and is concerned with the vertical and lateral changes in rank that can occur in the coal seams of a given field. It is therefore of importance in a resource study, particularly with regard to coking coal assessments. The second

aspect of rank concerns the exploration for oil and gas which normally are not found in rocks beyond a certain metamorphic stage. Carbonaceous materials (dispersed coaly matter including spores and pollen) are widespread in rocks outside the coal facies and are sensitive indicators of organic metamorphism. Studies presently under way suggest that rank data, determined microscopically, may be very useful in defining favourable or unfavourable areas for the occurrence of hydrocarbons.

3. Petrographic studies, including those aimed at examining the effect of petrographic composition on technological behaviour. These studies should be carried out in close co-operation with fuel technologists. There is a reconnaissance aspect to such studies in that detailed petrographic profiles should be prepared of coal seams from newly developing or virgin areas.

4. Studies on the mineral matter in coals and lignites, utilizing such tools as X-rays, spectroscopy and petrography. Such studies should be carried out to determine patterns of ash distribution, to discover whether or not concentrations might occur of such useful elements as germanium, uranium, molybdenum and vanadium, or concentrations of elements such as sodium which might have an adverse effect on coal-burning equipment.

TRAINING

Training for coal geology should include a good background in the classical geological subjects such as stratigraphy, structure, sedimentation and mineralogy. A background in fuel technology, coal petrology, botany, mathematics and chemistry is considered desirable along with some knowledge of economics, basic mining techniques and modern exploration methods.

MAJOR OBJECTIVES AND FUTURE TRENDS

The over-all objective of research in coal geology in Canada is to improve our knowledge of reserves and mining possibilities and to increase our fundamental knowledge of coal composition so that this resource can compete effectively with other fuels and with foreign coals. Specific objectives and trends in research will depend on future use of Canadian coal and may, in part, guide that use.

The immediate future will probably see increased export of Canadian coking coal. A market for coking coal in a western Canadian steel industry is also possible. Coal geology and petrography can assist by providing data on reserves and probable coking behaviour. More coal will be consumed in power generation in Canada, although the percentage growth in this market will probably not be as great as in the United States. Here again, geology will provide information on reserves and mining possibilities, as well as advise on particular problems relating to pollution and corrosion which may involve a study of ash distribution and composition.

Although not economically feasible at present, other markets for Canadian coal may develop in the future. These involve the use of coal as a raw material for chemicals and carbon, for conversion to liquids and gases, or its use in sewage treatment. Geology in these areas of research will again be concerned with reserves and mining possibilities, as well as relating coal composition to the quantity and quality of products from such processes.

Finally, the role of petrographic techniques in defining the stage of metamorphism of potential reservoir rocks appears to hold promise for petroleum exploration. It will probably be applied in increasing measure to evaluate the hydrocarbon possibilities of sedimentary basins.

CONCLUSIONS

1. Increase in reconnaissance evaluations of western Canadian coking coals through co-ordination of stratigraphic, structural and petrographic studies, with the objective of outlining mineable deposits. This work, which would involve a large field component, would be carried out in co-operation with exploration departments of private companies which would attend to drilling programs and the driving of prospect adits.

2. Development of geophysical techniques and the use of modern well-logging methods for coal exploration, particularly with regard to tracing of seam thickness, extent and structure.

3. Increased liaison and exchange of data between the various coal research groups in Canada. This is of much current importance for evaluating coking characteristics by means of physico-chemical and petrographic examinations.

4. Continued research of rank changes in coal and dispersed carbonaceous matter (including fossil spores and pollen) in order to determine variations in the degree of organic metamorphism. This area of study has much application for the search for oil and gas, because it permits a separation of favourable regions and depths.

5. Petrographic studies of lignite with emphasis on fundamental research as regards coal types, coal macerals, as well as distribution and nature of mineral matter. Such studies are of significance to item 6 also.

6. Appraisal of petrographic types of coal of different rank to determine their possible suitability as raw materials for non-energy use.

7. Increase in support staff (technicians, routine analysts) in organizations doing coal research, so that professional men can devote more time to the scientific problems that are involved.

8. Sponsorship of more research on coal in Canadian universities, either by industry or some government body.

9. More exchange of Canadian coal scientists with those of other countries.

10. Canadian participation with UN-sponsored coal surveys in developing countries, both as regards field work and petrographic evaluation of coking coals.

11. Promotion of conferences on coal in Canada, in co-operation with the C. I. M. M., with industry, or with provincial research agencies.

PALAEONTOLOGY

by the Palaeontology Subcommittee[1]
of the
National Advisory Committee on Research in the Geological Sciences

DEFINITION

Palaeontology is the study of ancient life, i.e. fossils. It embraces palaeozoology (ancient invertebrate and vertebrate animals), palaeobotany (ancient plants), palynology (ancient pollen, spores and some other, very small organisms), and palichnology (trace-fossils). It occupies an area between the biological and the earth sciences and is usually taught and practised as a geological discipline.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Palaeontology is concerned with:

(a) The identification, classification, and description of fossils;

(b) Recording the sequence of fossils preserved in rocks: such sequences provide the basic data for relative age-dating of all fossil-bearing rocks and for establishing a temporal framework for correlation of geological events;

(c) Ancient organisms as indicators of past environments and geography, and as constituents of rocks such as limestones, coal, etc.

(d) Deciphering and elucidation of patterns of organic evolution;

(e) The history of life.

Most of its practical applications derive from (b) and (c). Oil, natural gas, coal, and many other non-metallic and some metallic mineral deposits occur in sedimentary, fossil-bearing strata. Location of such economically valuable deposits, and the estimation of their extent and production yield, depend very much upon determination of spatial and temporal relations and patterns. Furthermore, palaeontology provides most valuable data for all regional (to a lesser extent also local), continental and intercontinental correlations and stratigraphic analysis, including stratigraphic analysis of the ocean basins. For evolutionary biology, palaeontology still provides the only "proof" that life has changed through time, beginning with the most primitive organisms and changing progressively to the highly complex fauna and flora of present day.

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[1] Chaired by Professor G.V. Middleton. Special thanks are due to Professor J.R. Beerbower and Professor W.K. Braun for their assistance in the preparation of this report.

PRACTICAL APPLICATIONS

The most important practical applications of palaeontology consist of the use of fossils (including microfossils, spores and pollen, and others) for:

(a) relative age dating (biostratigraphy)

(b) determination of environment of deposition (palaeoecology).

Both applications are of great importance in the search for oil, natural gas, coal, potash, sulphur, limestone, gypsum, salt, and many other industrial minerals, as well as some metallic mineral deposits.

HISTORICAL DEVELOPMENT

"Modern" palaeontology developed in the latter part of the 18th and the early part of the 19th centuries. Previous interest in fossils was solely curiosity-oriented.

Early in its development, palaeontology tended to branch into biological palaeontology, dealing with classification and evolutionary or environmental aspects, and into stratigraphic palaeontology, concerned primarily with fossils as age indicators. This unfortunate dichotomy dominated palaeontology for a long time and only during the last decade has the trend developed to unify stratigraphic and biological palaeontology.

Much early palaeontological work was done in Europe and the United States. In Canada, early studies were made at some universities, but the impetus was provided by the Geological Survey of Canada. This organization has since stayed in the forefront of Canadian palaeontological research.

During the past two decades, the growth of the western Canadian petroleum industry and the exploration of the vast northern territories have added new dimensions and new challenges. As a by-product of the ensuing boom in all disciplines of geology, the demand for palaeontological studies was accentuated. Unfortunately, the number of paleontologists did not increase proportionately to the mushrooming number of geologists. Furthermore, many of Canada's palaeontologists are foreign-born and educated. The newly issued directory of palaeontologists in non-communist countries lists 146 Canadians, but many of those listed are not actively engaged in palaeontological studies.

PRESENT LEVEL OF ACTIVITY

Palaeontologic research in Canada by government institutions, universities and industry is biostratigraphically oriented with the main efforts being directed toward establishing the age relationships of fossil assemblages, the correlation of the rock sequences in which these fossils occur, and reconstruction of the ancient environments in which these ancient organisms lived and under which the sediments accumulated. Such studies are fundamental to stratigraphy, to reconstruction of the geological history of any area and, at the same time, they form a necessary basis for all other palaeontological studies.

A broad framework of biostratigraphic subdivisions of post-Precambrian rocks has been established in Canada; some of the zones and units in the temporal framework are well-defined and have a duration and accuracy of one to three million years. Many other units are poorly defined; some are of no value.

Palaeoecologic studies have become popular in the past decade. Most of them appeared as by-products of biostratigraphic or other geologic studies and only lately have they become specifically conceived and executed with a purely ecologic objective. Also, they commonly remain one-sided and focused on rather narrow fields of interest. For example, many valuable data have accumulated in relation to the reef formation and limestone deposition in the Devonian sequences of western Canada. But only limited efforts have been made to investigate the sediment-organism interrelations in recent carbonate and reef sediments. Equivalent efforts concerning clastic rocks and their faunal contents are practically non-existent.

A growing awareness of the importance of recent ecologic studies has led to the initiation of studies on a partially integraded and interdisciplinary basis. Palaeontologists, biologists, sedimentologists, oceanographers and chemists try to work together to study the interplay of the many factors that influence the distribution, abundance and variety of modern faunal and floral communities. Such studies will serve as valuable models for the interpretation of fossil communities and will lead to a more meaningful reconstruction of ancient environments.

A trend to place emphasis on classification, morphology, ecology, evolution and case histories of selected fossil groups, in conjunction with or parallel to refined biostratigraphic studies, is slowly emerging. This "comprehensive" approach should greatly stimulate all branches of palaeontology, including biostratigraphy, and ensure an appropriate future for the science.

In the industry and government sectors, many paleontological studies are integrated with studies in stratigraphy, sedimentology, geochemistry, and other branches of geology. Many studies at universities, however, are independent or only partially integrated. Unfortunately, many palaeontological data are not published, especially those obtained by the industry, or they are published in instalments, or only a fraction of the results are made known, out of context and without reference even to the most important "background" information. Consequently, many palaeontological publications appear either too late or are fragmented and become of limited value. Commonly, they have no bearing on contemporary geologic thinking or geologic exploration, and very rarely do they influence the direction of geologic studies - as they should.

NEED FOR INCREASED ACTIVITY

More research is required to refine existing biostratigraphic correlations, to refine and calibrate palaeontological zonations, and to reconstruct palaeoenvironments and palaeogeography, quite apart from extending the same activities to areas as yet unexplored. This must be the main goal for many years to come in such a vast and "underexplored" country as Canada. The techniques used may remain the classical ones, with only minor modifications to utilize the more advanced technological facilities. Special emphasis should be placed on the efficient storage and retrieval of data and information to cope successfully with the mushrooming increase in knowledge. The publication of data, the distribution and availability of computerized data, and other forms of information transfer should be speeded up, and adequate financial support should be ensured for publication of well-documented and illustrated monographs.

The integrated project style of research should be encouraged. Close co-operation is needed between palaeontologists and biologists, sedimentologists, geologists and, most importantly, among palaeontologists themselves. More efficient forms of co-operation should be developed to overcome interdisciplinary problems and rivalries, and to avoid unnecessary duplication or excessive overlap of efforts.

An unbalanced distribution in the work load has been developing for some time, not necessarily approved by the majority of palaeontologists, but dictated by circumstances, availability of fossil collections and comprehensive geological data, library facilities, and financial resources. Government institutions and industry, with their full-time research staffs and relatively large financial bases, have assumed responsibility for satisfying the large-scale, biostratigraphic-geologic requirements, with the universities falling behind further and further in these respects. Consequently, large fossil collections, together with detailed and vitally important "background" data, have accumulated at a very few places. These same few institutions are, therefore, ideally suited to take over all palaeontological work including classification and description of fossils, palaeoecological studies, establishment and refinement of palaeontological zonations, construction of models (biologic or geologic), and comparison with present-day floras, faunas and ecological patterns. This leaves many universities (and some other less fortunate institutions) deprived of fundamental and necessary comprehensive fossil collections and geologic data. This development thus fosters concentration of efforts at very few places, and piecemeal efforts in others.

Since it is unlikely that this trend could be stopped, or even reversed, some forms of coexistence and co-operation must be developed, with government institutions, industry and universities sharing their research efforts, fossil collections, library facilities and other data, and "farming out" certain projects to institutions qualified to produce and publish adequate results in the shortest time.

It would be worth encouraging the development of the National Museum of Canada as the repository for palaeontological type and reference collections, the national showcase for palaeontological exhibitions, and an active, interdisciplinary research centre, as it is already for zoology, botany and, to a limited extent, vertebrate palaeontology. Presently, the Geological Survey of Canada fills some of these roles.

TRAINING NEEDS

Undergraduate training in all Canadian geological curricula involves some exposure to palaeontology. This training is barely adequate for conventional stratigraphic and systematic palaeontology, and commonly lacks full appreciation of the critical role of palaeontology in stratigraphy and historical geology. New approaches and methods are being introduced at some universities, but stringencies of geology requirements and, commonly, a lack of faculty interest and experience tend to discourage well-integrated palaeontological curricula. Nevertheless, such curricula are needed, just as much as for other geological disciplines.

A full graduate program ideally should include access to courses in:

(a) animal and plant morphology, physiology, and evolution

(b) marine biology and ecology

(c) population and community ecology

(d) population genetics and evolution

(e) statistics and computer usage

(f) geochemistry

(g) scientific Russian and German.

MAJOR OBJECTIVES AND FUTURE TRENDS

In Canada, the major objective must be to continue aspects of palaeontological studies directly related to practical applications, i.e. biostratigraphic and palaeoecologic studies. But development of both these fields depends on advances in the other fields of palaeontology which, therefore, should not be neglected.

Canada has a national duty to continue and greatly expand the search for Precambrian fossils in the vast Canadian Shield. Canada also possesses many world-famous localities and sequences of vertebrate, invertebrate and plant fossils which are critical to the elucidation of the history of life on our planet. Such fossil sequences should be properly curated, displayed, and made known to the public at large and should be scientifically described and published within reasonable time limits after their discovery. And the search should be intensified with the hope of finding equally important, new fossil sequences or exploiting the known ones more fully.

CONCLUSIONS

1. Every effort should be made to strengthen the conventional palaeontological work being undertaken in universities and government institutions. Industry should participate more fully in this process by publishing some of their palaeontological studies and by sharing their material and vast knowledge with universities and government institutions. Co-ordination and integration of palaeontological work in universities, government and industry should be encouraged by establishing a co-ordinating body in which <u>all</u> interest groups are represented. To a certain and limited extent, the Geological Survey of Canada has acted in this capacity, but its sphere of interest and its duties are too specific, or too narrowly defined, to be representative of a rapidly diversifying palaeontological and truly interdisciplinary scientific community.

2. Programs concerned with modern ecology — foremost, marine ecology and sedimentation — should be enlarged, with the universities participating more fully in such programs (professors, full-time staff members and students).

3. Theoretical and biological palaeontology and vertebrate palaeontology should be more fully supported and encouraged. "Applied" palaeontology

with its own built-in momentum does not need such special attention. Also, absolute emphasis should be placed on fully integrated studies.

4. Government institutions, industry and universities should be encouraged to interchange some of their fossil collections to guarantee that results are made public within a reasonable time limit, instead of holding such collections for an indefinite number of years.

5. More funds should be allocated for exchange of scientists, visits of foreign specialists to Canada, and travel by Canadian palaeontologists to other countries or within Canada to make detailed comparisons of their faunas, collect comparative material, and meet specialists in their own field. Also, palaeontologists should be more fully supported by qualified technicians, instead of having to perform the time-consuming laboratory preparations themselves. Modern expensive equipment is not lacking but often it is not efficiently utilized.

REFERENCE

Westermann, G.E.G. Directory palaeontologists of the world 1968, 2nd ed., Intern. Palaeontol. Union, McMaster University, Hamilton, Ontario, 1968.

PALYNOLOGY

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DEFINITION

Palynology is the study of pollen grains, spores, and other acid resistant microfossils such as dinoflagellates, diatoms, coccoliths, acritarchs, and chitinozoa, which are collectively referred to as palynomorphs. Palynology is a branch of paleontology, and is taught in either botany or geology departments in universities. Ecologists, archeologists, and allergists utilize palynology, but its chief economic application is as a stratigraphic tool in geology, chiefly in oil exploration. Oil companies, provincial governments (Research Council of Alberta), the federal government (Geological Survey of Canada), museums (Royal Ontario Museum) and universities employ palynologists.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Palynology is concerned:

(a) with the description and classification of extant and fossil palynomorphs;
(b) with the historical record of plant life and other biota, as recorded by the fossil spores and pollen grains and other microfossils;
(c) with the history of phytoplankton as evidenced, for example, by the remains of single celled Protista or their cysts (single-celled forms of life often develop skeletons capable of being preserved as fossils; these are extracted from the rock by acid treatment);
(d) with recording the sequence of palynomorphs (pollen, spores, etc.) in stratified rocks; this provides a basis for investigation of biological development for the dating and correlation of other stratigraphic sequences;
(e) with the determination of past environments, such as the delineation of old shore lines, climatic changes, forest history, etc.;
(f) with modern hayfever studies and honey grading, etc.;
(g) with archeological dating and paleoecology;
(h) with carbonization of spores and pollen; this is a indication (and provides a measure) of low grade metamorphism;
(i) with aeropalynology, for application to forestry and agriculture problems, plant pathology, pollination, air pollution, etc..

Practical economic applications stem from the extraordinarily resistant nature of the walls of spores, pollen and many other microfossils and from the fact that they may be carried by wind, water and insects over wide areas. Spores, pollen, and other palynomorphs may be obtained, from small samples from boreholes and outcrops in vast numbers. In addition, each fossil palynomorph is a complete morphologic entity and may be treated as a taxonomic unit. Because palynomorphs tend to be ubiquitous and abundant, results can be made more meaningful by statistical methods and computer analysis.

PRACTICAL APPLICATIONS

Studies of extant spores and pollen and their role as allergens has allowed the Canadian Government Travel Bureau to issue pamphlets indicating areas low in Ambrosia pollen which are favourable for people who suffer from hayfever.

Studies of extinct palynomorphs aid significantly in the dating and correlation of nonmarine sediments, such as the Cretaceous and Tertiary strata of Alberta, British Columbia and the Northwest Territories and the upper Paleozoic strata of eastern Canada. Palynology is valuable in the correlation of marine and nonmarine strata since spores and pollen are distributed by wind and currents and hence may cross from one environment to the other.

Only small amounts of rock are required for palynological studies, which makes them immediately applicable to the study of borehole samples (both core and cuttings) and very useful in oil exploration. The usefulness to the oil industry is in the field of correlation of strata, relative age dating of beds and paleoecological or environmental studies, which enable the oil geologist to trace old shorelines or detect the proximity of reefs.

The coal industry uses palynology to identify different seams in structurally complex areas where faults disrupt bed continuity; or in more gently dipping areas where lenticularity or paleo-erosion has caused interruption in the coal seams.

HISTORICAL DEVELOPMENT

Geological pollen studies began at the end of the 19th century by workers such as C.A. Weber and G. Lagerheim; Lennart von Post established pollen analysis as a separate discipline in 1916, when he applied palynology as a stratigraphic tool for the study of peat deposits in southwestern Sweden.

The early beginnings of palynological studies were linked with botanical pollen morphology and with coal and peat-bog investigations. It is only in the last 20 years that geological palynology has become a common tool for oil exploration. There are only about 25 active palynologists in Canada. On the other hand the U.S.S.R. reports 1,000, although the latter figure includes some technical personnel. There is only a relatively short list of publications and theses on Canadian palynology (less than 150). Studies in marine palynology have been initiated only in the past few years.

Up to 1966, 4,200 publications were produced on world palynology with a projected rate of 330 papers a year. Prior to 1966, there were an estimated 14,300 species of spores and pollen described in the literature and by 1975, 20,000 species descriptions are forecast.

Taxonomic and morphological studies linked with biostratigraphy have to be the immediate concern of palynologists as the science is still in the primary position of building up a vocabulary of terms for species and recording their occurrences.

PRESENT LEVEL OF ACTIVITY

The major efforts of the Geological Survey of Canada, oil companies, universities and research groups are biostratigraphic and taxonomic.

The building of a background of primary information is fundamental to the utilization of palynomorphs for correlative, ecological, and evolutionary studies. Publications on Canadian palynology appear at the rate of 30 to 40 per year. A large amount of information is deposited in the private files of petroleum companies, many of whom retain their research laboratories in the United States.

NEED FOR INCREASED ACTIVITY

Some oil companies have fairly complete registers of the stratigraphic ranges of many palynomorphs but the accompanying nomenclature often lacks international status. An increase in the number of publications on taxonomic studies of these palynomorphs should be accelerated to stabilize generic and species terminology. As it is sometimes difficult to obtain information from oil companies, university and research institutes should increase their efforts in the field of palynological taxonomic studies. Priority for study should be given to type-sections of previously described geological formations, as the knowledge of the palynological content would give a sounder basis for correlations.

The vast areas of Canadian continental shelves and the Arctic throw a considerable responsibility on the Geological Survey of Canada as the senior scientific body operating in these realms. Biostratigraphic studies in these areas require increased palynological support, and will require the employment of additional palynologists. The discovery of oil in northern Alaska has created an immediate urgency for expansion of biostratigraphic studies on the Canadian north.

The taxonomic, comparative, and evolutionary studies arising from the multiplicity of palynomorphs recoverable from even a few hundred feet of stratigraphic section may require a palynologist's time for much of a year. If collections were gathered only 100 miles apart in the sedimentary basins of Canada in the upper 5,000 to 10,000 feet of stratigraphic section, additional palynologists would be required to complete their study within a reasonable period of time. Paleontologists have been describing megafossils for over 150 years, so equivalent coverage of palynomorphs by palynologists will require additional workers to build up a comparative background of data in a short time. The need is urgent because of the unique role that palynology can play in future oil exploration.

TRAINING

Palynologists planning to apply their skills in a geological context should receive undergraduate training in a geology department with a minor in biology (taxonomy and ecology). He should continue in graduate work in sedimentation and stratigraphy.

Approximately 2 years of relatively concentrated study in palynology, following basic training, are required for an individual to acquire the minimum skills and general background necessary to be a practicing palynologist.

MAJOR OBJECTIVES AND FUTURE TRENDS

There is a pressing need for increased study of the biostratigraphy of palynomorphs in Canada. However biostratigraphic conclusions based on palynomorphs are only as good as the taxa from which these conclusions are derived so basic research on the description and classification of spores and pollen is a prime necessity.

Because of the economic implications, much of the palynological work in the next decade in Canada will be directed toward unravelling the stratigraphy of the potentially oil-bearing strata of the continental shelves and coastal plains. This will require correlative data from the accessible sections in the basins of British Columbia, the Yukon and western Canada.

The immediate objective would entail a restudy of type stratigraphic sections and a detailing of their palynological content. For the above reasons palynology of fossil forms will have to remain closely allied to the other branches of geology for some time to come.

The scanning electron microscope has been demonstrated as a valuable new tool in recording the detailed topography of certain palynomorphs. However, conventional transmitted light photographs will remain standard procedure for most workers for some time.

There is a great need to relate the fossil forms to their modern counterparts if any meaningful work is to be continued in paleoecology. In the strictly paleobotanical field there is need to relate the fossil spores and pollen to their leafy and woody counterparts. Cross reference works are required to relate woods, cuticles, and pollen in modern plants.

Recent advances in the understanding of such groups as the dinoflagellates, acritarchs, and chitinozoans (also recovered by palynological methods) will require specialists in these groups if stratigraphic applications to limestone sections are to keep pace with the palynological work on clastic sediments.

CONCLUSIONS

1. Several new appointments should be made in the field of palynology in the Geological Survey of Canada and/or in allied institutes such as the Bedford Institute and proper facilities, including technicians, supplied or enlarged for these appointments.

2. Canada lacks scientific journals that will publish integrated taxtaxonomic-biostratigraphic studies. Much Canadian material is published outside Canada. Supplementary funds should be made available to Canadian earth science journals to underwrite the added costs of plates, which constitute a very critical part of palynological taxonomic papers. Generally speaking Geological Survey publications tend to have an unfortunate delay in publication. Any delay requires continual revision of manuscript and proofs to avoid the creation of synonyms.

3. Financial support should go primarily to research on the palynology of geological type sections or zones in Canada as they are now known. This would place a proper emphasis on the important work of dove-tailing the new findings with the results of the last 150 years in conventional stratigraphy and stratal correlations.

4. Quaternary palynology needs additional support. Quaternary deposits are widespread in Canada. Our northern continental shelves lack the abundance of foraminifera found farther south and much more reliance will have to be placed on palynology for ecological and correlative studies.

5. Additional appointments within universities are needed. The number of palynologists absorbed per year into the labour market will probably never be large, even though vital to certain industries, so the case for the appointment of a palynologist to the staff of a university is weakened. This dilemma of staff-student ratio has to be circumvented. Partial but continuing support for some additional chairs of palynology would strengthen the science in Canada.

ECONOMIC GEOLOGY

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INTRODUCTION

The purpose of this review is to stress the importance of scientific activities in the field of economic geology as they apply to metallic and non-metallic mineral deposits and to outline future research objectives. An attempt is also made to review various aspects of mining exploration, metallogenic studies, and mining geology. Other aspects of economic geology, such as petroleum geology, coal geology, exploration geophysics and exploration geochemistry are treated elsewhere in this volume and need not be discussed here.

IMPORTANCE OF SCIENTIFIC ACTIVITIES

Much has been written on the importance of the mineral industry, particularly in recent months in connection with the government's White Paper on Tax Reform.[1] The major economic traits of the mining and the petroleum industries are summarized in the comprehensive report of the Solid-Earth Science Study Group of the Science Council of Canada.[2] It will thus suffice to limit this discussion to only a few features of the mining industry.

1. Economic development: according to the Dominion Bureau of Statistics, mining production reached a record value of $3.4 billion in 1968 (excluding fossil fuels). Oil and natural gas production was valued at an additional $1.3 billion.

2. Rapid growth: during the past hundred years, the population of Canada has increased by a factor of 5.7, the gross national product has increased by a factor of 14.5, whereas the value of mining and petroleum production has increased by a factor of 43. During the period 1945-68, the annual mineral output value increased 9-fold. The physical volume of mineral output increased 4-fold in 1950-68, compared with less than 3 times for the industrial economy as a whole. The real domestic product index in the mining sector grew at an average rate of 8.7 per cent during 1964-68, compared with 5.5 per cent in manufacturing, 2.3 per cent in forestry, and 1.7 per cent in agriculture. In 1968 the mining and petroleum output value was

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[1] Including a 39-page brief titled The possible effect of proposed tax reforms on mineral exploration in Canada, submitted by the Solid-Earth Science Study Group of the Science Council of Canada to the House of Common's Standing Committee on Finance, Trade and Economic Affairs, February 26, 1970.

[2] Blais, R.A. et al. Earth Sciences Serving the Nation, Science Council of Canada, Special Study No. 11, 1970.

equivalent to 7 per cent of the country's Gross National Product, compared with 4 per cent in 1945 (these percentages do not include the appreciable value of the manufacturing activities based on mineral supplies, nor the multiplying effect in transportation and various service industries).

3. Importance of exports: the total value of net Canadian exports of crude minerals and semi-fabricated mineral products amounted to 25.5 per cent of all domestic exports in 1968, providing the highest export yield of any Canadian Resource-based industry and an extremely important share toward our balance of international payments.

4. Importance of production: Canada is the free world's leading producer of nickel, zinc, silver and asbestos, and the second largest producer of molybdenum, selenium, sulphur, titanium, uranium and gypsum. It is an important producer of many other mineral products, including copper, gold, iron ore, lead, cobalt, magnesium, columbium, nepheline syenite, platinum-group metals, and potash.

5. Importance in regional development: no other industry has had such impact on regional development as the mining industry Relatively new centres of mining activity include northern New Brunswick (lead and zinc), Gaspé peninsula in Quebec (copper), New Quebec and Labrador (iron ore), Timmins (Kidd Creek mine) areas of northern Ontario (copper and zinc), the Thompson-Moak region (nickel) and the Flin Flon and Snow Lake areas (copper and zinc) of northern Manitoba, the potash-mining district of south-eastern Saskatchewan, the copper and molybdenum developments in British Columbia, the Whitehorse area (copper), the Mayo district (silver and lead) and the Anvil development (lead-zinc-silver) in the Yukon, the Pine Point area (lead-zinc) and the Yellowknife district (gold) in the Northwest Territories, etc. This broad regional development has resulted in the construction of many new towns in hitherto unpopulated regions, new railroads (more than 2,500 miles laid since 1945 to serve new mines), new airports and seaports. Several important mining towns have been in existence for more than 50 years, including Sudbury, Timmins, Cobalt, Noranda, Asbestos, Kimberley, and others.

6. Source of employment: according to the Mining Association of Canada[1], more than 130,000 Canadians are directly employed in mineral exploration, mining, smelting and refining. When it is considered that one worker in the mining industry may support five or more workers in other sectors of the economy, the social implications of mining become even more obvious.

7. Development of the North: together with oil and gas operations, mining is absolutely essential to the development of the North. The exercise of our national sovereignty over our vast northland, including the Arctic Islands and the water expanses between them, is very much a political necessity. To reach this goal as economically as possible, an effective infrastructure based in large part on mining and petroleum operations should be developed.

Economic geology is absolutely essential to mineral exploration. Together with exploration geophysics and geochemistry, it provides the scientific base for finding new mines and the essential guide to exploration

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[1] Brief of the Mining Association of Canada submitted to the Special Committee on Science Policy of the Senate, May, 1969.

within or near known orebodies. It is thus appropriate to review briefly the essential patterns of Canadian mining exploration, drawing freely on the data assembled by the Solid-Earth Science Study Group.

1. Level of mining exploration activity: during the period 1964-68, earth science expenditures in mining exploration climbed from $46 to $88 million (exploratory drilling included). In contrast, the value of 'metallics' and 'non-metallics' rose from $2 to $3 billion during these five years. Figure 1 shows the increase in annual mining exploration expenditures since 1950, and the writer's extrapolation of these expenditures to the year 1980. Many people will disagree with this extrapolation and argue against the validity of the seven-year cycle depicted in this figure; however, the graph is only meant to convey a general trend resulting from numerous factors, which are generally intangible at this time (such as the effect of new government legislation on the level of mining exploration activity); based on this graph, it is estimated that by 1980 these expenditures will exceed $130 million.

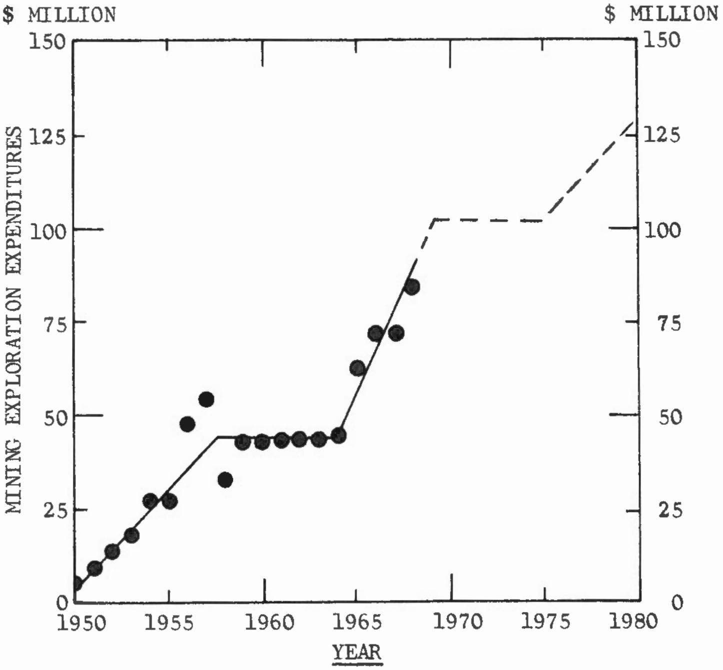

Figure 1: Graph showing the increase in Canadian mining exploration expenditures during period 1950-1968, and the writer's projection of future exploration expenditures to the year 1980.

2. Expenditures on earth science activities: the expenditures incurred in 1968 by six major mining companies (whose production value in 1968 exceeded $50 million each), other mining producers, and non-producers (exploration companies). This tabulation shows that six companies accounted for 38 per cent of all earth science expenditures of mining producers.

TABLE 1 – Expenditures on earth science activities in mining exploration, 1968

TYPE OF SCIENTIFIC ACTIVITY	EARTH SCIENCE EXPENDITURES	PERCENTAGE DISTRIBUTION		
		Six Companies	Other Producers	Non-Producers
	$ Millions	%	%	%
Basic and applied research	2	25	45	30
Scientific development	5	34	40	26
Scientific data collection				
(i) Exploratory drilling	33	35	33	32
(ii) Field surveys and laboratory studies	47	25	58	17
Scientific information	1	14	60	26
TOTAL	88	29	47	24

3. <u>Increase in mining exploration expenditures</u>: Table 2 shows the increase in mining exploration expenditures during the period 1964-68, as well as the relative importance of expenditures according to the various fields of scientific activity. Expenditures on geology and geophysics appear to have levelled off in 1966-68, whereas the expenditures on geochemistry (which are much smaller) have increased fairly steadily.

TABLE 2 – Expenditures on mining exploration, 1964-68

FIELD OF ACTIVITY	YEAR				
	1964	1965	1966	1967	1968
	$ millions	$ millions	$ millions	$ millions	$ millions
Geology	11	15	18	17	18
Geophysics	6	10	11	10	11
Geochemistry	2	3	4	5	5
Exploratory drilling	19	26	30	27	33
Other related expenditures	10	13	15	17	21
TOTAL	48	67	78	76	88

4. Mining exploration expenditures in relation to value of mineral production: this relationship is shown in Figure 2 for 49 mining companies whose mineral output in 1968 was $1.8 billion (63 per cent of the national mining production). The log-log scattergram in this figure shows a good statistical correlation between mining exploration expenditures and production value. The average mining company spends 4 per cent of its gross income on mineral exploration. Of course, the proportion of exploration expenditures to net profits is much higher than 4 per cent. A noteworthy feature of this graph is the group of companies in the upper left-hand corner of the figure, which spend very little in exploration in spite of their large mineral production. In contrast, 6 of the 49 company respondents spend five times more on exploration in relation to output value than the national average (see the points between the 10 per cent and the 100 per cent lines giving the ratio of exploration expenditures to mineral output value).

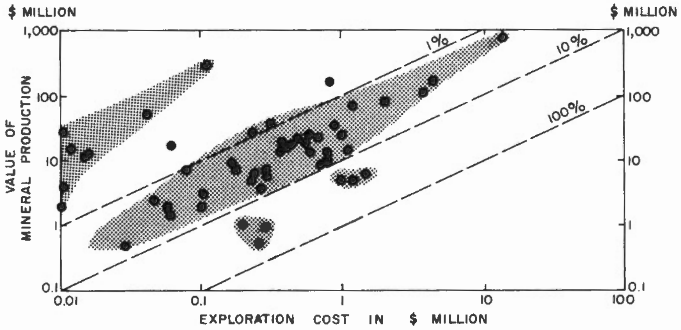

Figure 2 - Log-log scattergram of the mining exploration expenditures of 49 mining companies as a function of their mineral output value, which totalled $1.8 billion in 1968 (63 per cent of the Canadian mining production).

5. Earth science professionals in the mining industry: it is estimated that in 1968 there were about 1700 earth science professionals in the mining industry, compared to 2,200 in the petroleum industry. In terms of highest academic degree, 67 per cent had a bachelor's degree, whereas 20 per cent had a master's and 13 per cent a Ph.D. According to statistics obtained from the Solid-Earth Science Study (op. cit.), the number of these professionals has almost doubled during the period 1964-68.

IMPORTANCE OF RESEARCH

Research in economic geology is essential to our understanding of the structural and physico-chemical processes that have created mineral deposits, and to improvements in mining exploration technology. Without this research, exploration can only be haphazard and subject to diminishing returns in the face of rising exploration costs and increased difficulties of locating good mineral prospects.

The importance of this research is illustrated by the fact that we do not still possess satisfactory answers to many important questions, for example,

- why many important deposits of copper-zinc sulphides occur in the Archean volcanics of the Canadian Shield?
- what are the chances of finding several multimillion-ton copper orebodies in the Coppermine basalts?
- is norite more favourable for nickel deposits than, say, augite gabbro, other conditions being equal?
- what made the Kidd Creek ore deposits so amazingly big and rich?
- what happens to a body of polymetallic sulphides when it is tectonically deformed?
- how can we predict that a quartz vein will yield high gold values at depth?
- which trace elements in pyrite hold metallogenic significance?
- if 'stratafugic' solutions from shales gave rise to the Pine Point lead-zinc deposits, where did the copper from these shales go?
- can we expect copper deposits in the Grenville?
- is there any regional structural control over the distribution of porphyry coppers in British Columbia?
- how do we explain the proliferation of native gold deposits in certain greenstone belts and their scarcity in others?
- under what paleotopographic and paleoclimatic conditions were the Knob Lake iron ores formed? Where did the silica leached from iron formation go?

Hundreds of more or less specific questions of this type can be asked, some of them directly applicable to mineral exploration, but they cannot be answered without additional research.

Geology has played a major part in the finding of new mines in Canada, either through the direct application of geological concepts or the 'orientation' of geophysical or geochemical surveys. The examples which may be stated include

- the geological theory that led to the development of the lead-zinc deposits in the Pine Point area, Northwest Territories;
- the concepts that guided the exploration for massive sulphides in the volcanics of the Noranda and Timmins areas, with the resultant discovery of the Vauze, Lake Dufault, Delbridge, and Kidd Creek Mines;
- the definition of the stratigraphic and sedimentological controls affecting the uranium mineralization in the Blind River area;
- the geological concepts that led to the geophysical exploration for nickel in the Thompson area of northern Manitoba;
- the realization of the stratigraphic controls affecting the distribution of zinc-copper sulphides in the Mattagami area of northwestern Quebec;
- the outlining of the structural and lithological ore controls in the Bathurst area of New Brunswick;
- the geological concepts that guided exploration in southeastern Saskatchewan, where the world's largest potash deposits have been found;
- the structural hypothesis that led to the discovery of the Campbell shear at Yellowknife;
- the definition of the structural, lithological and textural guides to iron ore exploration in the Labrador trough, etc.

To be successful, economic geology must generally bridge the various geological disciplines. It must, in addition, be pursued in close relation to geophysics, geochemistry, physical chemistry, mining and metallurgical technology, and mineral economics.

As the world's third largest diversified source of minerals and the world's largest exporter, Canada may continue to enjoy additional prosperity as long as new sources of minerals are found to meet market demand. It has often been stated that in 1985 the world will require about twice the quantity of metals as was consumed in 1967, and by the year 2,000 this need is expected to reach four times the level of 1967 production. Our mining industry may be expected to grow at a rate similar to that of world demand providing our mineral exploration, mining, ore dressing, smelting and refining technologies are continually improved, costs remain reasonable, and fiscal legislation encourages mineral exploration and research. We cannot be complacent about the present status of Canadian reserves in most mineral commodities. In the case of copper for example, it should be realized that at the present rate of production the discovery of a copper deposit of the size of Granduc in B.C. (32 million tons averaging 1.93 per cent Cu) is needed every 18 months to balance Canadian copper production. A rising rate of production will naturally require an increase in the discovery rate.

The Solid-Earth Science Study G roup has reported (op. cit.) that for every 9 new mines brought into production annually since 1950, an average of 4 of these mines have depended on old showings. Of the total of 160 mines that started, or re-started or were planned for early production in 1955-68, about 47 per cent were first discovered before 1950 and nearly 20 per cent before 1920.

HISTORICAL DEVELOPMENT

Canadian research and development in the geology and origin of mineral deposits has been rather haphazard and fragmented, depending largely on the personal interest of individuals. With a few notable exceptions, mining companies have tended to avoid active involvement in fundamental geological research. Applied research in geology is also at a low level (see Table 1) compared to the large expenditures on exploratory drilling, field surveys, and routine laboratory investigations. Except for six large companies each spending about $85,000 annually on all forms of earth science research, the average active mining company spends less than $7,000 annually on earth science research.

Yet, mineral exploration in Canada has been surprisingly successful, both in terms of ore reserves developed and types of deposits discovered. Field surveys, including those by the federal and the provincial governments, have been a key factor in this development. However, as the shallower and more easily discovered deposits are being rapidly depleted, the discovery of deeper seated or more remote ore deposits will require more sophisticated methods than used heretofore. With the concomitant trend toward large opencast mining operations, frequently involving a very small margin of unit profit, it is visualized that geology will play an important role, particularly in grade control, slope stability studies and dewatering.

In the early days of Canadian mining exploration, prospecting of outcrops and stream sediment panning were the only available means of discovery. The Geological Survey made important contributions by indicating favourable areas for prospecting, e.g. the work of W. Logan in the Eastern

Townships, of A.P. Low in the Labrador trough, and of R. Bell in the Pine Point area, Northwest Territories.

Improvements in transportation and access early in this century spurred mine discoveries. For example, the Cobalt silver camp and the Sudbury nickel-copper district were actually found through railroad-cut exposures of rich mineralization. The advent of the bush hydroplane facilitated early discovery of many ore deposits, starting with the discovery of rich silver-cobalt-radium mineralization at Great Bear Lake.

Continual improvements in cartography and expanding geological field surveys since the beginning of this century have been instrumental in the finding of many mines. Several deposits were actually found during geological reconnaissance and mapping by government geologists, e.g. the finding by Gray of a large cinnabar deposit in British Columbia, while doing mapping for the Geological Survey of Canada in 1937, and the discovery by Retty of ilmenite in the Upper Romain River region in 1941, which led to the discovery of the huge ilmenite deposits at Lac Allard north of Hâvre Saint-Pierre.

The early formulation of geologic hypotheses to explain ore discoveries has played an important part in the exploration of several Canadian mining camps, e.g. the work of W.G. Miller in the Cobalt silver camp, and the studies of A.P. Coleman and others in the Sudbury nickel field, all dating to the beginning of the century. Since then, geological theories have continued to play an important role in the exploration of many areas, although these contributions have been sporadic.

In the mid-1930s, when aerial photography became available, mining exploration was greatly facilitated by improved cartography and broad interpretation of regional geology, particularly in the mountainous regions.

Since the 1930s, geophysical exploration has been extremely successful in locating new mines, and in the last decade geochemical exploration has become a useful prospecting tool in many areas. In the last few years, there is growing emphasis on the use of statistics and operations research, and the combination of geological, geophysical and geochemical methods for improving exploration strategy.

PRESENT LEVEL OF ACTIVITY

Mining exploration activity in Canada is one of the highest in the world. Yet, industrial research in metallogenesis appears to be at a very low level, except for a few large mining companies and a growing number of petroleum companies becoming engaged in mining exploration. This is rather surprising for an industry which is so dependent on new sources of minerals and, indirectly, on the formulation and testing of new concepts of ore search. With a few notable exceptions, most Canadian research in metallogenesis has been by government and university geologists. It is symptomatic that the Geology Division of C.I.M. does not have a research committee, whereas the Alberta Society of Petroleum Geologists has had an active research committee for years. In spite of the efforts of a few devoted individuals, it would appear that the Mineral Deposits Subcommittee of the National Advisory Committee for Research in the Geological Sciences has not succeeded in influencing markedly the trends of economic geology research in Canada. Perhaps it is time to redesign some of our institutions to achieve better coordination and obtain greater 'involvement' of practitioners regarding policies on economic geology research.

Economic geology research in our universities is at a deplorably low level compared to other fields of geological sciences. Of 509 earth science grant applications submitted to the National Research Council by university professors in late 1968, only fifteen were directly concerned with economic geology research. Of the $3.2 million granted by the National Research Council in grants-in-aid of university research in the earth sciences in the spring of 1969, only 3.7 per cent were allocated to economic geology, 1.3 per cent to exploration geophysics, and 0.9 per cent to exploration geochemistry. The total for these three important fields (5.9 per cent) was less than the financial support provided to university research in paleontology (6.9 per cent), mineralogy and crystallography (6.3 per cent), sedimentology and stratigraphy (6.2 per cent), and isotopic geochemistry (6.2 per cent). Inasmuch as these grants are allocated on the basis of the scientific excellence and number of applicants, it must be concluded that competent academic researchers in economic geology are relatively scarce, or else they have little time for research. It is also revealing that there were only two applications for geological research in industrial minerals and natural structural materials (the output value of these materials in 1968 exceeded $900 million), and these two applications were submitted by professors of physical geography.

In mining geology, the present level of research activity in Canada is minimal. Very few mines have a research geologist, in spite of the fact that very substantial additions to ore reserves occur as extensions of known orebodies, or are found near them. Not uncommonly experienced mine geologists must log in detail thousands of feet of drill core, and relog them two or three times to unravel complex geological settings and find essential lithologic, mineralogic and structural ore controls; in order to do their job properly, they must be given sufficient time and freedom from routine chores if they are to pursue long-range investigations and seek solutions to important geological problems. Due to operational priorities, some mines are started with the bare minimum of geological mapping. In many mines, valuable geological information is irretrievably lost or never analyzed in detail because of insufficient competent staff. In contrast with metallurgical plants where research is generally a sustained activity, many people consider there is little need for geological research after the orebody is found and delineated. In fact, interest and activity in geological research in a mining project follow generally the pattern depicted in Figure 3 below. There are several examples in Canada of major mines which have been studied in fair detail in their

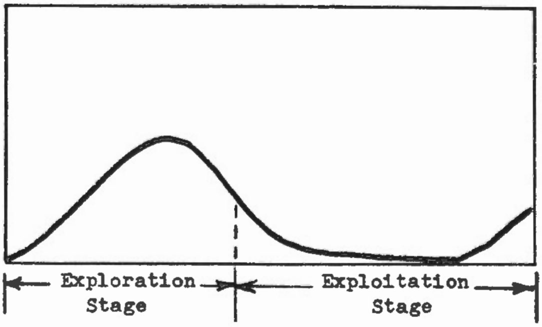

Figure 3 - Ideogram showing the general interest and activity in geological research during the main stages of a profitable mine. Interest and activity build up again when the end of ore reserves is in sight.

initial stages, but have not been subjected to detailed metallogen investigations during the later production stages when the orebodies were fully exposed in three dimensions and thus ideally suited for geological research.

TRAINING

Role of Universities

1. Many university professors have had insufficient practical experience to give students a proper background in economic geology. This can in part be corrected by more selective hiring of academic staff, by more competitive salaries paid by universities, and by more industry scientists participating in student training. Consulting by university professors should be encouraged as means for them to acquire applied research experience in industry, and for their students to tackle research problems of economic or technologic significance. Mining companies should sponsor periodic visits to their operations by university professors and cooperate fully in arranging field trips and mine visits for university students. Industry geologists should take a more active part in the Visiting Lecturers program of the Canadian Institute of Mining and Metallurgy and in regional geology student conferences.

2. The major duty of faculty is teaching. This function should be fertilized by, but not sacrificed, to research. There is a widespread feeling in industry that research in university geology departments is assuming too much importance in relation to the efforts spent on training a sufficient number of the type of professionals needed by the 'industry of tomorrow'. During the academic year 1968-69, 10 of the 19 geology departments offering post-graduate programs had a total graduate student enrolment of 328, versus a total of only 385 second-, third- and fourth-year students. Forty-four per cent of all graduate students in geology are non-Canadians. To add another disquieting note, the total graduation in geology (B.Sc. to Ph.D.) has not noticeably increased during the past twenty years, although the mining exploration expenditures have increased 17-fold, federal government support of earth science research in universities has increased by a factor of 35, the number of departments granting master's degrees by a factor of 2.3, the number of Ph.D. granting departments by a factor of 6.5, and the size of geology faculty by a factor of 4.6. During the past 20 years, the addition of one professor to total faculty in geology in Canada has resulted on the average in the 'production' of 1.4 additional graduates in geology; surprising as it is, this latter performance is no worse than in several other professional fields for which statistics are generally expressed in terms of ratios of all students (including numerous non-professional students) to size of faculty. In contrast, the number of geologists employed by the mining industry has increased by 64 per cent during the last five years, but only 15 per cent of all Canadian geology graduates at all levels entered this industry. Our universities are currently supplying not more than one-third of industry's earth science manpower requirements, the rest being obtained through immigration (in 1968 more geologists immigrated to Canada than the total number of geology graduates at all levels from our 30 departments of geology).

3. Universities should provide basic education and training, leaving to industry and other employers the highly specialized training. Our Ph.D. geology students are often trained with excessive specialization. To make

matters worse, following their graduation these new professionals generally want to continue doing the same type of work as done for their thesis. In other words, their Ph.D. appears to constitute an end in itself, rather than a stepping stone toward utilitarian needs.

4. Post-graduate courses and research opportunities in mining geophysics and exploration geochemistry are severely lacking in our geology departments.

5. There is a general feeling in industry that the geological training program in Canadian universities should be strengthened with respect to mathematics (especially statistics), electronic data processing, physics, and chemistry. The unifying concepts in geology should receive greater attention, and the principles of mineral economics and operations research should be stressed. In order to accommodate these additions, the somewhat irrelevant or overly specialized aspects of training should be curtailed. Balance in curriculum content should be achieved through better consideration of national manpower needs, and more effective inter and intra-departmental coordination and cooperation.

6. Canadian geology should remain field-oriented. In general, faculty research should not be done in isolation from the geology of rock masses, where it tends to be trivial rather than fundamental, providing some highly precise information of uncertain significance and relatively little new thought about geology.

7. Students should have a better appreciation of the economics of mine finding and mining operations. Their academic training should include exercises in concise report writing, drafting and simple surveying, as well as numerous field trips in the company of their professors. Their laboratory should be the field. Professors should initiate them to solving real and practical problems, in addition to awakening them to their future social responsibilities.

8. Faculty should avoid training fascimiles of themselves. They should continuously modify their courses in relation to the rapid development of science and technology and the probably national needs of the future. For example, it may well be that environmental geology and courses in social sciences will become integral parts of the 'geological curriculum' in the not too distant future.

Role of Industry

1. One of the greatest obstacles to obtaining adequate professional manpower requirements in geology is the cyclical character of mining exploration. When the level of exploration is low, university enrolment plummets and many geologists transfer to other occupations. During such periods, perhaps staff could be retained and directed to long-range investigations, and some personnel could be sent to universities for additional training. Government agencies should expand their own earth science activities to absorb the surplus manpower and stimulate more exploration activity.

2. Qualified geology students have too often been employed as technicians, line-cutters, samplers, cooks, etc. with little opportunities for learning or practising their science. The feeling is widespread among Canadian geology students that the mining industry is really not very interested in their professional services. While most students are willing to acquire the basic skills, they resent doing this, repeatedly, summer after summer. Industry would

do well to pay more attention to the 'human element' and give more responsibility to qualified students. It should find means of improving its 'image' in the universities.

3. With regard to re-training of staff, the mining industry would be well advised to institute a system of leave of absence with full pay to some personnel who have the capacity and the inclination to further their knowledge and pursue applied research in universities or government agencies during a few months. Before management considers this to be a luxury it should examine trends in such forward fields as electronics, chemical engineering, aeronautical engineering and the automotive industry.

4. More opportunities should be given to junior personnel to attend scientific meetings and field trips, especially to geologists residing in remote areas.

5. Earth scientists in industry should play a more active role in national advisory committees on earth science research and be encouraged by management to accept responsibilities in these committees and learned societies.

Role of Government Agencies

1. Traditionally, the Geological Survey of Canada and the provincial departments of mineral resources have provided the training grounds and research opportunities for thousands of Canadian geologists, many of whom are now leaders in the mining industry. By providing employment to inexperienced geology students, they have created a pool of competent personnel from which industry has drawn heavily. Government agencies must continue to play this vital function.

2. In order to improve training given in universities and allow greater cross-fertilization of scientific ideas, government agencies should encourage some of their personnel to continue their research in universities, where they could be in residence for one or more years while still at the employ of their respective agency. These earth scientists could become 'research associates' and participate in academic life, including supervision of graduate student research.

Role of Technical Institutes

1. Institutes such as the Haileybury School of Mines have been extremely useful to industry by providing qualified technicians for all sectors of exploration and mining. Many of these graduates now hold key management positions. These institutes must be fully supported by government and industry.

2. Graduates from these institutes should be given entrance credits in Canadian universities, in order that the best qualified could further their scientific education.

Teaching of Earth Science in Secondary Schools

It is felt that the most important single factor contributing to the relatively low earth science enrolment in Canadian universities, and affecting to some degree the intellectual quality and psychological characteristics of university students, is the general lack of a good earth science program in secondary schools across Canada. Unless such a program is introduced, and a sufficient number of teachers are adequately trained, the present shortage of engineers and scientists in the mining industry will become worse in the future. Every effort should be made to convince provincial departments of education that earth science should be an integral part of the science program in high schools. The literary discourses in physical geography and the amateurish courses in geology should be abolished and replaced by an earth science course in which the fundamental principles of physical sciences can be taught within the frame of reference of man's environment, in relation to what the student can actually see and personally experience, and what is really relevant to the physical world in which he lives.

PROGNOSIS AND CONCLUSIONS

Rarely in nature can we see mineral deposits in the making, and whatever we may find are only small bits of evidence for very few specific types of mineralization. There is no such thing as a general theory of ore deposition akin, say, to the theory of magnetism. It is not surprising, therefore, that ideas on ore genesis have been largely based on field observations. Microscopic and chemical measurements in the laboratory on natural samples and artificial systems have supplemented these observations.

Too often the available *facts* have given rise to widely different interpretations, with the unfortunate result that an individual's views on ore genesis have been more influenced by his 'faith' in a particular point of view rather than impartial observation and scientific deduction. Although neptunist versus plutonist arguments have been largely settled with regard to rocks, it is surprising how frequently these arguments are still raised about ore deposits. This has not prevented the discovery of many new ore deposits for the simple reason that most exploration is conducted on the empirical basis of looking for new ore in geological settings similar to those of known deposits. However, as new deposits become harder to find, scientific methods must be used, including the analysis of the various modes of formation and deposition of constituents of orebodies. With projected mineral reserves becoming rapidly depleted with respect to projected demand, there is growing recognition in government and some parts of industry that a more rigorous approach to mining exploration is needed compared to yesteryear's methods.

Research during the past 10-20 years has brought some important advances in metallogenic thinking, including:

1. *The realization that ore deposits are closely related in space and time to the geological environment in which they occur*.

2. *This realization has led to the belief that the key to the genesis of many mineral deposits lies in their host rocks*, and not in some hypothetical plutonic source at great depth. Thus, modern economic geology research should include the *total environment* of mineral deposits, rather than only the ore itself.

3. *It has been recognized, albeit slowly, that ore deposits and their surrounding rocks are chemical systems and that it is useless to propose a theory of ore genesis based on field observations without ensuring that such hypothesis is also compatible with the available information on similar chemical systems*. The interpretation of mineral deposits and their associated alteration in terms of phase equilibria is becoming an important part of metallogenic research. It has sparked intensive investigation on phase studies

of sulphide, oxide, sulphide-oxide, and sulphide-silicate systems. The resultant new knowledge provides for a more rational interpretation of natural systems.

4. The interpretation of several types of mineral deposits has been appreciably refined through studies of both stable and radioactive isotopes.

5. Fluid inclusions in some ores provide important insight into the minimum temperature of ore deposition and the nature of ore-forming solutions.

In addition to the above, the prognosis for economic geology in Canada should include:

6. A decompartmentalized approach toward mineral deposits geology. The present segmentation of efforts should be replaced by functional, multidisciplinary and integrated studies of new concepts and regions of interest. Exploration geology will undoubtedly become increasingly interrelated to exploration geophysics and geochemistry, mineral economics, and new mining technology.

7. A systems approach to mineral exploration, including an important operations research component. Conceptual models of exploration targets will be tested by mathematical simulation. Techniques of ore reserve estimation and grade control will become more rigorous, based on detailed mathematical analysis of ore values distribution and operational variables.

8. Computer-processable data banks will be widely used by industry in planning exploration strategy. Provincial departments of mines will need to develop fully computerized data files. Staff engaged in exploration will need to adapt quickly to these changes and acquire special training in computer technology in order to carry out the multivariate analyses that these data banks will permit.

9. The quality of subsurface geological interpretation will need to be improved through greater resolution and more discriminate analysis of aerogeophysical surveys, and the miniaturization and automation of down-hole geophysical instruments. Considering the great advances in geophysical well logging, the mining industry should provide major support for research in automatic logging of the hundreds of thousands of diamond drill holes that have been drilled in recent years, many of which could still be open and available for such investigations.

10. Revolutionary methods of drilling exploratory holes must be found, both to lower drilling cost and to reach greater depth. The mining industry is currently spending more than $30 million a year on exploratory drilling, not to mention all the diamond drilling associated with development work. Yet, there is practically no research carried out in Canada to improve diamond drilling technology, in part because diamond drilling is a very competitive business. A major government-industry joint research effort in this regard is long overdue, not only because of the importance of exploratory drilling in Canada but also in view of the fact that drilling expertise is an important exportable commodity, as well as a component in programs of technical assistance to developing countries.

11. Improved methods of diamond drill hole surveying should be found, including the design of inexpensive and accurate survey instruments. It is rather anachronistic that in this space age, when laser beams can measure the distance to the moon with an accuracy of a few inches, we still do not know where many of our diamond drill holes are exactly situated at a depth of a few hundred feet.

12. Core storage libraries should be established by government in all mining districts, with the full cooperation of industry. Telescoped core of interest should be systematically collected for general identification and research purposes, and as means of increasing the effectiveness of exploration methods.

13. It is visualized that in the years to come provincial departments of mines will need to exercise more leadership in establishing progressive legislation to preferentially encourage scientific mineral exploration, increasing their earth science activities, improving their information services, and establishing field research units in mining districts. It would also be in the national interest that a Council of Mineral Resources Ministers be instituted, with a permanent secretariat to undertake or sponsor the basic studies required to establish mineral development policies.

14. Future developments in economic geology are inextricably linked to the research and other scientific activities of the Geological Survey of Canada. It is essential that the quantity and quality of the research carried out by this agency be at least maintained in the years to come. The specialized investigations in the economic geology series should receive particular encouragement. Likewise, national metallogenic analyses should increase in number.

15. The growth of economic geology in this country will in part depend on our ability to extract from foreign literature the scientific information of interest. Canadian geologists need to be more cognizant of foreign literature written in the main languages other than English.

16. In view of the importance of mining exploration in this country, and the low level of research activity in mining exploration, it appears essential to establish as soon as possible one or two 'centres of excellence' in mining exploration research through the cooperation of universities, industry, and government. In this regard, the reader will find in Special Study No. 11 of the Science Council of Canada (op. cit.) a useful set of principles to guide the establishment of these centres.

17. Finally, it is essential to improve the coordination and increase the level of financial support in research relating to mineral resources. Following the recommendation of the Science Council of Canada in its Study No. 7, a National Advisory Committee on Mineral Resources Research should be established to deal with the following major aspects:

(a) Mineral exploration;
(b) Mineral production, beneficiation, extraction, and processing;
(c) Mineral polocy (including mineral economics).

ACKNOWLEDGMENTS

The writer is very much indebted to the members of the Mineral Deposits Geology Subcommittee of the National Advisory Committee for Research in the Geological Sciences for their most valuable advice on several of the topics discussed in this paper. Special thanks are expressed to H.K. Conn and A.E. Buller, successive chairmen of this subcommittee, for having prepared discussion papers on the general topic of mineral deposits geology. Twenty other readers were kind enough to review critically the original draft of this paper. However, the writer assumes full responsibility for the opinions expressed and the statements made herein.

PETROLOGY

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DEFINITION

Petrology, the science of rocks, is concerned with the composition, classification, and origin of rocks and their relation to their geological environment. It is best defined in terms of its two broad subdivisions of petrography and petrogenesis.

Petrography is the description and classification of rocks in the field, in hand specimen and in thin section. Petrogenesis is the study of processes by which rocks are formed. The breadth of these two simplified definitions serves to emphasize the difficulty of placing any limitations on these disciplines. Detailed petrographic descriptions refer to the mineralogy, texture, chemical composition and field setting of the rock in question. The final evaluation in each of these categories requires that the petrographer use information derived from microscopy, analytical chemistry, mineralogy, X-ray crystallography, statistics and computer science. Similarly the study of petrogenesis usually requires detailed knowledge of the mineralogy and chemistry of the rocks as well as their field setting. Petrographic studies are a necessary prerequisite to all studies of petrogenesis. Petrogenesis also makes use of aspects of geochemistry, volcanology, structural geology and geophysics.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

The mineral and fossil fuel resources in the world occur in association with a wide variety of rock types. It is thus of vital significance for the exploration and development of these resources that the petrographer be able to characterize these rocks adequately. Petrography is also an important tool in studies of ceramics, aggregates and building stones.

Petrogenesis is usually a more fundamental study than petrography and consequently the results find fewer immediate practical applications. In the long term however, studies of petrogenesis have great potential as an aid to the discovery of new resources. The results of these studies lead to a greater understanding of the various processes taking place within the earth; particularly of the manner in which various elements are segregated and distributed in the various rock types. If the rock-forming processes are well understood they can contribute to the discovery of new resources.

PRACTICAL APPLICATIONS

The practical application of petrological research lies in increased awareness of the diversity and physical restrictions that exist in mineral systems. Many diverse natural processes result in the formation of economic mineral concentrations from a wide variety of rock types. Hence, the most advanced and theoretical types of study that involve rocks have a potential economic value. Most of the practical applications of petrology are found in its traditional field and microscope studies. They are the heart of regional and detailed geological mapping and are thus of fundamental importance to most geological studies. The research fields have practical importance in that an understanding of the details of a geological process may enable the geologist to predict distribution of rocks and minerals in unknown areas of an igneous or metamorphic complex.

HISTORICAL DEVELOPMENT

The investigation of rocks in Canada by visual, optical and analytical techniques has been carried on almost as long as the Geological Survey of Canada has been in operation. Such investigations have often served to supplement field investigation particularly where rock types were obscure or unusual. Since the beginning of this century similar studies have been carried out by staff and graduate students in many Canadian universities. On the whole the work has been mainly concerned with observations made in the field and with the petrographic microscope. Relatively little attention has been paid to the chemical composition of rocks and their constituent minerals.

All research work in petrology must have a firm foundation in field work and Canadian petrologists have an excellent reputation in this regard. From the time of their foundation each of the various Canadian geology departments attached prime importance to field work. Consequently the experience and training of the Canadian field petrologist is among the best in the world. The recent trends toward greater diversity of research effort require, however that some graduate students may not spend as much time on field work as in the past.

Despite significant advances in petrology in other countries there is little or no evidence of any change in the approach to petrology teaching and research in Canada until about 1950-1955. At that time, although the fundamental aspects of petrology such as field and microscope studies were developed as well as those in other countries the more modern aspects of petrology were almost totally lacking in Canada. Several important steps have been taken during the last 15 years to alter this situation. Each of these steps serves to enhance the view that it has become increasingly difficult to place limits on the study of rocks. The expansion of facilities for conventional and rapid chemical analysis of rocks and minerals at the Geological Survey of Canada and several universities emphasizes the fact that chemical data, once considered peripheral to petrology are now an integral part of the science. Analytical techniques have so developed in the last 15 years that highly sophisticated instrumental procedures are replacing conventional chemical analyses. Instruments such as the X-ray fluorescence spectrograph, the atomic absorption spectrometer and the electron probe are essential facilities for a modern comprehensive group of research petrologists. The large volume of data from such analytical laboratories gives rise to problems of interpretation that may require elaborate statistical manipulation and computer sorting. The world wide petrological community has not yet found a universally acceptable solution to this problem.

The development of high temperature and high pressure experimental studies that were so significant in the development of petrology in other countries had little impact among most Canadian petrologists until about 10 years after the Second World War. Laboratory studies of natural and synthetic systems at elevated temperatures and pressures - a field championed by Canadian-born petrologists living in the United States - were carried out at only one Canadian university as recently as 1962. Neither the universities nor the various government departments were able to provide the relatively high level of financial support required for this type of research. Such studies cannot be divorced from petrology. Several laboratories have been established during the last 5 years, but only on a very limited scale. A serious omission, however, is the lack of experimental studies concerned with the nature of the earth's mantle. At the present time only two universities have the facilities to carry out experiments at pressures above 10Kb and neither of these is yet in operation.

Some of the most significant advances in our understanding of processes in petrogenesis have resulted from the application of the principles of physical chemistry and thermodynamics to the study of rocks. This is a vital aspect of petrology that received only limited attention in Canada until about 5 years ago.

PRESENT LEVEL OF ACTIVITY

The comments above suggest some increase in activity in Canadian petrology during the last 5 years. Several university departments have employed petrologists who bring one or other of these new approaches to teaching and research in petrology. However, with two significant exceptions, the approach to such "modernization" where it has been attempted seems to be on the scale of one man per department. The highest levels of activity in petrology research are in the traditional field and microscope studies, in obtaining relatively inexpensive but rapid and accurate chemical analyses of rocks and minerals, and in high temperature-pressure studies of natural and synthetic systems related to rocks.

NEED FOR INCREASED ACTIVITY

The great majority of petrological theories are based on a vast amount of data often collected by many workers using a variety of techniques and approaches to the problem. Field relations provide the most fundamental of all geological observations and perhaps the biggest single gap in Canadian geology is a knowledge of the detailed, and in some areas regional, field relations in the Canadian Shield. Increased activity should be encouraged in field petrology.

Many aspects of physical science now provide significant information for petrology. These should be developed and integrated with traditional aspects of the science. In particular the application of thermodynamics and physical chemistry to the study of rocks should be expanded. This is presently one of the most rewarding fields of petrological research for the study of both magmatic and metamorphic rocks. Petrology will advance in the future only to the extent that these disciplines are integrated with traditional petrological studies. Most of the significant advances in petrology over the last 25 years have been made by application of interdisciplinary studies. It therefore follows that increased emphasis should be placed on such work.

There should be increased studies of the fundamental principles of solid state reactions on the basis of ligand field theory. These studies should lead to a much clearer understanding of chemical reactions in both igneous and metamorphic rocks. The development of widely accepted statistical procedures for the processing of petrological data should receive more attention. Rock classifications based on either the chemical or mineralogical constitution of the rocks should have a sound statistical foundation. A third field in which future development is desirable is the application of stable isotope studies, particularly oxygen isotope data, to the determination of equilibration temperatures in igneous and metamorphic assemblages.

Other areas of research, not necessarily interdisciplinary, in which increased activity is most desirable include the study of mineralogical reactions at pressures above 10Kb. This aspect of petrology has developed more rapidly in the last 10 years than any other branch of the science. In view of Canadian interest in the Upper Mantle Project it is most unfortunate that experimental studies have not been carried out in any of our universities or research centres. Combined field and laboratory studies of selected regions will continue to produce new concepts in petrology. However, in view of the very detailed field microscopic and analytical studies which are required, the future significant studies of this type cannot be undertaken by any one individual. Research teams must be developed to produce the necessary data in a reasonable length of time.

Study of the relation between rocks and ore deposits should be greatly expanded. During the last 10 years much progress has been made in experimental study of sulphide phase equilibria. It is now time for a concentrated study of both simple and complex systems involving a wider variety of mineral groups such as oxides and carbonates as well as silicates and sulphides. This work will require the increased co-operation of petrologists, economic geologists and structural geologists.

TRAINING

The continuing emphasis on interdisciplinary studies in the future of petrology requires an undergraduate training in basic science. It would appear that those scientists making the greatest impact in petrology will, in future, be those who have had the greatest exposure to physics, chemistry and mathematics. With few exceptions, until the middle of this decade a training in petrology in this country was sadly lacking in its basic science content. The main emphasis in training appears to have been to produce a general "hard rock" geologist suited to the requirements of mining companies and various government bodies. There has been no attempt to produce a petrologist who could contribute to the future of his science. This is in part reflected by the fact that it is difficult to identify any leading Canadian petrologist, appointed during the last 10 years, who has received his Ph. D. training in Canada. Many geology departments are now reviewing the curriculum for undergraduate and graduate students. The desirability of adding courses in basic science usually conflicts with attempts to add courses in newly emerging branches of geology.

It will be increasingly difficult to achieve a balance between a sound training in geology and the necessary background in mathematics, chemistry and physics. A partial solution may be to increase the teaching of these subjects in the geology departments themselves - particularly for more senior students.

The emphases in training have changed in some centres during the last 3 years but this trend should be accelerated throughout the country.

MAJOR OBJECTIVES AND FUTURE TRENDS

The most important objective in petrology must be a complete understanding of the processes by which the rocks were formed. A better understanding of these processes would give a clearer picture of reasons behind the association and distribution of the various rock types and the ores related to them. In order to achieve this objective, petrologists must obtain the best possible classification of rocks. This is perhaps an academic objective in itself, but as new approaches are adopted in petrology the traditional classifications must be continually re-examined.

Future trends in petrology will be influenced to a large degree by developments in the associated sciences of mineralogy, geochemistry, geophysics, inorganic and physical chemistry, statistics and computer science. The petrologist of the future must have the basic training to take full advantage of these developments. It is not sufficient for the petrologist to make blind use of data collected by geochemists and geophysicists; he must be able to make his own independant critical judgement of the data.

One of the most important roles of the future petrologist will be to select and evaluate information gathered by geochemists and geophysicists, and to determine its relevance to problems of petrology. Integration of each of these disciplines into a research team has begun in some centres and will undoubtedly continue.

Increased automation in the gathering of microscope observations and analytical data has already begun and will no doubt accelerate in the next decade. With the exception of more convenient methods of transportation, however, few advances have been made in field aspects of petrology. It is difficult to see a fundamental improvement in these techniques but efforts should be made to review the manner in which field data are presented.

CONCLUSIONS

1. Training in petrology should be based on a strong background of basic science, preferably equivalent to first year mathamatics, physics and chemistry followed by second and third year courses in mathematics and either chemistry of physics.

2. The various government surveys should be encouraged to accelerate detailed and regional mapping in the Precambrian Shield. Petrological fact, theory and fantasy can only be separated when put to the test in a field environment.

3. Increased emphasis on the theoretical petrology should be encouraged in Canadain universities.

4. Strong financial support should be provided for interdisciplinary groups of research workers whose studies bring together specialists in the traditional aspects petrology and also those in chemistry, mineralogy, geophysics and statistics.

5. More attractive financial support should be provided for research associates and post-doctoral fellows to keep a continuous supply of top quality research workers in this country. This will greatly increase the productivity of those centres now operated almost exclusively by teaching staff and graduate students.

VOLCANOLOGY

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DEFINITION

Volcanology is concerned with the origin, migration and emplacement of molten igneous material and associated solids and fluids, particularly in relation to their characteristics when erupted at the surface. In matters of origin and migration within the crust volcanology merges into the fields of igneous petrology, physical chemistry and geophysics. In matters of emplacement upon the crust, volcanology merges into the fields of geomorphology, geography and the social environmental sciences.

SIGNIFICANCE OF RESEARCH

Volcanic activity has been involved in a major part of the geologic history of Canada, including those parts represented by the Precambrian Shield, Appalachians, Cordilleran and Franklinian (Innuitian) regions. Thus an appreciation of the role of volcanism is important to the understanding of earth history.

Volcanic-rich belts are traditionally favourable areas for prospecting for ore deposits. In particular, massive sulphide deposits are closely associated with volcanic rocks. This metallogenic relationship warrants detailed investigation on the petrology and chemistry of volcanic accumulations as a direct aid to mineral exploration in Canada. Volcanic concepts will be considered and used increasingly in the search for hidden ore deposits particularly those at deeper levels in the crust.

Volcanic rocks constitute our most widespread and readily available sample of the interior of the earth and may be expected to provide important clues on the nature of processes operating in the formation and differentiation of magmas.

Volcanic rocks of a particular age provide significant insight into the composition of the Upper Mantle at that time. The wide range of geologic ages represented in volcanic rocks in Canada provides opportunity to study possible secular changes in Mantle composition.

Certain parts of Canada particularly in British Columbia may be threatened by volcanic eruption and earthquakes. More information on these potentially destructive activities based on geophysical instrumentation is desirable to help minimize destruction of human life and properties. In this connection quite large areas could be seriously affected by ash falls following paroxysmal explosions of the Mazama (Oregon) type. These have occurred in quite recent and historic time. As well, the possibilities of developing sources of geothermal power in areas of recent igneous activity should not be neglected.

HISTORY OF RESEARCH IN VOLCANOLOGY

Until the mid 1950s volcanic rocks as such in Canada had received limited attention from a purely scientific viewpoint. There had been some significant pioneer studies in both Precambrian and Phanerozoic terrains, and considerable areal mapping and much prospecting of volcanic-rich belts in Canada had been completed, but little was known about volcanic structures and processes and the petrochemistry of volcanic rocks in Canada

Although many important volcanic-enclosed ore bodies were discovered years ago such as the Flin Flon and Horne mines, the discovery of numerous base metal deposits, some of major dimensions, in volcanic rocks during the late 1950s accelerated interest in volcanic rocks and volcanic processes.

Considerable advances have been made in the last fifteen years. Large numbers of chemical analyses are available from certain areas and some investigators have acquired considerable experience and knowledge in recognizing various types of volcanic deposits and the types of processes they represent. The metallogenic implications of this new knowledge is under continuous analysis and in constant use.

PRESENT LEVEL OF ACTIVITY

The present level of activity is modest, but certainly much higher than at any time in the past. Nevertheless, it fails to meet some of the basic challenges offered by the wide range of volcanic rock types and ages in Canada and their economic potentialities. The number of Canadian earth scientists engaged in volcanic studies is small. Only a few government institutions and universities in Canada include active programs or offer relevant courses.

NEED FOR INCREASED ACTIVITY

Because of the youthful stage of volcanic studies in Canada it is fair to say that increased activity is required at all levels and in all aspects.

The main emphasis for some time to come should be upon collection of the fundamental data of the volcanic belts. Specifically included are the geometry, distribution, compositions, and ages of volcanic forms and units in the belts including mineral occurrences. This may be expected to contribute substantially to the elucidation of fundamental petrogenetic problems including those of mantle-crust relations and history.

Additional specific areas requiring increased activity include:

a) The provision of more geophysical data on volcanic belts in Canada.
b) The performance of more experimental petrologic work on volcanic rocks.
c) Increased geochemical studies including isotopic relations of volcanic rocks around orebodies.
d) Oceanographic studies of major submarine volcanic accumulations.
e) Greater attention by Canadian volcanologists to those areas of the world which display active volcanism as a basis for interpreting volcanic phenomena both recent and ancient in Canada.

IMPORTANT OBJECTIVES AND FUTURE TRENDS

The most important future objectives of volcanological studies should be:

a) To search for and establish major petrographic provinces in Canada and relate them to the tectonic development and geologic history of the regions in which they occur. In this regard, volcanic rocks may serve as potent clues to paleotectonic environments.

b) To search for and establish the metallogenic relations between volcanic rocks and ore deposits. Specifically included are studies of geothermal centres (hot springs-fumaroles) and related ore-bearing fluids.

c) To correlate compositional variations in volcanic rocks with the experimental data on the origin and differentiation of magmas in order to gain insight into the composition of the Mantle and its variations in space and time, and of the processes involved in development of the earth's crust.

d) To evolve the techniques of volcanic stratigraphy to the same level of use as those of sedimentary stratigraphy.

e) To search for and determine the role of submarine volcanism in the process of ocean floor spreading particularly as it may affect continental North America.

CONCLUSIONS

1. Greater numbers of earth scientists are required in the major fields of volcanic studies in Canada - volcano-stratigraphic, geochemical, geophysical, experimental, oceanographic and metallogenic.

2. The metallogenic aspects of volcanic studies in Canada should be investigated on a broader scale by specialists in that field. The metallogenic record is unusually well preserved and exposed in Canada. Collaboration with geochemists, geophysicists and experimentalists is desirable.

3. Increased training and research are required on the nature of volcanic processes. This should be done not only at university level but should also involve geologists who are primarily concerned with areal mapping in regions containing volcanic rocks. One way to attain this goal is to have more field trips to better areas in Canada led by those with most experience with volcanic rocks. It is also important that direct contact be made and close ties be established with workers in the main active volcanic areas of the world. This is best accomplished by frequent exchange of visits and studies in the field. The importance of 'two-way' contacts is stressed.

4. More experimental work should be undertaken on the synthesis and crystallization of igneous rocks including high pressure (>20 kbars) studies. Such work should be geared to volcanic problems in Canada. The great increase in knowledge of experimental petrology in recent years makes it more difficult for the geologist involved in field and chemical studies of volcanic rocks to keep abreast of the significance of the experimental work. For this reason, close cooperation between the field geologist and experimentalist is desirable. This may be best achieved if both are working in the same institution. This would minimize the danger of large amounts of data being collected in a vacuum.

5. More geophysical work on volcanic belts is required - seismic, gravity and paleomagnetic.

6. Better dating of volcanic belts is a necessity. This applies to detailed problems within specific belts e.g. those of Phanerozoic age in British Columbia, and to general problems of dating in, for example, the numerous Precambrian belts.

7. The feasibility of developing specialized institutions of volcanic studies in Canada should be investigated. Presumably such institutions would resemble existing Centres for Volcanology e.g. Oregon, but would be adapted to special Canadian problems. Alternatively active participation in existing Centres should be considered.

8. Data retrieval bank is required for chemical compositions as well as isotopic and age data pertaining to volcanic rocks and minerals in Canada.

9. Isotopic studies (Sr, Pb, O, etc.) of volcanic rocks should be undertaken to attempt to understand problems of magma genesis, contamination, involvement of connate and meteoric waters in modifying compositions and possibly as an agent in actually stimulating volcanic eruptions and explosions.

ACKNOWLEDGEMENT

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METEORITE CRATER INVESTIGATIONS

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DEFINITION

The investigation of meteorite craters on Earth is part of the study of interactions and encounters between members of the Solar System, particularly between the inner planets and meteorites, asteroids and comets. The field of crater investigations includes the search for and identification of impact sites on Earth, and the determination of their structure, the geophysical, geochemical and mineralogical properties of their rocks and their geologic history. It also involves experiments concerning the dynamic properties of geologic substances and analogous materials.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

The search for meteorite craters in Canada has drawn attention to hitherto neglected features of Canadian crustal rocks, introduced new ideas to the study of old problems and stimulated new approaches to earth science by comparing terrestrial features with those of the Moon and nearby planets. It is one of the main avenues by which Canadian scientists, with relatively modest expenditures, can contribute to studies concerned with the history of the Solar System, the origin and abundance of meteorites, asteroids and comets, the origin and history of surface features on the Earth, Moon, Mars and similar planetary bodies and to the history of the more stable parts of the Earth's crust.

The analysis of field and laboratory observations, coupled with pertinent experiments, has led to a better understanding of the dynamic properties of the Earth's crust and the nature of its response to high-energy shock pulses. These results have application to the field of rock mechanics and to the contemplated use of nuclear explosions for large excavations. The studies are also of significance to the mining and oil and gas industries as a number of circular structures have ore deposits associated with them, or have attracted the attention of oil companies. A better understanding of the role impact may have played in the formation of these structures could materially assist their commercial investigation and evaluation.

PRACTICAL APPLICATION

Attention has already been directed to the economic importance of crater studies in a number of areas, such as Sudbury, Ontario and Vredefort, South Africa, where impact on a large scale has been suggested as being the major structural event controlling the formation or present distribution of ore bodies. Structures of probable impact origin in areas underlain by sedimentary rocks have received considerable attention from oil companies, as possible traps for oil or gas similar in some respects to salt diapirs.

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Undoubtedly a more detailed knowledge of impact structures and the many forms they may take will assist the search for economic deposits in these areas. On the other hand, if as some have suggested, many of the circular structures studied in Canada are related to intrusions of deep-seated origin, then they may indicate important deposits of rare-earth elements or diamonds.

The development of the theory of crater mechanics as a branch of rock mechanics has been stimulated by the study of natural craters and this interaction will continue as studies proceed. The use of large explosions including nuclear events for peaceful purposes is another field of interaction between experiment and observation.

The drilling program initiated by the Dominion Observatory to study possible impact sites has had the further benefit of helping Canadian drilling companies develop techniques for drilling into deep lakes in winter. New methods have been evolved and valuable experience gained under difficult conditions.

HISTORICAL DEVELOPMENT

The extraterrestrial origin of meteorites has been accepted by the scientific community for about 160 years, but the realization that structures up to tens of miles across have been formed on Earth, throughout geologic history, by the impact of asteroid-size bodies is only now gaining acceptance by an appreciable number of scientists.

The discovery in the late 19th century of the Barringer Meteor Crater in Arizona initiated a long controversy between those who rejected, and others who strongly advocated, its meteoritic origin. By the 1930s and early 1940s the debate had spread to include a number of structures in Europe, South Africa and the United States. Such structures were called 'cryptovolcanic' by W. Bucher. R.S. Dietz introduced the alternative term 'cryptoexplosion' and became a leading proponent of their impact origin, coining the name 'astrobleme' for ancient impact sites. By 1960, E. Shoemaker and others had applied recent advances in the theory and experimental study of cratering by hypervelocity impact and nuclear explosions to the Barringer crater, successfully explaining its structure and mineralogy by the impact theory. There has been a great increase in the study by observation and experiment of shock deformation and metamorphism, from which has come a number of criteria for the recognition of old, eroded impact structures which no longer have associated unaltered meteoritic material.

Canadian involvement in the field began with the discovery during World War II of the New Quebec crater and its initial investigation by V.B. Meen of the Royal Ontario Museum in 1950-51. He established the crater's strong structural similarity to the Arizona crater; at more than twice the size of the latter it was considered to be the largest relatively fresh meteorite crater on Earth known to that time. In 1951 a crater of similar size but much greater age was discovered in Algonquin Park, Ontario from air photographs taken by Spartan Air Services Ltd. Beals, Millman and Innes at the Dominion Observatory realized that many old craters might be preserved on the relatively stable Canadian Shield, and initiated the world's first systematic search for ancient meteorite craters using air photographs, maps and other information.

The outcome of the search has been most successful. To date eighteen sites have been identified in Canada for which structural and mineralogical evidence of an impact origin has been advanced. An even greater number of possible sites are considered worthy of further investigation. Canadian investigations have been distinguished by the broad approach taken to the problems of crater identification and analysis. Gravity, magnetic, seismic, resistivity, structural, topographic and petrographic methods have all been employed. Even more important has been the pioneering use of diamond drilling to investigate the deep zones of a number of the craters. This program, begun in 1955, has received world-wide acclaim as a demonstration of drilling for scientific purposes and is considered a model for investigators from other countries. To 1967, 32 holes totalling 43,023 feet of drilling have been completed at a cost of approximately $550,000. The results have given the most complete information available on the structure of large features of the type attributed to impact and on the nature and distribution of shock effects in geologic materials. Some cores have been of great value to sedimentologists and studies of heat flow have been made in a number of drill holes.

In Canada the Dominion Observatory has two scientists and one technician employed full time in this field, with part time participation from four other scientists. The cost of the Observatory program has averaged about $100,000 per annum in the last five years. At the Geological Survey of Canada one geologist has devoted approximately one-third of his time to investigations in this field while other members of staff and field assistants have been involved from time to time. About $10,000 per annum has been spent on this activity.

For the most part other Canadian agencies have not been involved in crater studies as such, but in some cases provincial mapping programs or industrial exploration activities have encompassed structures of interest to crater studies. In recent years the Quebec Department of Natural Resources has mapped two of the largest structures in Quebec as part of their regional geologic mapping program; and the Saskatchewan Department of Mineral Resources has mapped the area containing the Deep Bay crater. Two structures which have attracted commercial exploration activity recently are those at Carswell Lake in northern Saskatchewan, and at Steen River in northern Alberta. Expenditures on these activities are not known, but are undoubtedly considerable.

Participation by Canadian universities in crater studies has been directed mainly at the investigation of aspects which are ancillary to the governmental programs. The university projects include age determinations and geochemical studies (Carleton and McMaster Universities), sedimentology (Queen's and Toronto Universities) and heat flow (University of Western Ontario). Altogether as many as six staff members or graduate students have been involved in current or recently completed projects.

A comparable number of U.S. scientists, mainly under N.A.S.A. contracts, have been directly involved in studies of Canadian craters as possible impact sites, involving expenditures averaging an estimated $30,000 per annum. In some cases Canadian scientists involved in crater studies have cooperated with scientists from the U.S.A. and Europe in a number of programs, such as the high-explosive cratering experiments at the Defence Research Board's experimental station at Suffield, Alberta, and studies of some of the Observatory drill core.

NEED FOR INCREASED ACTIVITY

The leading position enjoyed by the Canadian crater studies can only be maintained by a steadily increasing effort, in line with those of other countries. The main requirement is to continue the search for and study of further possible impact sites at approximately the present level, while conducting a more intensive study of specific craters. The German approach to the study of the Ries crater, in which a number of institutions have combined to form a multidiscipline study group, is one method of making good use of relatively limited resources to study a large crater.

Detailed drilling programs, similar to that at the Brent crater successfully completed in 1967, are needed at several other Canadian craters, including the New Quebec crater, and a number which have been only partially drilled to date.

MAJOR OBJECTIVES AND FUTURE TRENDS

Until a general consensus has been reached, the first objective of these investigations remains the delineation of more definitive criteria for the origin of the structures which have been attributed to meteorite impact. Continued detailed studies of structure, mineralogy, geochemistry and tectonic setting are required to determine the cosmological, geological and economic significance of the features being investigated.

The importance of impact cratering to the structural evolution of the earth's crust has still not been fully determined. Information about the Moon, Mars, meteorites, asteroids and other bodies of the solar system is accumulating at an ever increasing rate. The analysis of much of these data requires the full study of terrestrial craters. Further, it has been suggested that impact cratering has been an important influence in the early history of the planets and may have played a role in developing inhomogeneities in the Earth's crust and upper mantle, including the distribution of metallogenic provinces. The growing importance of crater studies as an integral part of the planetary sciences should be maintained for at least several decades.

CONCLUSIONS

1. The considerable natural advantage enjoyed by Canada in harbouring the most complete assemblage of ancient craters in the world, including some of unique aspect, is a valuable scientific resource which should be husbanded in the interests of Canadian science generally. Canadian research in this field should be maintained at or above the average level of the past ten years, and every effort should be made to involve a steadily increasing number of Canadian earth scientists in this endeavour.

2. Future investigations of the Canadian structures should maintain the search for definitive criteria of origin; continue the analysis of observational and experimental data by comparison with models of both hypervelocity impact and explosive volcanism; define their structural peculiarities so that those involved in commercial exploration can readily identify them and assess their economic potential; extend associated studies of broad tectonic and cosmologic considerations.

3. Techniques employed in the past should continue to be used, including systematic diamond drilling. However, increased emphasis should be given to mineralogical studies using electron microscopy and electron microprobe methods and to geochemical studies.
4. Consideration should be given to developing study groups similar to the German group for the study of the Ries crater. The pressure from American scientists to study the Canadian craters is steadily increasing, particularly since manned lunar missions have taken place, and can only be met by a viable Canadian effort, combining field, laboratory and theoretical studies.
5. Developments in the field of crater studies illustrate the need for broader undergraduate programs in Earth Science in Canadian Universities giving increased attention to solid state physics and the study of the planet Earth as a member of the Solar System. Reference may be made to some programs in planetary science being developed in the United States.

CRYSTALLOGRAPHY

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DEFINITION

A dictionary defines crystallography as the science of the interatomic arrangement of solid matter, its causes, its nature and its consequences. Crystallography as related to the solid-earth sciences may thus be regarded as a branch of mineralogy concerned with the elucidation of the internal properties of minerals. Such internal properties include the definition of the unit cell and space group of any mineral, and ultimately the detailed crystal structure of the phase. Diffraction techniques are most commonly used in crystallographic investigations, but other methods of investigating the solid state (e.g. resonance spectroscopy) should not excluded from the scope of crystallography if the results may have direct crystallographic significance. There is a problem in defining the limit where the science of solid state takes over from crystallography, so for the purposes of this report I shall regard the practical aspects of crystallography as being confined to the use of diffraction (X-ray, electron, neutron) and optical methods.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Crystallography both pure and applied is of active interest to more scientific disciplines than any other branch of science, with the possible exception of mathematics. It is quite probable therefore that research and development by geological oriented crystallographers may bestow benefits on other branches of science (e.g. M.J. Buerger of M.I.T.) and conversely the earth sciences may often reap rewards from developments made by chemically or physically oriented crystallographers.

To consider the significance of research and development of crystallography as related to the solid-earth sciences it is necessary to view the two-fold aspects of the subject separately.

(a) Crystallographic methods are employed in the systematic characterisation of minerals by their crystallographic properties such as X-ray diffraction patterns, unit cell dimensions, lattice and space group, and also optical parameters. These measurements constitute a valuable basis for the classification of minerals and routine identification of similar species. This is a continuing aspect of the discipline, which, while not subject to much change in terms of research and development, is fundamental to the crystallographic needs of the geologist by providing a rapid, reliable and precise method of mineral identification to assist in the understanding of rocks, ores and soils. This aspect will be referred to as 'routine crystallography'.

(b) The determination of crystal structure is the ultimate aim of the crystallographer and the results, in terms of interatomic distances, lattice energies, co-ordination numbers, etc., are of vital significance in understanding the properties of minerals. Such information, in conjunction with other physical and chemical approaches, may lead to better understanding of the genesis of minerals, formation of orebodies and of the stabilities and phase relationships of minerals at different environments in the earth. Further, practical results may accrue. For example, a thorough understanding of the properties of a mineral is vital in the design of an efficient ore beneficiation process. This aspect will be referred to as 'specialized crystallography'.

Perhaps an aspect of crystallography almost as important as complete structure determination, is the study of defects and imperfections in the crystalline state. The mechanical, electrical and physical properties of materials are often more dependent on the defects than on the basic structure. Besides diffraction methods, other techniques as thermoluminescence, electron microscopy are often employed in the study of defects, and hence such activities are considered peripheral to the main subject and more in the realm of solid state research.

PRACTICAL APPLICATIONS

Crystallographic studies in the solid earth sciences have practical applications which extend into many different fields. It must be emphasized that knowledge of the crystal structure of a mineral is absolutely essential to an understanding of its chemical and physical properties. Only when this is fully known can the behaviour of minerals in their manifold environments be understood and predicted.

For example, the formation of minerals and their phase relationships within the earth are bound up with these factors. The geophysical prospecting methods depend on the physical properties of minerals within the crust, and a detailed understanding of their crystallography is of inestimable value in this respect. In the ore beneficiation process, the surface properties of minerals are often utilized to accomplish separations and again these relate back to the crystal structure. Finally in the field of utilization of minerals, as abrasives, construction materials or as raw materials for some further process, glass manufacturer or metal refining, again the crystallography is of paramount importance.

Thus from the point of view of exploitation of our natural resources it must be seen how important is a complete understanding of the crystallography of minerals.

HISTORICAL DEVELOPMENT

Crystallography has always been associated with the subject of mineralogy, and the first crystals to be studied in depth were minerals. For this reason the subject has become an integral part of mineralogy departments, and consequently is closely allied with the study of the solid earth. Before 1912 all crystallographic study was morphological or optical, but after this date X-ray methods were developed and the scope of the subject greatly enlarged through the ability to investigate crystals internally. Centres specializing in crystal structure determination have developed, principally in the United States and Europe (west and east), but facilities for less sophisticated work are now available in virtually all institutions where any mineralogical studies are undertaken. This is certainly true of Canada, and it may be assumed that all groups studying the solid-earth sciences have access to crystallographic facilities capable at least of achieving 'routine crystallographic' ends.

In Canada 'specialized crystallography' was developed at the University of Toronto in the school of M. A. Peacock. Until his death in 1950 Peacock attracted many students of crystallography, some of whom have established crystallographic facilities in other Canadian universities, though none have developed into what could be called a crystallographic centre, consistently attracting high calibre graduates for post-graduate research on crystallographic problems. The impetus given by Peacock's crystallographic centre at Toronto has been largely dissipated and current crystallographic work related to the solid-earth sciences is sporadic.

Canada has been a member of the International Union of Crystallography since its inception in 1948, and played host to the International Crystallographic Congress in Montreal in 1957. Canadians have been and are active on the executive committee and on special commissions. This year Canadians will be hosts to a school on crystallographic computing to be held in Ottawa. There are 92 Canadian entries in the 1965 World Directory of crystallographers, of which 32 have mineralogical or geological backgrounds or interest. However despite this apparent strength of earth-science oriented crystallographers there is really only one crystallographic centre in Canada, the National Research Council, where until recently much detailed crystal structure work was done under W. H. Barnes on vanadates and related minerals. Recently the emphasis at N. R. C. has been turned towards organic crystallography.

The sulphosalt group of minerals is the main one in which significant crystallographic developments have been made springing originally from the Peacock school in Toronto.

PRESENT LEVEL OF ACTIVITY

Crystallographic activity in the Canadian earth-sciences at present is widely distributed as far 'routine crystallography' is concerned. Perhaps this is to be expected in view of the exceptionally fortunate position of Canada with respect to mineral occurrences. However the determination of crystal structures of minerals is done sporadically and at only a few establishments. An exception is the Mineral Sciences Division of the Department of Energy, Mines and Resources in Ottawa where a group has recently been established to study the structural crystallography and crystal chemistry of a number of minerals, particularly those which are important from an economic point of view, such as sulphides and arsenides. This group employs automatic X-ray diffraction apparatus, electron probe microanalysis and Mossbauer spectroscopy. Computing facilities are available to control experiments and process results. Beyond this, the crystallographic activity in Canada is small, with work published in the last year coming from Universities of Western Ontario, McGill and McMaster.

Several crystallographic laboratories have been set up in Canadian universities in the last few years, but almost all are concerned with organic crystal structures. Thus, although elaborate crystallographic facilities are not set up primarily for earth scientists, they might well be available to a great many if the appropriate steps were taken. Often an earth scientist is unaware of crystallographic work relevant to his field, being performed in other departments of his university. Clearly there is a need for collaboration here.

In terms of international reputation in the field of crystallography, Canada enjoys a high position, as has been mentioned above. The earth-science aspect is less well represented, but probably no worse than any other country of comparable population and development such as Australia or Japan. This judgement is made on a rough assessment of published work. This does not remove the need to change this situation, since in the countries such as the USSR, which is comparable to Canada geologically, there is great emphasis on the development of crystallography and mineralogy, and this is probably closely connected with the similar role of the USSR as a producer of raw materials. Incidentally the numbers of crystallographers (all types) to be compared with Canada's 92 for a few other countries are: Australia 135, India 246, Japan 300, Spain 85, USA 1250, USSR 280. In this context of crystallography in general Canada is perhaps slightly under-represented, but the percentage with mineralogical interests, 35 per cent in Canada, is significantly higher than any of the other countries listed above: Australia 22 per cent, India 10 per cent, Japan 17 per cent, Spain 30 per cent, USA 16 per cent, USSR 18 per cent.

I have made a rough appraisal of the number of papers by Canadian earth scientists published in recent years with the idea of determining the proportion of work concerned with crystal structures as opposed to more routine mineralogical works of a crystallographic nature. The ratio is probably 1 to 10.

NEED FOR INCREASED ACTIVITY

The conventional crystallographic investigation will continue to use X-ray diffraction as the most fundamental tool, but other methods of investigating the solid state can also be employed. This must involve collaboration with other scientists concerned with the solid state, since the equipment needed for neutron diffraction or the various types of resonance spectroscopy is expensive to buy and maintain and will not normally be acquired in geology departments. Thus joint work with other specialists, such as solid state physicists, physical chemists, and the use of their facilities, will allow crystallographic knowledge to be more effectively applied to the solution of problems concerned with detailed structure, bonding, crystal field etc.

In addition the advantages to be achieved through the use of computers must be appreciated. The efficiency of experimental procedures and the accuracy and precision of results can all be improved vastly through the use of automatic instruments and computers. This is probably true in crystallography more than any other field of the solid-earth science.

TRAINING

The main obstacle to expanding crystal structure studies in Canadian earth science departments is the scarcity of trained personnel. To be successful, a crystallographer must have a physical-chemical background. This combined with an interest in geological problems gives a rather rare breed. True, there have been, and are, crystallographers with principally geological backgrounds who have contributed greatly to the field as a whole, but with the increased specialization which is taking place it seems unlikely that this will happen much in the future. Some increased level of co-operation is required between departments in universities so that existing resources may be utilized more efficiently. It is a great waste if there is a first rate crystallography laboratory in the chemistry department, while a crystallography student in geology struggles with inadequate facilities and instruction. In this way the crystallographic competence of earth scientists may be improved without enormous investment in equipment which might not be utilized efficiently. Further the status of crystallographers from the earth sciences may be raised so that chemists no longer have exclusive domination of the field.

It is a fact of life that Canada draws heavily on brains trained outside the country, and this is a perfectly healthy state of affairs by which crystallography frequently benefits. While this situation may in time change, it will be slow, particularly in the more specialized branches of science, and in the meantime, crystallography courses may be set up in one or two earth science departments. The recent attempt to establish an honours course in crystallography at McGill University is a praiseworthy step.

MAJOR OBJECTIVES AND FUTURE TRENDS

Crystallography in the earth sciences has two roles to fulfill (routine and specialized). The first of these, the routine procedure for identifying and characterizing minerals in geological or mineralogical investigations, is already being achieved in a more or less satisfactory manner.

The second objective is open ended, as minerals are being used in ever more sophisticated ways. Specific directions in which research will develop may be towards structural determinations at elevated temperatures and pressures, to increase understanding of mineral behaviour in all regions of the crust. At normal temperatures and pressures more detailed structural analyses may be attempted. As the crystal structures of all common mineral groups are known, at least in their basic features, the next stage is to delve into known structures in greater detail with higher accuracy, with more sophisticated methods and with increased collaboration with other scientific specialities. This will require more reliance on automatic instrumentation and advanced computing facilities which are inseparable from present day advancement in the physical sciences. In addition, new mineral structures must be solved. Geological materials, as opposed to the materials a chemist works on, often offer more opportunities to develop new ideas about the crystalline state. For example, nonstoichiometry is the rule in geology, and the study of nonstoichiometric compounds can contribute much to science.

The practical and economic applications of the results of such endeavours are beyond the scope of this report, but there can be no doubt that activity in such a basic field as crystallography is a prerequisite to advancement in many branches of earth science, both pure and applied.

RECOMMENDATIONS

This report has attempted to establish that there is a real need for increased crystallographic activity in the earth sciences. However, because the role of crystallography is relatively small in the geology curriculum, it is unrealistic to expect any one geology department to expend the money required to set up a modern crystallography laboratory (at least a quarter of a million dollars, and more if spectroscopic and non X-ray techniques are included). A solution could be for a government body to set up such a laboratory where students could also be trained. One university might be selected to receive a grant to establish such a facility. An experiment along these lines has been tried in the USA at Virginia Polytechnic Institute, and at McMaster University the crystallographic laboratory is shared by several departments. Alternatively a centralized institute of say, mineral sciences, could be established, where scientists from many disciplines could work together on the solution of problems in the earth sciences. Crystallographic work other than conventional crystal structure determinations would be undertaken. This institute might not double as a training centre as the alternative proposed above, but would produce results more directly than an institution where scientists are involved in activities other than research. The immediate practical benefit to Canada would be greater from something organized along these lines.

As far as the acquisition of competent earth science crystallographers is concerned, there appear to be two possibilities. Suitably trained people may come from outside Canada, a source which has and is providing many scientists of all disciplines, and this should be maintained. Secondly students may be trained on home ground, either in a full scale centre devoted to this (as suggested above), or they must be produced through channels already in existence. To increase productivity and quality through these channels, we must foster co-operation and joint studies between earth science departments and between all engaged crystallographic work within universities.

If these recommendations are heeded, then Canada has a chance to make significant crystallographic advances in the earth sciences, with consequent impact on the nation's scientific, social and economic development.

STRUCTURAL GEOLOGY

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DEFINITION

Structural geology is an exciting and expanding science, and there are few places more suited than Canada for its pursuit. It is the investigation of products and processes of deformation of rocks through geological time. It is concerned with the three-dimensional geometrical analysis of deformed rocks, with the sequence and nature of movement that can be deduced from this analysis, with the mechanics of this movement, and finally, with the forces responsible for the evolution of the structure. At different points in the scale of structural phenomena, structural geology becomes tectonics, and tectonics becomes geotectonics. The boundaries are not well marked, and there is a wide choice of definitions, but it is generally accepted that structural geology is most concerned with the deformation of discrete rock masses, tectonics with the internal geometry and movement pattern of coherent crustal segments, and geotectonics with the global relationships among these segments. Tectonophysics has emerged as the study of the same relationships, but from the perspective afforded by physics and geophysics.

Geochronology (by radiometric, paleontological and other dating methods), geophysics, tectonics, and structural geology are all interdependent. In the study of crystalline rocks, structural geology merges into petrology – rock fabric and texture, diffusion and recrystallization, mobilization and reaction being legitimate fields of both. In the study of non-crystalline rocks, structural geology draws heavily from stratigraphy and paleontology, and overlaps with the sedimentological investigation of depositional basins. In the investigation of the rheologic properties of rocks and rock masses the subject overlaps with tectonophysics and rock mechanics.

SIGNIFICANCE OF RESEARCH AND PRACTICAL APPLICATIONS

Structural geology and tectonics (treated together in this presentation) are primary tools in the investigation of the physical evolution of the Earth. The sequence of movements recorded in the rocks can be integrated with a time scale calibrated with data from paleontological, radiometric, or paleomagnetic sources. The fabric and configuration of deformed rocks (with their mineralogy if they have been metamorphosed) provide a record of processes operating deep within the crust, and a gauge of the mechanical behaviour of rocks under natural conditions. Structural geology is an essential component of any investigation of the Earth's history.

Rock structures are major factors in determining the location and optimum conditions for excavations or construction sites. The proper understanding of rock structure may also be a vital key in the prediction and eventual control of earthquakes and landslides. Rock structures also control the localization of many deposits of metallic minerals, industrial minerals, and petroleum and structural geology is thus an indispensable tool in the exploration and exploitation of mineral resources.

Tectonic syntheses can outline broad metallogenic provinces – major segments of the crust which contain characteristic types of economic deposits. More detailed investigations of structure can determine the locations of these deposits themselves, and structural investigation of these deposits can elucidate their relative structural age, and provide information essential to their development. The successful exploitation of oil and gas is similarly dependent on both broad and detailed studies leading to the identification of structural traps.

HISTORICAL DEVELOPMENT

Structural geology is a latecomer among sciences. If the progression from general description to precise or quantitative evaluation to experimental investigation can be applied as the yardstick of the growth and maturity of a natural science, structural geology is an unruly teenager. Vague general descriptions based on unquestioned concepts used to be the rule, and still form the bulk of structural "reasearch" in Canada. Precise geometrical measurements, accurate reconstructions, and experimental synthesis of natural structures and rock fabrics have at last begun and careful, well-documented field studies are growing in number. Outside Canada, experimental structural geology is developing very rapidly, but the technical problems of laboratory experiments are formidable. Conditions can now be duplicated over only a small segment of the natural range of the environment and at unrealistically high strain rates. Techniques are improving rapidly, however. Theoretical studies based on mathematical models, although relatively new, offer further promise of success, but the necessary data on the level of absolute strain in rocks, the actual rates of deformation, and the mechanical properties of rock masses under different natural conditions are largely lacking.

Structural geology in Canada was once chiefly concerned with the geometry of ore deposits, and to a lesser extent with that of oil traps. Commonly the structural investigations of ore bodies were restricted to descriptions, without an attempt to develop the significance of the observations beyond time-worn simplifications. However structural geology is of increasing value as an aid to exploration for oil and minerals, and seems destined to regain a position of major importance in economic geology within the framework of metallogenesis, under the guise of tectonics. In the search for petroleum, structural interpretation based on field observations, on drilling, or on geophysical information is an indispensable ingredient.

PRESENT LEVEL OF ACTIVITY

Current activity in structural geology in Canada is without doubt greatest in the petroleum industry, where it is integrated with sedimentological, stratigraphic, palaeontological, and geophysical work, and is largely field-oriented. In the geological world at large, great attention is being given to the new theoretical, experimental, and quantitative aspects of structural geology and rapid progress on each of these fronts is to be expected.

Until quite recently, most of the structural geology in Canada has been conducted as part of general geological field projects, and has involved routine descriptions, utilizing only a fraction of the data available in the rocks. The need to integrate structural investigations with other types of study is stressed elsewhere in this paper, but the average field geologist can no longer be assumed to have an adequate working knowledge of structural geology. The grasp of mathematics, geometry, and mechanics now required demands that structural geologists become specialists and that special structural studies be undertaken. The Geological Survey of Canada has recognized this by recruiting structural specialists and there are many projects now being conducted by the Geological Survey in which structural geology plays a significant role. Still, the number of structural specialists in Canada is small, and few universities employ more than one.

The contributions to structural geology by Canadians has been considerable, although due to the activities of relatively few people. Part of the explanation for these successes is the exceptional opportunity for field observations afforded by Canadian geology. The nature and evolution of folds and thrust faults in the Rockies worked out by Douglas and others, the study of the tectonic evolution of the Canadian Cordillera by Wheeler and his colleagues, and the unravelling of the tectonic history of the Canadian Shield by Stockwell and his co-workers are all excellent examples of this work on different scales. Interest, experience, and expertise in structural geology are currently growing at a rapid rate in Canada.

At the moment, research on the structures of the continents has been overshadowed by the dramatic results of the investigation of the ocean floors. We can anticipate a rapid increase in activity as the implications of ocean-floor spreading are realized and evaluated against the structural record of the continents themselves.

Current work in structural geology may be classified and described as follows:

1. Regional and local field investigations involving structural geology at all scales. There is increased need for detailed structural studies integrated within a sound framework of regional geological data.
2. Structural geology is applied to economic problems, much as the detailed investigation of individual ore deposits, and with the broad, regional investigation of their tectonic setting (metallogenesis). Structural research is of equal or greater importance to petroleum geology, and is an essential component of most exploration programs. Although relatively little has been published, oil companies are certainly the largest current performers of structural geology in Canada. The growth of engineering geology in Canada, parallel to developments that have already taken place elsewhere, may be expected to involve the application of structural geology and rock mechanics to a much broader range of engineering and urban problems.
3. Experimental studies have shown no substantial progress or new development in Canada. Rock mechanics research, is expanding, however, and takes place in ten Canadian universities, characteristically in the departments of mining or engineering, and at the Mining Research Centre laboratories of the Federal Mines Branch in Ottawa and Elliot Lake.
4. Interest in numerical analysis and model theory applied to structural geology is steadily increasing, and the statistical manipulation of large volumes of numerical data is becoming commonplace. The computer lends itself naturally to structural geology. There are already several projects

involving the collection of field data in machine-processable form, and attempts are being made to devise mathematical models of folding using small increments of deformation.

NEED FOR INCREASED ACTIVITY

There will be a natural expansion of all fields of structural geology, as a result of its modern development. So little experimental work outside the field of rock mechanics is now being done in Canada that at least one centre for experimental studies must be developed as soon as possible. The major effort, however, should involve detailed, precise, analytical structural investigations of the superb natural phenomena exposed on the Canadian subcontinent. There is a great need for systematic comprehensive description on a massive scale, supplemented by compilation interpretation, hypothesis. Most of the successful and fundamental work to date, of which examples were cited earlier, has had these essential ingredients. The accessibility of computers, and the means they provide for statistical manipulation of data and for topology will provide a powerful spur in this direction. Coupled with this acquisition and synthesis of data should be theoretical studies based on mathematical models, which appear to have a good chance of simulating natural conditions. These studies do not require expensive laboratories, although computing facilities are essential.

TRAINING

Structural geologists have to become specialists. Structural geology is concerned with the physical properties of materials, and thus is heavily dependent on mathematics and physics. Adequate backgrounds in both disciplines are a prerequisite for the modern approach to the subject. Specialization in structural geology can safely be left to the post-graduate level, but the ability to think in three dimensions must be developed as a basic skill at an early stage in the undergraduate level. There should be more opportunity in Canada for students to associate with groups of scientists specifically concerned with structural and tectonic problems, and for them to gain practical experience of the subject in the field.

MAJOR OBJECTIVES AND FUTURE TRENDS

The principal objective of structural geology is the understanding of the nature, evolution, and origin of the deformation of rocks and of the dynamic processes at work in the Earth's crust. The trend toward quantitative, theoretical, and experimental aspects of structural geology can be expected to continue. As a minimum, Canada should maintain a "watching brief" in all these aspects of the subject, and should continue to expand its already substantial contribution to the descriptive and analytical side. Canada is particularly well suited for this because of the extent and variety of rocks exposed and the resulting opportunity for meticulous observation in a broad range of environments and scales.

CONCLUSIONS

1. At least one centre for experimental work in structural geology (as distinct from rock mechanics) should be established. Ideally such a centre would be one in which visiting workers are freely welcome, so that work within it could become an important adjunct to a variety of field investigations across Canada.
2. Structural geology should be recognized as a separate and special form of field investigation, so that structural specialists can conduct regional field studies leading to the establishment of fundamental geometrical facts. Many regional geologic investigations presently start from an unfounded assumption that these facts are already in existence. This activity need not impede the necessary growth of interdisciplinary investigations of regional tectonic phenomena benefiting from the interdependence of structural geology and other aspects of the earth sciences.
3. Viable groups of scientists concerned with structural geology should be developed in a few geological departments and institutes, to supplement the thin but necessary line of isolated specialists now strung out across the continent. At the same time, a much more effective link with industry should be forged.
4. Means should be developed to attract scientists with a background in mathematics and physics and an interest in geology (or vice versa) to work on structural problems, specifically using the new approaches afforded by computer applications to mathematical modelling and statistical synthesis.

TECTONICS AND GEOTECTONICS

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DEFINITION

Tectonics is the study of the nature and causes of deformation of the earth's crust. It pertains to structural elements, embracing the largest and broadest features and, as the scale of structures decreases, merges with the field of structural geology. Tectonic concepts permeate many different fields of geology, serving to unify them. Tectonics has two closely related aspects - geotectonics which deals mainly with the geological attributes of the earth's crust, and tectonophysics, which deals mainly with the physical properties of the crust. Although tectonics and geotectonics are considered by some to be synonyms, tectonics has many far-reaching connotations and is used herein as being the broader term. Tectonophysics is covered in a separate report.

Geotectonics draws on data principally from the geological fields - structural geology, stratigraphy, metamorphism, volcanism, geochronology, geochemistry, sedimentology, petrology and geomorphology. Accordingly, many geotectonic analyses are concerned largely with the continental masses. Because all contributing fields are involved with temporal ordering of their data, a large part of geotectonics is likewise concerned with the tectonic evolution of various segments of the earth's crust.

Tectonophysics draws on data mainly from the geophysical fields-seismology, geomagnetism and paleomagnetism, gravity, and heat flow. Most of the data are essentially measurements of the physical characteristics of the earth, being particularly valuable where geological data are meagre, such as in oceanic regions and is the subsurface parts of the continental crust.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Many aspects of tectonics have a parctical and economic value; three examples are:

(1) Study of the relationship between metallogeny and tectonics, wherein the genesis of mineral deposits is integrated with the tectonic evolution of the region and metallogenic intervals (orogenic, volcanic and depositional) are established.
(2) Studies of the effects of earthquakes, their relationship to bedrock characteristics, structural features and surficial deposits, and prediction of the probability of future occurrences.
(3) Analyses of the structure of sedimentary basins and continental shelves, together with interpretation of seismic, magnetic and gravity data, in order to ascertain their petroleum potential.

Most serious students of tectonics have been motivated by the search for new knowledge being concerned with the ordering of data on a large scale, the internal constitution of the earth, and the underlying causes of diastrophic processes. Tectonic concepts also find application in the newly developing fields of marine geology and lunar research.

PRACTICAL APPLICATIONS

Tectonics contributes to the renewal of petroleum reserves in guiding exploration of the new sedimentary basins of northern Canada and the continental shelves, and also, in the densely drilled sedimentary basins, through relating tectonic behaviour of the basement to the distribution of porosity in the reservoirs.

In the field of metallogeny the contributions of tectonics should continue to grow, for in belts of orogenically deformed rocks the metals and minerals have a geological environment or habitat that embraces many or all elements of the tectonic environment of the rocks. Tectonicists have to expand our knowledge of the tectonic framework to make it a still more effective tool for the metallogenist and economic geologist in the delineation of the most favourable areas and associations for mineral exploration.

HISTORICAL DEVELOPMENT AND PRESENT LEVEL OF ACTIVITY

Tectonics in Canada has only in the last decade emerged from its former state of being largely speculative, "arm-chair" geology to its current position of being a vital, dynamic and essential part of the earth sciences. Much of this improvement in stature may be attributed to the great increase in geological knowledge, not only in Canada but in the whole world. The tectonicist has many more facts on the geology of the continental masses at his disposal and is beginning to acquire hard data on the geology of the ocean basins, the hitherto largely unknown sector of the earth's crust.

On an international scale much current research in tectonics is centered in projects of the International Upper Mantle Project (1) and those of the commission for the Geological Map of the World (2) to which Canadian geologists and geophysicists have made significant contributions. The Royal Society of Canada symposium on the Tectonics of the Canadian Shield in 1962 (3), the Canadian Institute of Mining and Metallurgy symposium on the Tectonic History and Mineral Deposits of the Western Cordillera in 1966 (4), and the recent symposium on Recent Crustal Movements have spurred additional national and regional activity. Continuing collaborative projects, such as the Cordilleran Structure Project of the National Advisory Committee on Research in the Geological Sciences (5) between geologists in several different fields, and "Project Pioneer" have been of significant volume in the Canadian Shield in Manitoba. The recently published Tectonic Map of Canada by C.H. Stockwell (6) categorizes rocks according to their depositional and orogenic tectonic environments and the fifth edition of the Geology and Economic Minerals of Canada (7) includes regional tectonic syntheses of structural, stratigraphic and sedimentological data, and to a lesser extent also of metamorphic, magnetic and metallogenic data.

NEED FOR INCREASED ACTIVITY

Canada is one of the few countries of the world that is large enough to encompass many different geological provinces. It also has a multiplicity of orogenic belts ranging in age from Archean to late Tertiary. Canadian geologists, accordingly, have almost unlimited opportunities to contribute to tectonic knowledge. This can be done not only by initiating new projects but by synthesizing existing data.

Tectonic considerations should form a part of the initial objectives of any geological investigation. This should lead to many conclusions being drawn on the tectonic implications of the investigation by the investigator himself rather than having the conclusions await a subsequent analysis by someone else. More collaborative studies should be undertaken, particularly interdisciplinary studies, as these have the innate advantage of including the broader tectonic problems as part of the frame of referrence regardless of the more specific objectives of the individual disciplines and subdisciplines.

There needs to be more interpretation of the tectonic significance of the geological and geophysical data that are presently available. This should be done not only for each of the various geological regions of Canada but also systematically in some detail by smaller units. Tectonic analyses should also be made by individual subject, such as volcanism, plutonism, metamorphism, structural types, sedimentation etc., particularly as related to changes with time.

TRAINING

It is desirable to introduce tectonics into the curriculum at an early stage concentrating on the basic and fundamental aspects of the various theories and leaving more sophisticated explanations and documentation to more advanced educational levels after the student has assimilated the principles of the various contributing fields. The important thing is that the facts be clearly established and differentiated from the theory that is presented to explain them, and that several theories be presented. The student should be encouraged to think, to doubt, and to constantly question.

Training of geologists should be kept as broad as possible or else, in the future, there may be no tectonicists. However, in these days the trend towards specialization is increasing. It is probable that only through tectonics will a specialist be kept informed of the contributions by other specialists to knowledge of the earth.

MAJOR OBJECTIVES AND FUTURE DEMANDS

1. Establish in greater detail the tectonic evolution of Canada by major geological province and by regional units; relate mineral deposits to the tectonic environment; integrate our knowledge of tectonics and metallogeny with that of contiguous regions.
2. Determine the thickness of the constituent layers of the crust throughout Canada to provide limits for the analysis of the tectonic elements evident in the near-surface rocks; ascertain the configuration of crustal layers of the Canadian Shield and their relationship to Precambrian geosynclines and orogens; determine the extent and configuration of the crustal layers of the craton beneath the bordering Phanerozoic orogenic belts.
3. Establish criteria with which to subdivide and correlate Precambrian rocks, particularly the Archean, in order to determine the early tectonic history of the crust with greater precision and to provide a tectonic framework which would assist future geochronological investigations, particularly those directed towards determining the age of the oldest crust.

CONCLUSION

Establish a committee on tectonics to stimulate research on tectonics in Canada.

REFERENCES

1. Canadian Upper Mantle Report, 1967; Geol. Surv. Can., Paper 67-41.

2. Commission for the Geological Map of the World; Reports of the Secretary General, Prague, 1968; Paris, 1966 and previous.

3. The tectonics of the Canadian Shield, J.S. Stevenson, editor; Royal Soc. Can., 1962.

4. Tectonic history and mineral deposits of the western Cordillera; Can. Inst. Mining Met., Spec. vol. No. 8, 1966.

5. Current research in the geological sciences in Canada 1967-68; National Advisory Committee on Research in the Geological Sciences, Geol. Surv. Can., Paper 68-54 (and other previous reports).

6. Tectonic Map of Canada, Map 1251A; Geol. Surv. Can., 1969.

7. Geology and economic minerals of Canada, 5th edition, R.J.W. Douglas, editor; Geol. Surv. Can., Econ. Geol. Rept. No. 1 (in press).

TECTONOPHYSICS

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DEFINITION

In 1849 when Naumann wanted a word for the science of the structure of the earth's crust and the movements and forces which have produced it, he borrowed the term tectonics from architecture. (Both words have a common root.) To emphasize the new significance, he coined the word geotectonics and the two have been used indiscriminately ever since. On the whole tectonics is more embracing and is more often used, while the tendency has been to confine geotectonics to discussion of the largest features. Thus, common usage grades the terms structural geology, tectonics and geotectonics to apply to a rising scale of size. These terms are old and originally had purely geological connotations (1, 2, 3, 4, 5). When geophysicists had developed methods capable of making useful contributions to tectonics, N. L. Bowen coined the word tectonophysics to emphasize the importance of including geophysical results and of considering physical principles in studying the earth's structure and the forces which have produced it. This word is still included in only a few dictionaries (6) and its chief use has been as the name for one section of the American Geophysical Union and as title for a journal. Although emphasizing geophysics, it is not limited purely to physical aspects, because these cannot be properly discussed without some knowledge of geology. Tectonophysics might therefore be considered to be a wider term than tectonics, but in practice this is hardly true. Tectonics probably remains the broader term, and tectonophysics is used when it is desired to emphasize geophysical aspects.

Different authorities define and use these words in various ways but in this paper emphasis will be placed on the geophysical aspects and extensive geological discussion of tectonics will not be undertaken.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

A knowledge of the structure and motions of the earth's crustal features is fundamental to geology and geophysics.

For over a century scientists in pursuit of a broad understanding of the earth have identified minerals, rocks and fossils and mapped the distribution of rock types, but a satisfactory synthesis of the earth's behaviour and history was not achieved. The situation improved when geophysical observations provided better information about the invisible interior of structures, but geophysics did not produce the full solutions which some exponents had expected. Something else was needed.

All early ideas involved the concept that the earth is a relatively immobile body with vertical motions dominant over horizontal. Today this concept is being effectively challenged and many scientists now support the idea of large and relatively rapid continental displacements. They hope that interpretation of the voluminous data collected by geologists and geophysicists in terms of continental drift will provide a better understanding of the structure and behaviour of the earth.

Recent meetings of the major American scientific societies reveal an intense preoccupation with tectonics and especially with tectonophysics and a great trend in favour of the new ideas concerning continental drift. With some exceptions such as the Upper Mantle Symposia in Ottawa in 1965 evidence of concern about the subject has been less marked in Canada.

If the concept of continental drift is accepted it will shake the whole of earth science and will mark a turning point in our ideas about the earth. Heretofore progress in the study of the earth has only been possible in specialized or local studies, while university courses emphasize the descriptions of rocks, minerals and fossils or the collection of geophysical data and its interpretation according to simplified models. A multitude of good accounts of small areas exist, but no one has seemed able to put them together. Brief summaries of the earth's history and behaviour are lacking. The author (7), following the ideas of Kuhn (8) claims that the acceptance of continental drift is desirable and will amount to a major scientific revolution, but Beloussov (9) advances arguments against these views.

PRACTICAL APPLICATIONS

The replacement of ideas about a relatively stable earth with fixed continents by ideas about a highly mobile one with moving continents will profoundly affect many ideas about the origin, sources and distribution of orebodies and petroleum deposits.

In petroleum geology the writer has first-hand knowledge of the keen interest of major oil companies in continental drift, especially as it relates to the discovery of off-shore oil occurrences. One company has already taken up huge leases off the east coast of Canada because of conversion of their geologists to belief in continental drift. Oil in the Arctic is now being found in older rocks which are thought to have been formed under tropical conditions in lower latitudes.

In mining a major company has circulated a brochure relating how they were led to important phosphate deposits by arguments based on drift. The similarities in geology and in gold, diamond and manganese deposits across the South Atlantic Ocean are well known.

A greater value lies in developing a proper framework and mechism to aid in ore prediction and herein the new ideas have untold value for the future.

HISTORY AND CURRENT CANADIAN SITUATION

(a) General History

In the early decades of the Industrial Revolution, between 1760 and 1830, when geology was emerging as a science, the earth was realized to be a complex body because its strata were observed to be frequently contorted and faulted. Popular belief attributed such formations to abrupt cataclysms, but gradually the contributions of such men as Guettard, Werner, Cuvier, Hutton, Smith and Lyell established the view that the earth's crust has been slowly shaped by the same forces that act today.

Since no source of internal energy for the earth was then known, it was thought to be cooling. The contraction theory was adopted and was long dominant. According to it cooling produced compression and mountain building. The primary movements were considered to be vertical in direction. The discovery of radioactivity in 1896 weakened the case for cooling and contraction. Joly (1909) pointed out that the earth might be heating and might periodically become unstable. This led to a multiplicity of other theories, many of which still clung to the dominance of vertical motion and the fixed position of continents, but substituted other causes for mountain building. Many Soviet scientists considered that heating produced vertical uplift and oceanization of continental crust (2). Others considered that the earth might be expanding (10, 11, 12). Dutch scientists advocated periodic instability (13). Many supported different forms of convection currents (14, 15, 16). Most attempted to explain the cause of tectonic events without seriously disturbing the standard and accepted belief of geologists and geophysicists in the permanence of ocean basins and in the fixed position of continents. Scheidegger (17) and Beloussov (2) have reviewed these and other theories well.

A parallel, but long a minor development, was the notion that great horizontal displacements, called continental drifting, had been dominant during the earth's history. According to Harland (18), Fisher "postulated a relatively fluid interior with convection currents rising beneath the oceans - especially the mid-Atlantic ridge" in 1880, and Pickering's work in 1907 on the origin of the moon stimulated Taylor and Baker to revive older ideas about continental drift.

The chief proponent of continental drift however was Alfred Wegener (19) who, by his detailed arguments and books published from 1912 to 1930, did more than anyone else to establish the idea of large horizontal displacements of the earth's surface. In spite of the fact that he was a physicist, his geological and biological arguments were generally sound and were not disproved; rather it was his geodetic measurements and physical causes that were proved wrong. Another physicist, Jeffreys (20), was a very strong opponent and the fact that Wegener had made mistakes and produced untenable physical arguments prevented the wide acceptance of his ideas until other physicists had showed how to avoid his errors.

Geologists, especially in the southern continents (21) had noted close similarities between continents and some supported drift. They included such distinguished Alpine geologists as Argand (22) and Staub (23) who by careful mapping had established the true complexity of mountains and who recognized a need for great shortening. Unfortunately the contortions of the rocks were such that they could not be fully seen on the surface and every tunnel through the Alps led to different if improved interpretations. This opened the way for critics like Bucher (24) to doubt the need for shortening and ridicule continental drift. Supported by the physicists, most geologists in North America (25) and in Eurasia rejected drift. A fundamental problem was that no one knew much about any part of the earth, except those small portions exposed as the land surface.

Fortunately physicists gradually developed instruments and techniques which provided an understanding of the nature of the ocean floors, a better if still imperfect view of the interior of the earth, and a numerical time scale for earth processes. Then chemists began to offer reasonable explanations of these observations. Most development has occurred since 1945 and since 1966 new discoveries have revolutionized ideas about tectonics.

Unfortunately some division still remains. Many of those who developed the instruments and ideas of this new revolution are not geologists and do not understand the complexity of the earth. Geologists have contributed much to the new ideas on sea-floor spreading, but many of their papers have been published in specialized reviews (26, 27) or geophysical journals. Textbooks on historical or physical geology have not incorporated these new ideas although many are now attempting to do so.

A brief review will show how new these ideas are. Until 1956 arguments in favour of drift were inconclusive, but in that year several papers on paleomagnetism gave results which suggested relative movements between continents. Further work has supported and refined that view. In the same year Ewing and Heezen proposed the existence of a continuous world-encircling mid-ocean ridge system. This also has been abundantly confirmed. In 1960 Hess proposed that the sea-floor was being generated along the mid-ocean ridges and was spreading away from them to be reabsorbed again in ocean trenches and under young mountains. In 1963 Vine and Matthews proposed that reversals in the earth's magnetic field were imprinting the sea-floor and could provide a time scale. Fortunately McDougall, Cox, Doell and Dalrymple had been able to date reversals. This theory has now been applied successfully to much of the ocean basins (28). Supporting evidence has been provided by discovery of the increasing age of oceanic islands and cores away from ridges, by the discovery and explanation of great faults and fracture zones (29, 30, 31), and of increasing thickness of sediments away from ridges (32).

Morgan (33) and Le Pichon (34) elaborated the concept into a theory of rigid plate tectonics. They held that motion is largely confined to the joins between a few large plates which are marked by earthquakes. These ideas, derived from the study of magnetics and seismicity, have now been fully supported by independent studies of the direction of motion of earthquakes (35). The key discovery has been that magnetic imprinting provides a precise record of the movement apart of rigid plates, sufficient to enable the rate and direction of closure of mountain systems to be calculated. This is a tremendous addition to tectonics.

A few opponents still object vigorously for one of two reasons. Some, like Jeffreys (20) and Beloussov (9), quite ignore the new discoveries and restate old objections which many consider to be avoidable by suitable modification of the theory. Others emphasize small exceptions which do not appear to fit the theory. Meyerhoff (36), for example, indicates one Miocene sample from the mid-ocean ridge is contrary to expectations, but ignores over 1,000 other dated samples which fit the theory. Hess attributed this odd sample to a human error. Others who have raised objections on particular grounds include Stehli (37), Axelrod (38), MacDonald (39), and Worzel (40), but many believe that their evidence is inadequate or can be answered by modifications of the theory.

Two excellent Soviet books on the subject of tectonophysics are available in translation (41, 42).

(b) Canadian Situation

Most Canadians were not early or enthusiastic supporters of continental drift, nevertheless many have made significant contributions to the new ideas.

The Geological Survey of Canada has carried out the most extensive precise aeromagnetic survey yet published. This throws much new light on structure of the Canadian Shield (43, 44, 45). In addition, Morley, who has had charge of the work, discovered the explanation of oceanic magnetic anomalies as early as Vine and Matthews (47) but could not get his paper accepted until later (48). The Dominion Observatory and Geological Survey have also been active in carrying out magnetic surveys over the North Atlantic and Iceland (49, 50) which provide support in evidence for continental drift. Bedford Oceanographic Institute has carried out the most detailed survey yet made of a section of the Mid-Atlantic Ridge using several geological and geophysical methods (51). Wilson (52) has contributed ideas about the closing and opening of the Atlantic Ocean. He coined the term transform faults which has been widely accepted as an explanation for oceanic fracture zones. He has made other suggestions about the geology of ocean basins and large faults (7).

The Dominion Observatory has established a network of modern seismological stations and a large array at Yellowknife. These have contributed to the world-wide knowledge of seismic activity. One useful aspect of this has been the preparation of maps defining zones of earthquake hazard (53). Mansinha and Smylie (54), have published an important theoretical paper relating major earthquakes to movement of the poles.

McConnell (55) has used post-glacial uplift to draw conclusions about the mobility of the upper mantle, and has compiled reports on thicknesses of the crust determined by seismic methods (56). H. D. B. Wilson and colleagues have investigated the structural provinces of the Canadian Shield using a wide variety of geological and geophysical techniques in conjunction but most of their work has not yet been published (57).

Thicknesses of the continent were early investigated by Hodgson and much work has continued all across Canada. A large group has co-operated with American geophyscists in the Lake Superior region (58). Another major investigation involved the geology and geophysics of the Hudson Bay region (59). The tectonophysics of the prairies have been a subject of special interest to petroleum companies and to the universities in Alberta and Saskatchewan (60, 61). The Defence Research Board has used large explosions to investigate structure.

A gravity map of Canada has been published (62) and gravity and seismic data have been extensively used to interpret the structure and tectonics of the Appalachian and coastal regions of Eastern Canada (63, 64, 65, 66, 67, 68). These have been helped by measurements of isotopic ages and paleomagnetism (69, 70).

In the Canadian Shield the combination of geophysical and geological data has helped elucidate the structure (57, 71, 72, 73, 74). Other interdisciplinary studies have been made in the Prairies and the Cordillera (60, 75, 76, 77, 78, 79).

In international affairs besides collaborating with the United States, Canadians have played a leading part in the Upper Mantle Project of which C. H. Smith is the Deputy Secretary General and has been responsible for the organization of symposia on the application of geology and geophysics together to elucidate tectonic problems (80, 81). G. D. Garland is Secretary-General of the International Union of Geodesy and Geophysics and organized a symposium in Canada on Continental Drift (82). T. H. Clark organized a symposium on appalachian tectonics (83) and his book on the geological evolution of North America (84) is an important contribution to tectonics, although too early for the latest geophysical ideas. Keen had dealt with tectonophysics of ocean floors in his book on marine geology (85). The author organized a symposium at Montevideo on continental drift in the South Atlantic region.

Many Canadians have been active in other contributing fields including heat flow, age determinations and paleomagnetism. Scheidegger's important review of geodynamics (17) was written while he was in Canada. Jacobs, Russell and Wilson (86) tried to bring geological and geophysical ideas together to deal with the structure and history of the earth, but too early to include the modern change of view. Tozer (87, 88), now at Toronto, has been one of a few who have contributed much to the theory of mechanisms of drift. P. M. Clifford (89) has developed one aspect of this subject. An important symposium largely dealing with tectonophysics was organized in Ottawa by Baer and Norris (90).

PRESENT LEVEL OF ACTIVITY

The previous section has mentioned enough examples of Canadian work to indicate the general level of activity.

One of the fields of special activity in tectonophysics today is the whole subject of ocean-floor spread and investigation of the ocean floors (26). Coupled with this are investigations of reversals in the earth's magnetic field and steady progress in paleomagnetism. The success of these investigations has been coupled with great progress in seismology (35, 91). Previously the distribution and direction of motion of earthquakes was not understood. Today, according to Oliver and other seismologists, it can all be accounted for by global plate tectonics (34). There is some hope that earthquakes may be predictable.

The thickness of the crust of the earth is being regularly measured (56). The depths to other boundaries between shells of the mantle is being measured and related to high-pressure geochemistry of silicates (92). Gravity surveys are being steadily pursued and coupled with seismic data to give better interpretations of the behaviour of continental margins, mountains and other structures (93).

Age determinations are better understood and are more accurate than formerly. By combining several age methods various phases of accumulation and metamorphism can now be distinguished. This is giving better understanding of shields.

WHERE IS INCREASED ACTIVITY NEEDED MOST?

The discovery of sea-floor spreading and its acceptance by the vast majority of those engaged in marine geology is a great event in geological history. Many who claim to accept the new ideas do so only partially. Here is where the greatest changes are needed, in integrating new discoveries with older knowledge.

Scientists like all humans enjoy the familiar and prefer progress by gradual steps to drastic change. They would prefer to make a nice, neat discovery in their favourite field - usually that of their Ph. D. degree - rather than to change fields to a new one where there is greater scope. Seismologists like to continue to study earthquakes, paleontologists to continue to examine fossils. It is right that this should be so, but it produces a tendency to support established fields and it is often hard to get support for thoroughly new ideas. In Canada this has been aided by the policy of the granting agencies (which are excellent in most respects) to allow scientists complete freedom of choice in their fields of research. While this has admirable aspects, it has meant that it has been difficult to build up the geophysical side of earth science and still harder to get students well trained in both geology and geophysics. Too large a proportion of earth scientists work in some old subjects, too few in the new and still fewer in multiple fields.

In all but a few new universities in Canada there are well-established departments of geology. It can be taken that all do an excellent job in the traditional fields. However, few of these departments have build up geophysics as fast as the importance of its discoveries warrants. What is worse is that geophysics has often started up independently. In such cases geophysicists are likely to lack the help and understanding which geology could provide.

While it is easy to fully occupy a student's time with a complete course in geology without much geophysics and equally true the other way about, this does students a great injustice. Progress is most rapid at the common interface of subjects. To correct this some favourite courses will have to be dropped, or reserved for graduate work in order to give students a broader introduction to earth science. The greatest need in tectonophysics is joint approach. Progress is being made, but should be hastened.

Another aspect is that industry tends to attract those interested in prospecting and the universities tend to be impoverished in those with the most practical interests. This too needs to be counteracted.

In the past geology was called a descriptive science and so it was. When this ceased to be regarded as respectable, departments added more mathematics, physics and chemistry to the curriculum, and geophysics also developed independently. While these developments are to be welcomed, their full impact is not universally appreciated. Geophysics and geology still need to be better integrated. Description is no longer enough; explanations are becoming possible if geology and geophysics are used together.

The great need is to get away from the old descriptive habits and realize that synthesis of such description has become possible. New minerals, new fossils, new map-areas, new geophysical surveys are but parts of the means to an end and that end is to give a reasoned account of the earth's history and behaviour.

COMMENTS ON TRAINING

If one considers the curriculum of universities over the span of their history one sees constant and great change. Students once chiefly learned the classics, philosophy and divinity. Today most students have dropped these subjects and new ones have taken their place. It is the same within individual disciplines. Fifty years ago the undergraduate curriculum in physics still largely consisted of classical physics. Today the place of much of this has been taken by computer science, electronics and modern physics.

The changes have taken place not because the former subjects were in error, but because the new subjects are more powerful and more generally useful. The dropped subjects have been left for a few specialists or for graduate work.

The same change is needed in earth science.

The curriculum varies from university to university, but the recent changes have been so rapid that it is safe to say that some departments have probably not kept pace. Many are only now realizing that geophysics is equally important and requires as large a staff as geology, and they are still a long way from accepting the implications of drift as well. It takes a long time to produce textbooks and the rate of change is such that the newest textbooks on historical and structural geology and on physics of the earth seem strangely old fashioned, even as soon as they are published.

Geology and geophysics have suffered from a lack of students. In part this is due to lack of desire of city dwellers to go to the field, but it is believed that the image of geology could be improved by placing early emphasis on the excitement of these new discoveries in continental drift and in investigation of other planets and thus lead students to see that it is helpful to learn some paleontology, mineralogy, or geophysics. Too often students are expected to proceed in what may seem a logical order, but one which fails to capture their enthusiasm early.

MOST IMPORTANT OBJECTIVES AND FUTURE TRENDS

The great power of science has been its capacity to predict. This was true hundreds of years ago when early astronomers discovered how to foretell eclipses. Through genetics, prediction has proved invaluable in agriculture. The great reputation of physicists has come from the ability of modern technology to implement the results of their research.

In view of this it might seem astonishing that geologists should place such great emphasis on "facts" and so little on theory, often called "armchair geology". While no one can deny the value of good observation, surely the experience of the more basic sciences is that eventually a time comes when prediction becomes possible. Certainly it is what every economic consulting geologist must aim for.

The lack of confidence of geologists in prediction is not arbitrary, but has been based on their experience that prediction was usually wrong. The earth is so complex that this is still true of details. The hope now is that the present drastic change in thought will make sound predictions possible about major aspects of the earth, if not about the details.

Another objective often achieved in the basic sciences has been generalization. The voluminous and meticulous observations of Tycho Brahe provided the basis and were all embraced in the few simple laws which Kepler and Newton derived from those data. Today there is much effort being put into computer programming of geological observations. This is necessary and good, but it would be even better to generalize and synthesize the data into simple explanations.

Vine and Matthews showed how to reduce a mass of magnetic observations on the ocean floor into a simple story. The same is now happening in global tectonics and seismology. It should be the aim of all earth science.

Up to now geologists have been able only to make observations. They have had to teach others by describing methods and data. Today the state of having sound theories, of making better generalizations and of achieving some synthesis, as is done in other sciences, opens as a possibility. This can use the basic sciences which are already being introduced into college programs. The basic aim of tectonophysics should be in the direction of seeking to synthesize information into a general theory of the behaviour and movements of the earth's crust.

REFERENCES

1. Oxford English Dictionary, Oxford, vols. F-G and T, 1931.

2. V.V. Beloussov: Basic problems in geotectonics; McGraw-Hill, New York, 1962.

3. P.B. King: The tectonics of middle North America; Princeton Univ. Press, 1951.

4. J.G. Dennis, ed.: International Tectonic Dictionary; Am. Assoc. Petrol. Geol., Mem. 7, 1967.

5. American Geological Institute: Dictionary of geological terms; Doubleday, New York, 1957.

6. Encyclopedia Britannica, Chicago, vol. 21, 1967.

7. J.T. Wilson: Static or mobile earth: The current scientific revolution; Proc. Am. Phil. Soc., vol. 112, pp. 309-320, 1968.

8. T.S. Kuhn: The structure of scientific revolutions; Univ. of Chicago Press, 1962.

9. V.V. Beloussov: Debate about the earth: An open letter to J. Tuzo Wilson; Geotimes, vol. 13, pp. 17-19, 1968.

10. S.W. Carey: A tectonic approach to continental drift; in Continental drift, a symposium, S.W. Carey, editor, Univ. of Tasmania, Hobart, pp. 177-355, 1958.

11. B.C. Heezen: The rift in the ocean floor; Sci. Am., vol. 203, pp. 98-110, 1960.

12. L. Egyed: A new dynamic conception of the internal constitution of the earth; Geol. Rundschau, vol. 46, pp. 101-121, 1957.

13. F.A. Vening Meinesz: Relative movements of continents; Koninkl. Ned. Akad. Wetenschap, Ser. B, vol. 66, pp. 3-7, 1963.

15. A. Holmes: Radioactivity and earth movements; Trans. Geol. Soc., Glasgow, vol. 18, pp. 559-606, 1931.

16. F.A. Vening Meinesz: The earth's crust and mantle; Elsevier, Amsterdam, 1964.

17. A.E. Scheidegger: Principles of geodynamics; Springer-Verlag, Berlin, 1958.

18. W.B. Harland: Essay review, The origin of continents and oceans; The Geol. Mag., vol. 106, pp. 100-104, 1969.

19. A. Wegener: The origin of continents and oceans; Dover Publications, New York, 1966.

20. H. Jeffreys: The Earth; Cambridge Univ. Press, 1959.

21. A.L. du Toit: Our wandering continents; Oliver & Boyd, Edinburgh, 1937.

22. E. Argand: La tectonique de l'Asia; Congr. Geol. Intern, XIII, vol. 1, pp. 171-372, 1924.

23. R. Staub: Der Bewegungs-mechanismar der Erde; Berlin, 270 pp., 1928.

24. W.H. Bucher: The deformation of the earth's crust; Princeton Univ. Press, 1933.

25. American Association of Petroleum Geologists: Theory of continental drift, a symposium; Am. Assoc. Petrol. Geol., Tulsa, Okla, U.S.A., 1928.

26. R.A. Phinney, ed.: The history of the Earth's crust; Princeton Univ. Press, 1968.

27. G. Piel: Gondwanaland revisited: New evidence for continental drift; Proc. Am. Phil. Soc., vol. 112, No. 5, 1968.

28. J.R. Heirtzler et al.: Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents; J. Geophys. Res., vol. 73, pp. 2119-2136, 1968.

29. H.W. Menard: Marine geology of the Pacific; McGraw-Hill, New York, 1964.

30. L.R. Sykes: Mechanism of earthquakes and nature of faulting on the mid-ocean ridges; J. Geophys. Res., vol. 72, pp. 2131-2151, 1967.

31. W.R. Dickinson and A. Grantz, eds.: Proceedings of conference on geologic problems of San Andreas fault system; Stanford Univ. Publ., vol. 11, 1968.

32. J. Ewing and M. Ewing: Sediment distribution on the mid-ocean ridge; Science, vol. 156, pp. 1590-1592, 1967.

33. W.J. Morgan: Rises, trenches, great faults, and crustal blocks; J. Geophys. Res., vol. 73, pp. 1959-1975, 1968.

34. X. Le Pichon: Sea-floor spreading and continental drift; J. Geophys. Res., vol. 73, pp. 3661-3685, 1968.

35. B. Isacks, J. Oliver and L.R. Sykes: Seismology and the new global tectonics; J. Geophys. Res., vol. 73, pp. 5855-5900, 1968.

36. A.A. Meyerhoff: Abstract, 1969 Ann. Meeting; Am. Assoc. Petrol. Geol., 1969.

37. F.G. Stehli: A paleoclimatic test of the hypothesis of an axial dipolar magnetic field; in The history of the Earth's crust, R.A. Phinney, editor, Princeton Univ. Press, 1968.

38. D.I. Axelrod: Fossil floras suggest stable, not drifting continents; J. Geophys. Res., vol. 69, pp. 1665-1669, 1967.

39. G.J.F. MacDonald: The deep structure of continents; Rev. Geophys., vol. 1, pp. 587-665, 1963.

40. J.L. Worzel: Discussion in P.M.S. Blackett et al.; Phil. Trans. Roy. Soc. London, Ser. A, vol. 258, pp. 137-139, 1965.

41. I.E. Gubin: Lecture notes on basic problems in seismotectonics; Intern. Inst. of Seismol. & Earthquake Eng., Tokyo, 1967.

42. V.A. Magnitsky: The internal structure and physics of the earth; N.A.S.A., Tech. Transl. F-395, 1967.

43. L.W. Morley: Magnetic anomaly map of Canada; Geol. Surv. Can., Map 1255A, 1968.

44. L.J. Kornik: An aeromagnetic study of the Moak Lake-Setting Lake structure in northern Manitoba; Can. J. Earth Sci., vol. 6, pp. 373-382, 1969.

45. P.H. McGrath and D.H. Hall: Crustal structure of northwestern Ontario: Regional magnetic anomalies; Can. J. Earth Sci., vol. 6, pp. 101-108, 1969.

46. F.J. Vine and D.H. Matthews: Magnetic anomalies over ocean ridges; Nature, vol. 199, pp. 947-949, 1963.

48. L.W. Morley and A. Larochelle: Paleomagnetism as a means of dating geological events; Roy. Soc. Can., Spec. Publ. No. 9, pp. 40-51, 1964.

49. P.H. Serson, W. Hannaford and G.V. Haines: Magnetic anomalies over Iceland; Science, vol. 162, pp. 355-357, 1968.

50. E.A. Godby, R.C. Baker, M.E. Bower and P.J. Hood: Aeromagnetic reconnaissance of the Labrador Sea; J. Geophys. Res., vol. 71, pp. 511-517, 1966.

51. F. Aumento: Magmatic evolution on the Mid-Atlantic ridge; Earth and Planet. Sci. Letters, vol. 2, pp. 225-230, 1967.

52. J.T. Wilson: Did the Atlantic close and then reopen?; Nature, vol. 211, pp. 676-681, 1966.

53. W.G. Milne and A.G. Davenport: A distribution of earthquake risks in Canada; Bull. Seismol. Soc. Am., vol. 59, pp. 729-754, 1969.

54. L. Mansinha and D.E. Smylie: Earthquakes and the earth's wobble; Science, vol. 161, pp. 1127-1129, 1968.

55. R.K. McConnell: Isotatic adjustment in a layered earth; J. Geophys. Res., vol. 70, pp. 5171-5188, 1965.

56. R.K. McConnell Jr., R.N. Gupta and J.T. Wilson: Compilation of deep crustal seismic refraction profiles; Rev. Geophys., vol. 4, pp. 41-55, 1966.

57. D.H. Hall and Z. Hajnal: Crustal structure of northwestern Ontario: Refraction seismology; Can. J. Earth Sci., vol. 5, pp. 81-100, 1969.

58. M. Berry and G.F. West: An interpretation of the first arrival data of the Lake Superior experiment by the time-term method; Bull. Seismol. Soc. Am., vol. 56, pp. 141-171, 1966.

59. C.S. Beals, ed.: Hudson Bay, Centennial volume; Dept. Energy, Mines & Resources, Ottawa, 2 vols., 1969.

60. E.R. Kanasewich: Deep crustal structure under the plains and Rocky Mountains; Can. J. Earth Sci., vol. 4, pp. 937-946, 1966.

61. E.R. Kanasewich: Seismicity and other properties of geological provinces; Nature, 208, pp. 1275-1278, 1966b.

62. M.J.S. Innes: Gravity map of Canada; Dom. Obs., Ottawa, 1968.

63. D.L. Barrett, M. Berry, J.E. Blanchard, M.J. Keen and R.E. McAllister: Seismic studies on the eastern seaboard of Canada: The Atlantic coast of Nova Scotia; Can. J. Earth Sci., vol. 1, pp. 10-22, 1964.

64. C. Keen and B.D. Loncarevic: Crustal structure on the eastern seaboard of Canada: Studies on the continental margin; Can. J. Earth Sci., vol. 3, pp. 65-76, 1966.

65. R.E. Sheridan and C.L. Drake: Seaward extension of the Canadian Appalachians; *Can. J. Earth Sci.*, vol. 5, pp. 337-374, 1968.

66. D.K.B. Fenwick, M.J. Keen, C. Keen and A. Lambert: Geophysical studies of the continental margin northeast of Newfoundland; *Can. J. Earth Sci.*, vol. 5, pp. 483-500, 1968.

67. A.C. Grant: Seismic-profiles investigation of the continental margin northeast of Newfoundland; *Can. J. Earth Sci.*, vol. 5, pp. 1187-1198, 1968.

68. A.K. Goodacre, B.G. Brule and R.V. Cooper: Results of regional underwater gravity surveys in the Gulf of St. Lawrence, Canada; *Dom. Obs.*, Gravity Map No. 86, 1969.

69. C.T. Harper: Isotopic ages from the Appalachians and their tectonic significance; *Can. J. Earth Sci.*, vol. 5, pp. 49-60, 1968.

71. R.A. Gibb: A geological interpretation of the Bouger anomalies adjacent to the Churchill-Superior boundary in northern Manitoba; *Can. J. Earth Sci.*, vol. 5, pp. 439-454, 1968.

72. F.S. Grant: Two gravity profiles in the Manicouagan-Wabush area of west-central Quebec; *Can. J. Earth Sci.*, vol. 5, pp. 895-906, 1968.

73. G.S. Murthy, W.F. Fahrig and D.L. Jones: The paleomagnetism of the Michikamau anorthositic intrusion, Labrador; *Can. J. Earth Sci.*, vol. 5, pp. 1139-1144, 1968.

74. H.C. Palmer: The paleomagnetism of the Croker Island complex, Ontario, Canada; *Can. J. Earth Sci.*, vol. 6, pp. 213-218, 1969.

75. A.E. Bally, R.L. Gordy and G.A. Stewart: Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains; Bull., *Can. Petrol. Geol.*, vol. 14, pp. 337-381, 1966.

76. H.S. Hasegawa: Surface waves observed close to large chemical explosions at Suffield, Alberta; *Can. J. Earth Sci.*, vol. 5, pp. 185-198, 1968.

77. B. Caner, W.M. Cannon and C.E. Livingston: Geomagnetic depth sounding and upper mantle structure in the Cordillera region of western North America; *J. Geophys. Res.*, vol. 72, pp. 6335-6351, 1967.

78. B. Caner and D.R. Auld: Magneto-telluric determination of upper mantle conductivity structure at Victoria, British Columbia; *Can. J. Earth Sci.*, vol. 5, pp. 1209-1220, 1968.

79. R.A. Stacey and L.E. Stephens: An interpretation of gravity measurements on the west coast of Canada; Can. J. Earth Sci., vol. 6, pp. 463-474, 1969.

80. T.N. Irvine, ed.: The world rift system, report of symposium, Ottawa; Geol. Surv. Can., Paper 66-14, 1966.

81. W.H. Poole, ed.: Continental margins and island arcs; Geol. Surv. Can., Paper 66-15, 1966.

82. G.D. Garland, ed.: Continental drift; Roy. Soc. Can., Spec. Publ. No. 9, Univ. Toronto Press, 1966.

83. T.H. Clark, ed.: Appalachian tectonics; Roy. Soc. Can., Spec. Publ. No. 10, Univ. Toronto Press, 1967.

84. T.H. Clark and C.W. Stearn: Geological evolution of North America, 2nd edition; Ronald Press, New York, 1968.

85. M.J. Keen: Marine geology; Pergamon Press, Oxford, 1968.

86. J.A. Jacobs, R.D. Russell and J.T. Wilson: Physics and geology; McGraw-Hill, New York, 1959.

87. D.C. Tozer: Heat transfer and convection currents; Phil. Trans. Roy. Soc. London, Ser. A, vol. 258, pp. 252-271, 1965.

88. D.C. Tozer: Towards a theory of thermal convection in the mantle; in Chap. 11, The Earth's mantle, T.F. Gaskell, editor, Academic Press, London, pp. 325-354, 1967.

89. P.M. Clifford: Flood basalts, dike swarms and sub-crustal flow; Can. J. Earth Sci., vol. 5, pp. 93-96, 1968.

90. A.J. Baer and D.K. Norris, eds.: Research in tectonics; Geol. Surv. Can., Paper 68-52, 1968.

91. M. Barazangi and J. Dorman: World seismicity maps compiled from ESSA, Coast and Geodetic survey, epicenter data, 1961-67; Bull. Seismol. Soc. Am., vol. 59, pp. 369-380, 1969.

92. A. Ringwood, ed.: Petrology of the upper mantle; Australian Natl. Univ., Canberra, Publ. No. 444, 1966.

93. J.L. Worzel: Deep structure of coastal margins and mid-ocean ridges; in Submarine geology and geophysics, W.F. Whittard and R. Bradshaw, editors, Colston Paper, No. 17, Butterworths, London, pp. 335-362, 1965.

ROCK MECHANICS

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DEFINITION

Rock mechanics is the study of the effects of forces on rock. Geologists, geophysicists, civil and mining engineers are all concerned with these effects. Research in rock mechanics is concerned with both basic mechanisms and applications to assist the construction and mining industries.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

The objective of rock mechanics is to obtain the predictability enjoyed by other applied mechanics subjects. Production costs, safety and conservation would benefit from such an advance. A fuller understanding of tectonics by the geologist and geophysicist could also follow.

With the present level of knowledge in rock mechanics, although some of the natural phenomena can be treated quantitatively, most aspects can only be appraised or described qualitatively. For example, the stability of slopes in soft, altered rocks can be analyzed by methods similar to those developed for soil mechanics; however, in the case of unaltered rocks the properties of the rock mass are generally significantly different, giving rise to the need for new and better techniques of testing the rock mass. Structural geology has a major contribution to make in this area.

In a sense, Canada has more rock problems and more requirements for rock research than most other countries. For example, as a crude index of activity, rock is being excavated currently at the rate of approximately 40 million tons a year by the construction industry and 400 million tons a year by the mineral industry. Also, the construction industry is driving about 10 miles of rock tunnels a year, and the mineral industry is driving about 175 miles of development drifts and crosscuts; these figures will rise to about 15 miles and 225 miles respectively by 1976 (1). Any advances that can be made to improve understanding of the factors influencing the breakage of rock and the maintenance of stability could produce great returns (e. g. approximately $100 million a year is spent on drilling and blasting rock, and savings up to as much as 30 per cent of these costs could result from successful research permitting better design of blasting patterns and selection of explosive types).

In addition, more concern will be required on the environmental effects of construction and mining in Canada. Like the European operators, planning to avoid or control subsidence, waste embankments and damaging shocks will be of increasing concern and can all be assisted by advances in rock mechanics. The more critical problems associated with public safety such as the stability of waste dumps (remember Aberfan), natural slopes (viz. the Vaiont disaster), and dam foundations (e. g. Malpasset failure) need no amplification.

It is widely recognized that the returns from research in this area will not be easily obtained, requiring a rare blending of the skills of the geologist, the physicist, and both civil and mining engineers. Nevertheless, Canada could be a world leader, in view of the size of the gross revenue from the industries concerned, with all the economic and social benefits that go with such a position (which few countries enjoy outside the United States).

HISTORICAL DEVELOPMENT

Although not called by the present name, rock mechanics as an analytical science developed from mine surveying in Europe some 50 years ago. The subject made advances as a result of the organization of periodic European symposia primarily concerned with coal mining, the first taking place in 1947 at Heerlen, in Holland. Parallel interest developed in South Africa because of severe rockburst problems encountered in mining at depths of 10,000 feet. Early work was also started in connection with dam projects. In addition, geologists have been trying for many years to establish, in effect through rock mechanics studies, analytical models to improve understanding of tectonic processes. In 1956 the first Rock Mechanics Symposium was held in the United States, followed by annual conferences sponsored by the small group of universities particularly interested in the subject (Colorado School of Mines, University of Minnesota, Missouri School of Mines, Penn State University, later Texas University and the University of California (Berkeley)), and more recently by the Inter-society Committee on Rock Mechanics (a consortium of 10 U. S. professional societies).

The first Canadian Rock Mechanics Symposium, stimulated by ground control problems in mines, was held in 1962 at McGill University, sponsored jointly by the federal Mines Branch and McGill, Queen's University and the University of Toronto. The fifth symposium, held in 1968, was expanded to include topics in construction and geology (2, 3, 4, 5).

PRESENT LEVEL OF ACTIVITY

At the present time, the largest Canadian research group concerned with rock mechanics is in the Mining Research Centre of the federal Mines Branch, with staff in Ottawa and Elliot Lake. Research is conducted on stability problems connected with surface slopes and underground openings, on the mechanics of breakage produced by various forms of energy (e. g. explosive impacts, thermal shock and mechanical impact), and on the integration of advances in structural geology into the analysis of the mechanical behaviour of rock masses.

Research work is also being conducted in many university departments of Mining, Civil Engineering, Geology, and Geophysics. Both master's and doctoral theses are being produced, primarily at McGill and Queen's but also at Alberta, British Columbia, College Royale Militaire, Ecole Polytechnique, Laval, New Brunswick, Saskatchewan, and Western Ontario.

Some mining companies have modest research laboratories. Those companies that have separate staff for this work are Cominco Limited, Falconbridge Nickel Mines Limited, International Minerals and Chemical Corporation, and the Iron Ore Company of Canada. Several other companies are engaged in field research projects in co-operation with the Mines Branch.

NEED FOR INCREASED ACTIVITY

The Canadian Advisory Committee on Rock Mechanics (CACRM) promotes communication within the subject. Liaison members have been exchanged with the EMR National Advisory Committee on Research in the Geological Sciences and the NRC Associate Committees on Geodesy and Geophysics, and on Geotechnical Research, the U. S. National Academy of Sciences Committee on Rock Mechanics, and the AIME Committee on Rock Mechanics. The Committee represents Canada on the executive council of the International Society for Rock Mechanics. A bibliography of Canadian contributions to rock mechanics is kept up to date (6, 7). A subcommittee of the CACRM was set up to formulate a tentative classification of rocks with respect to their mechanical properties so that the communication of such information between laboratories, engineers and practitioners could be made more efficient. This working group has just completed its task, and a tentative classification system has recently been published (8). More work is warranted on this important aspect of the subject, primarily on the categories dealing with the rock mass as opposed to the rock substance.

A new working group of the Committee has been set up to determine the research and development requirements to provide instruments to predict rock conditions (with respect to stability primarily, although ore grade information could also be of value) beyond the immediate excavation face, recognizing that with the advent of rapid excavation techniques the ensuring of safety and economy will make such information of great importance. Another newly formed subcommittee will review the outstanding needs for controlling the surface effects of mining so that the conservation of natural resources, as well as the avoidance of damage to surface installations, can be better achieved.

The subject of needs and priorities in rock mechanics is one of the major concerns of the Canadian Advisory Committee on Rock Mechanics (one of its subcommittees periodically appraises and recommends priorities for government research on this subject). Also, a commission has been set up under the International Society of Rock Mechanics that is currently attempting to answer these questions. At the present time, no comprehensive recommendations have been agreed upon.

Nevertheless, it can be suggested that field studies to develop engineering methodology for applying the information that is now being produced is important. The large amount of money being spent every year to break rock away from its formation and reduce it to a fine size warrants increased research. Increasing underground urban requirements are stimulating great interest in mechanized tunnelling (9). Dam and highway construction, particularly in mountainous terrain, have serious rock problems. Improved mining efficiency (recognizing the importance of the industry to the economy) is a continuing requirement in the face of leaner orebodies, deeper workings, and the increasing significance of conservation.

TRAINING NEEDS

With the initiation of grants-in-aid of mining research to universities by the Mines Branch in 1963, the training of students and the staffing of university departments concerned with rock mechanics has been greatly improved. Nevertheless, the resources available to the universities for supporting training and basic research work in this area are meagre when it is recognized that the subject requires a multidiscipline team effort as well as a considerable increase in volume of work to make it commensurate with the magnitudes of the industries concerned with rocks (10).

In this regard, the Canadian metal mining industry is of an absolute size comparable to those of the United States and the U. S. S. R. , and hence disproportionate to our population. Consequently, unless we are to be followers in the technology of a key industry the level of Canadian research should also be disproportionate. This would require a very large increase in funds, including funds to permit the universities to undertake more intensive projects. Hopefully, the primary industries concerned with rock environments together with the manufacturing industry will increasingly undertake the expensive development work that is necessary to achieve the payoff from research in this area.

Aside from increased funding, improvement could probably be made in the effective use of existing research funds by increased co-ordination of effort throughout the country. The successful organization and co-ordination of mining research in South Africa through specialist panels of industry, university and government representatives provides somewhat of an ideal, although the variety of Canadian problems makes the task more difficult.

CONCLUSIONS

The cost of research on rock mechanics in Canada is probably of the order of 0. 02 per cent of the value of that part of industrial production concerned with excavating or constructing on or within rock. Firm figures would not only require statistics that are not presently available but an economic study of the concepts involved. In any event, it is clear that more money could be spent with a good prospect of high returns (limited economic studies of individual research projects have shown benefit/cost ratios of the order of 10 to 100).

Expansion of research in any area of technology is dependent not only on funds but on the availability of suitable people and on the effects of diverting activity from overlapping subjects. In an attempt to apply judgment on all these factors, I would recommend that:

1. The funding of government research in rock mechanics be stabilized at the present levels and only be expanded into the development area if industry does not provide sufficient initiative to fulfill national interests.
2. The grants-in-aid of rock mechanics research to universities to support basic research should be increased immediately to $250,000 per year, and then expanded at the annual rate of 25 per cent for about 10 years.
3. Industry be encouraged (if necessary with cost-sharing schemes through the Mines Branch) to expand its development efforts both in operations and in producing new equipment for the home and export markets - a level of activity costing about $80 million per year would probably be reasonable.

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REFERENCES

1. Gyenge, M., and Verity, T. W. Tunnelling research requirements? Mines Branch Min. Res. Centre Intern. Rep. MR 68/101-ID 1968.
2. Proceedings, 1st Can. Rock Mech. Symp., McGill University, Montreal, Sept. 7-8, 1962.
3. Proceedings, 2nd Can. Rock Mech. Symp., Queen's University, Kingston, Dec. 6-7, 1963
4. Proceedings, 3rd Can. Rock Mech. Symp., University of Toronto, Toronto, Jan. 15-16, 1965.

5. Proceedings, 4th Can. Rock Mech. Symp., CIMM and CACRM, Ottawa, Mar. 29-30, 1967.

6. Bibliographies of Canadian contributions in the field of rock mechanics. Bull. CIMM, vol. 57, No. 625, pp. 540-545, 1964; Bull. CIMM, vol. 58, No. 635, pp. 320-321, 1965; Bull. CIMM, vol. 59, No. 654, pp. 1198-1200, 1966; Bull. CIMM, vol. 60, No. 662, pp. 655-656, 1967; Bull. CIMM, vol. 61, No. 674, pp. 758-759, 1968.

7. Coates, D. F. Development of the Canadian advisory committee on rock mechanics. Bull. CIMM, vol. 60, No. 664, pp. 881-882, 1967.

8. Patching, T. H., and Coates, D. F. A recommended rock classification for rock mechanics purposes. Bull. CIMM, vol. 61, No. 678, pp. 1195-1197, 1968.

9. Rapid excavation - significance needs - opportunities committee on rapid excavation. National Academy of Engineering, Nat. Res. Council, Pub. 1960, 1968.

10. Rock mechanics research. Nat. Acad. Sci. Pub. 1466, 1966.

HYDROGEOLOGY

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DEFINITION

Hydrogeology is the science dealing with the character, source and mode of occurrence of underground water. As such, it is an integral part of hydrology, the science that deals with water on earth. However, there is no part in the study of groundwater that can be explained without an intimate knowledge of geology. Similarly, many geological phenomena can be understood better with a proper understanding of the relevant groundwater processes. Thus, hydrogeology can either be used auxiliary to geology or, in a wider sense, as a study of an important natural resource. This dual nature of hydrogeology was well illustrated by the results of a recent questionnaire among Canadian hydrogeologists(1). Although most Canadian hydrogeologists consider themselves still primarily geologists, there is a growing trend toward a greater affiliation with hydrology.

The fundamental working hypothesis in hydrogeology is the continuity of the hydrologic cycle. Strictly speaking, the domain of hydrogeology is confined to the saturated portion of the underground arc of the hydrologic cycle. In practice, however, most hydrogeological research includes the unsaturated portion of the underground arc as well. As a consequence, the fringes of hydrogeology overlap with those of soil physics, microclimatology, river hydrology and limnology.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Total groundwater use in Canada, excluding private industrial supplies, is estimated at 452 million gallons per day, or approximately 20 per cent of the entire municipal and rural water consumption. An estimated 5.5 million Canadians use groundwater as their daily source of water. The value of Canada's annual groundwater production is of the order of 80 million dollars. Current Canadian groundwater reports convey the impression that bedrock aquifers are relatively unimportant as compared to Pleistocene aquifers. Although this may be true from an over-all national standpoint, it is certainly not true from a regional standpoint. For instance, the fractured bedrock aquifers of the carboniferous areas in the Maritimes are of great significance for large water supplies, as are the carbonate aquifers of the Niagara Peninsula, the Paleozoic aquifers of Manitoba, and the Cretaceous aquifers of Alberta. In addition, the interaction between groundwater movement and petroleum migration may be of significance throughout the Western Canada Sedimentary Basin.

PRACTICAL APPLICATIONS

It would be wrong to demonstrate the value of hydrogeology by estimating Canada's groundwater consumption only, for hydrogeology is not merely concerned with groundwater as a resource but also with the interaction between groundwater and other parts of our environment. The following examples will serve as illustrations.

Hydrogeology plays an important part in watershed management, for it is the groundwater regime of a drainage basin that determines the low flow in its rivers. Consequently, improvement of the low-flow regime requires changes in the groundwater regime which, in turn, are related to changes in land use. Studies on this subject are part of the East Slopes (Alberta) Watershed Program.

Other applications of hydrogeology pertain to the classical geotechnical investigations near dam sites and proposed canals. Another family of hydrogeological investigations deals with underground storage and disposal. The most important of these are underground gas storage and underground disposal of radioactive wastes. The zone of saturation is also a potentially important medium to store flood waters in areas where sites for surface reservoirs have become scarce or where existing reservoirs have become filled with sediment. Finally, the recent advances in hydrogeology with respect to the simultaneous solution of regional heat-flow and groundwater flow will be of extreme importance for a better understanding of low pressure - low temperature mineralization.

HISTORICAL DEVELOPMENT

Originally, all studies of Canada's groundwater resources were performed by the Geological Survey of Canada, where they were initiated in 1875 by drilling for groundwater for the Transcontinental Railway. Since 1908, groundwater studies were carried out by the Borings Division of the Survey and later in conjunction with the mapping of Pleistocene deposits. At that time, personnel to investigate groundwater resources were lacking in provincial agencies.

However, as these agencies have developed in size they have gradually assumed a larger role in the management of provincial water resources. The federal government's role in the provinces has increasingly become one of support to provincial activities by providing financial and technical assistance, basic data and research. Starting in 1945, there has been a gradual increase of provincial water-resource studies, most of which are geared to resource evaluation as a basis for better resource management. As a consequence, 94 per cent of all Canadian hydrogeologists are employed by government agencies, and 70 per cent of Canada's hydrogeology studies are essentially provincial resource evaluations (1, Table 1).

PRESENT LEVEL OF ACTIVITY

In 1967, there were 65 hydrogeologists in Canada, engaged in a total of 130 projects. Ninety of these were classified as resource evaluations, whereas 40 were considered to be research projects. The ratio between federal and provincial levels of activity was about 1:6. In terms of expenditures, Bruce and Maasland (2) reported for groundwater research a federal expenditure of $364, 000 against a total provincial expenditure of $276, 000.

The strong research content of the federal groundwater program is consistent with the constitutional division of responsibilities. The strong provincial emphasis on resource evaluation as compared to the research emphasis of the federal program has produced an unequal degree distribution of hydrogeologists among Canadian agencies. Although the total Canadian population of hydrogeologists shows a normal degree distribution for a given group of earth sciences of 57 per cent B. Sc., 23 per cent M. Sc., and 20 per cent Ph. D., more than one half of all Ph. D. hydrogeologists in Canada are employed by the federal government.

NEED FOR INCREASED ACTIVITY

A need for increased activity exists at three different levels. These may be referred to as innovation, diffusion and reorganization. Of these, diffusion may be the most important activity and the most difficult one to achieve. By innovation is meant the creation of new solutions to problems that have not yet been dealt with in a manner consistent with the level of present-day technology and scientific knowledge. In this context, the following problems deserve urgent attention: salt-water intrusion, fracture flow and flow through poorly permeable materials (including non-Darcy flow), movement in deep flow systems (and its possible relation to petroleum migration), hydrogeological guidelines for waste-disposal site evaluation, and the economics of groundwater use. With innovation we must also include the need for more precise knowledge of Pleistocene deposits in Canada, particularly with respect to their occurrence at depth. The intense exploration program of the Saskatchewan Research Council is a shining example in this respect.

By diffusion is meant the active and vigorous distribution of new solutions among possible users. Too often, research stops at the innovation stage and important discoveries go unnoticed for years as a result of insufficient follow-up. Hydrogeology has made rapid advances lately, particularly in the analysis of aquifers and non-aquifers, in the mathematical description of such concepts as "regional homogeneity" or "regional permeability", in the mathematical description of regional groundwater flow, and in the quantitative relation between groundwater flow and regional thermal fields. These advances deserve to be tested and integrated in current concepts of low temperature - low pressure mineralization, hydrochemical prospecting, chemical limnology, and soil mechanics. In the light of these advances, it should no longer be necessary, for instance, to initiate geochemical sampling programs without reference to regional groundwater flow. Conversely, hydrogeologists have to search much more diligently for modern measuring and monitoring techniques.

The need for reorganization is apparent in some provincial resource agencies. At present, groundwater resources in some provinces are studied and administered separately from surface water resources. This situation stems generally from the link between groundwater and geology, but it may lead to misunderstanding among provincial resource administrators.

TRAINING

Education in hydrogeology should be part of an interdisciplinary graduate program in hydrology. The interdisciplinary nature of such a program would permit students to enter with undergraduate training in mathematics, physics, chemistry, engineering, geology or meteorology. This is now a common arrangement at a number of American universities where graduate programs in hydrology are either organized under an interdepartmental committee or as a graduate faculty within a university department. None of the Canadian universities offers an interdisciplinary curriculum in hydrology, although the Engineering Science Department of the University of Guelph offers a M. Sc. degree in hydrology with courses in surface water and groundwater hydrology. The Geology Departments of the Universities of Alberta, Manitoba, Western Ontario and Dalhousie offer graduate courses in hydrogeology, but the interdisciplinary nature mentioned above has been left to the initiative of the individual professors. In principle, however, there is a sufficient number of Canadian universities with an involvement in hydrogeology. The degree of involvement, however, has not yet reached the level of truly interdisciplinary curricula. The Agassiz Centre for Water Resource Studies at the University of Manitoba is a promising start in this direction.

MAJOR OBJECTIVES AND FUTURE TRENDS

The strongest trend in hydrogeology seems to be an increasing alliance with hydrology resulting from the recognized importance of groundwater as a water resource. This trend may result in a significant loss to the geological community of knowledge on processes that are of fundamental importance to geology and geochemistry. With regard to subject matter, hydrogeology will soon encompass more aspects of water economy. The monetary value of groundwater in storage will make the current concept of safe yield untenable, which means that economic guidelines must be established in order to deal rationally with the desirability - or indeed necessity - of groundwater mining. The development of conceptual models for resource management is advancing rapidly. Newly developed groundwater models must be incorporated in these management models. Further technological developments will take place to improve present methods of withdrawing fresh groundwater from coastal aquifers.

CONCLUSIONS

1. Research programs in hydrogeology should include hydrological as well as geological aspects of groundwater, in order to prevent a possible alienation between hydrogeology and geology.

2. Canadian universities with programs in hydrogeology should be encouraged to establish interdisciplinary graduate faculties in hydrology.

3. More attention should be paid to the active dissemination of research results among possible users. In this regard, scientists must be encouraged to use more communication media than publications alone. Travelling exhibits and educational films must be used to a much greater extent than is now the case.

REFERENCES

1. Meyboom, P. Hydrogeology: a decennial appraisal and forecast. The Earth Sciences in Canada, Roy. Soc. Can., Sp. Pub. 11, pp. 203-222, 1968.

2. Bruce, J. P., and Maasland, D. E. L. Water resources research in Canada. Sci. Secretariat Spec. Study No. 5, 1968.

PERMAFROST[1]

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DEFINITION

"Permafrost" or "perennially frozen ground", may be defined as the condition of earth materials, including soil and rock, remaining below 0°C (32°F) continuously for a number of years. In the U.S.S.R. the term "geocryology" is widely used in referring to the study of the frozen zones of the earth's crust. This term is also used in Canada.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT

One half of Canada, comprising the Yukon and Northwest Territories and the northern parts of the provinces, is underlain by permafrost. This phenomenon has a strong influence on the economic development of northern Canada. Permafrost also extends over half of the Soviet Union and hence share most of the permafrost territory in the northern hemisphere. Because of the impact of permafrost on northern development, information is vital on its distribution and manner in which it affects development, particularly in the construction and resources industries.

Perennially frozen materials except rock and friction soils (sands and gravels which have been drained prior to freezing) normally have a moisture content very much in excess of normal soils. In some cases this may be as much as 1,000 per cent or higher. At the southern fringe of the permafrost region in the zone of discontinuous permafrost, the perennially frozen ground is in delicate equilibrium with the climate. Any thermal disturbance results in soil conditions which are unstable and unsuitable for any building purposes. Further north the thermal stability at depths below 2 metres increases but the thickness of the permafrost also increases. In these areas heavy structures, roads, dams and runways may be built by suitable techniques, but many other problems arise which are not yet satisfactorily solved. Some examples are:

1. In certain areas ground water supplies become nonexistent forcing a complete dependence on surface water.
2. Well (gas and oil) drilling problems become complicated and recovery of gas is inhibited under certain conditions due to deposition of gas hydrates in the casing at low temperatures due to permafrost.
3. Seismic velocities vary widely due to temperature and moisture (ice content) horizons. This is particularly true of Cretaceous sediments in

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[1] Report of the Permafrost Subcommittee of the N.R.C. Associate Committee on Geotechnical Research.

the Mackenzie Delta and on the Alaskan Arctic Slope and also the Proterozoic sediments of the Labrador Trough.

Many other examples can be quoted but one in particular should be mentioned. Certain types of long range radars are by their very nature extremely sensitive to alignment errors. Because certain of these radars are on very heavy structures and emit very large quantities of thermal and electromagnetic power, subsidence can and has taken place with consequent misalignment. This has had very serious consequences.

Oil refineries with heavy tankage and large pipe runs are also very sensitive to misalignments. A long history could be written on the efforts to prevent subsidence at one refinery in the Far North.

Because perennially frozen ground imposes a design and construction penalty, all research in the geotechnical field should be directed to solutions required to build on permafrost, and a warning should be given that some solutions may be extremely difficult. Thus, the final purpose of all research should be to bring these penalties to so low a figure that construction costs in permafrost areas will be comparable to construction costs elsewhere in Canada and preferably to anywhere in North America.

HISTORY OF RESEARCH AND DEVELOPMENT

Early references to permafrost in Canada are found in the records of early explorers and traders. The first economic impact of permafrost occurred at the end of the nineteenth century during the Klondike gold rush due to the fact that placer deposits were overlain by substantial thicknesses of perennially frozen material which had to be removed or thawed to win the gold. Prior to the Second World War there was little notice of permafrost in Canada although it was certainly a factor in the few northern developments of that period, notably the Hudson Bay Railroad completed in 1929 to Churchill, Manitoba. Permafrost also had to be considered in the development of petroleum at Norman Wells, N.W.T. on the Mackenzie River and mining operations near Great Bear Lake and Great Slave Lake.

Permafrost suddenly became of major concern in the Second World War in the construction of the Alaska Highway. Lack of knowledge on coping with permafrost conditions severely hampered the completion and maintenance of this vital project. Permafrost also posed severe problems in the construction of airfields for the Northwest Staging Route, the "Crimson" Route through northeastern mainland Canada and Baffin Island, and in the construction and operation of the Canol pipeline.

In Canada, as in the United States, the interest in permafrost awakened by the above mentioned projects has increased steadily in the postwar period. As a direct result, in 1950 the Division of Building Research of the National Research Council initiated research programs on fundamental aspects of permafrost and the associated engineering problems. This has continued to date with a full time staff of two research officers (geographer and civil engineer) and three technicians. These, so far as is known, are the only group working full time on permafrost research in Canada. However, in addition to the Division of Building Research group, there are other agencies of government studying various aspects of permafrost (see below) as it affects their own projects. These agencies nonetheless do not sponsor a continuing program of research.

PRESENT LEVEL OF ACTIVITY

In the Federal Government there are no more than five persons (see above) now actively engaged in types of permafrost studies having immediate application to present day northern activites. In the universities, only the University of British Columbia, University of Alberta, University of Saskatchewan and McGill University carry out active permafrost research programmes; Laval University could also be included to a certain degree. However, the total number of academic staff and students amounts to no more than fifteen persons. Consulting engineers competent to advise on permafrost design are equally limited and to our certain knowledge would not exceed five individuals. In the territorial governments most design engineers are capable of handling permafrost problems on an empirical basis but whether they would be equally capable of handling large contracts on a consultant basis is open to question. The fact of the matter is that should any large job be undertaken in northern Canada by a Canadian subsidiary of a U.S. company, without a doubt that company would approach the U.S. Army Terrestrial Sciences Centre rather than any Canadian organization, for advice, for the reasons stated above.

In the geological-geographical field the situation is somewhat better. Practically every university now gives some sort of course in geomorphology and its relationship to Quaternary geology, which throughout Canada must include permafrost or the influence of perennially frozen ground on terrain. Here, the number of individuals who may have some knowledge of permafrost as it affects surface features may run into hundreds. However, like so many university courses of this nature, the steps between knowledge and application are either not clearly expressed or deliberately left in abeyance.

Although many agencies have some concern with permafrost, the total Canadian effort is small and widely scattered across the country. Most of these spheres of activity are represented on the Permafrost Subcommittee of the National Research Council Associate Committee on Geotechnical Research. This Subcommittee meets periodically to discuss permafrost investigations in Canada and sponsors technical conferences.

In conclusion, one might say that in view of the recent developments in the Arctic Islands, Mackenzie Delta, northern Quebec and Baffin Island the present level of activity both in applied and basic research is totally inadequate.

NEEDS FOR INCREASED ACTIVITY

Activity is needed most in the mission-oriented fields (see Appendix A). The Permafrost Subcommittee has recognized that "the extraction industries comprising mining and the production of oil and gas, and the necessary transportation and communication facilities to support these operations are most important - in the economic development of Canada". This recommendation was submitted to the industrial (oil) representative on the Subcommittee, who was at that time the chairman of the Ice and Muskeg Committee of the Alberta Society of Petroleum Geologists. He agreed that in general this recommendation was acceptable to the industry but could be arranged in a more orderly manner (see also Appendix A). It is of interest to note that he also pointed out (private conversation) that "we should not have the impression that the only problems are technical problems. Certainly the humanities must be considered". The destruction of surface features are very much accelerated in permafrost areas by human activities, and these activities can affect the ecology (which in those latitudes is in very delicate equilibrium) with disastrous consequences.

From a geotechnical point of view the priorities which must be considered, in order of importance, are:

A. Design criteria for:
   1. Oil, gas and service pipelines
   2. Disposal of surficial waters
   3. Groundwater supply
   4. Foundation design of very heavy structures

B. Studies on:
   1. The complexities of the thermal regime in perennially frozen ground (see 1. above)
   2. Geophysical problems and those particularly related to seismology
   3. The mapping of permafrost

C. Studies to determine the economic consequences of permafrost.

In summation, activity must be increased drastically in:
   1. Design technology
   2. Thermal and geophysical research and speedy methods of mapping
   3. Economics

COMMENTS ON TRAINING

Academic training to date has been dependent on grants given principally by the National Research Council, Defence Research Board, and the Geological Survey of Canada. Guidance from a governmental point of view has been given in general by the National Research Council Associate Committee on Geotechnical Research (Subcommittee on Permafrost). This direction has, in the past, consisted in drawing attention to technical problems and their association to the more basic types of Quaternary research and geomorphology. The Subcommittee has also sponsored in the first instance a very large number of translations suggested by its members.

It has been assumed that, through such direction and the available grant money, undergraduate and postgraduate training will be undertaken, and to a great degree this has been the case. However, the relationship between the numbers of people who have been trained to those who remain in the field and are available today for mission-oriented research can be directly related to opportunity.

Until very recently such opportunities in Canada have been extremely limited; outside of the DEW Line, SAC facilities at Frobisher Bay, the Imperial Oil refinery at Norman Wells, the townsite of Inuvik, and the Alaska Highway,no major projects have been undertaken. However, with respect to Alaska and Greenland (i.e. in the U.S. Army sphere of interest) there have been some extraordinarily large projects, many of which would have confounded the best soils consultants without the added problems of permafrost. It is for this reason that there is probably a greater pool of permafrost expertise in the construction field in the United States than in Canada. This does not necessarily reflect on the training in Canada.

However, it can be said that due to the past lack of opportunity, training has been kept at a low level with the result that the present pool of trained people will be completely inadequate to meet the forseeable demands of the future.

Because permafrost, as soil mechanics, basically affects the technology of design, some courses concerning its nature should be given in designated high schools, community colleges and technical schools. However, encouragement for such training should only be given to those schools which will be directly affected by developments in the far north - e.g., high schools in Whitehorse, Yellowknife, Thompson, and Schefferville, and technical schools in northern British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec and Newfoundland.

The Subcommittee on Permafrost therefore suggests educational support might be given to:

1. Universities - University of British Columbia; University of Alberta; University of Saskatchewan; University of Manitoba; Lakehead University; McGill University (at Schefferville); University of Sherbrooke; Laval University; Memorial University;

2. Technical Schools and Community Colleges - Only those colleges which feed directly into the above universities, or into those regions in which the community is directly interested.

3. High Schools in Whitehorse; Yellowknife; Thompson; Schefferville; Labrador City; Churchill; and those high schools which may feed directly the community and technical colleges mentioned above.

IMPORTANT OBJECTIVES AND FUTURE TRENDS

The most single important objective today is to develop methods for pipeline technology in permafrost areas. It is reliably reported that there is a possibility of three hundred billion barrels of petroleum products on the Arctic Slope of Alaska and in the Mackenzie Delta region. The effect of the constant political pressure on all oil producers in the Middle East means that major North American oil companies will attempt to develop these very large reserves in North America against any contingencies which may arise. The distribution of much of this petroleum will be to the deficit markets, which are in the eastern and central part of the continent. This implies that a pipeline must be built and such a pipeline will have to come up the Mackenzie River valley to Edmonton. A pipeline of this nature would be 1,400 miles long and would run for over 1,000 miles through the permafrost region. The technology to build such a pipeline does not exist nor does the technology exist to build the associated refineries, pumping stations, and storage facilities.

A project of this magnitude would involve the expenditure of more than $500 million over, in all probability, the next seven years. Increased research activity must be looked at with this in mind. At 1/2 of 1 per cent of the above figure the research funding would be in the order of 2.5 million dollars over seven years or an expenditure of $360,000 per year for this one project alone. A not extraordinary figure but the main question is, can it be absorbed when one considers that total expenditures on permafrost research now run at not more than $120,000 per year. This would imply an immediate increase of at least four-fold for a probable total annual expenditure of $480,000. Furthermore with the development of energy resources close to areas of mineral resources, the development of the latter will also be spurred. However, since mining is generally conducted in rock, permafrost, omitting service lines and attendant foundation problems, can be an asset rather than a liability since it produces a dry mine thereby reducing mining costs to a great extent. Nevertheless, there will be problems which may seriously affect the economics, such as the higher costs for the construction of roads, airfields, foundations, etc.

Problems will certainly be encountered in the development of open-pit mining, and the experience of the Iron Ore Company of Canada already points this up. A further important objective with regard to mining is the question of whether permafrost rises in the subgrade. If so, extremely costly problems may be encountered where concentrates are stockpiled for a period which may exceed one year.

Future trends in permafrost research must therefore be mainly mission-oriented. Canadians are in a peculiar and fortunate position in this respect. The first efforts of this Subcommittee were to have <u>all</u> the relevant and important Russian and certain Japanese documents translated. The Subcommittee has also had access to documents translated in the United States, including all the permafrost research undertaken by the U.S. Army and Navy, which has been greater than generally realized and in some ways more sophisticated than that undertaken in the U.S.S.R. In addition several U.S.S.R. building codes which cover northern areas have been translated by the National Research Council and are available in Canada. It would therefore appear that in the immediate future there is a real requirement in geotechnology to relate all these works to pertinent forthcoming Canadian problems.

Since permafrost is basically a soil phenomenon it must by its very nature have multiple facies. A certain future trend and requirement will be for continued mapping at a greater rate and as this mapping is completed, inventories must be made of areas where problems unique to the geomorphology and climate occur. These localized areas should then be related to the information presently available and mentioned above.

The North, and in particular the Far North, will always, certainly in the foreseeable future, have a resources oriented economy. However, with the cheap energy which may soon become available in certain localities, such as the Mackenzie Delta and which are in reality not much farther north <u>climatically</u> than northern Newfoundland, there is a good possibility that this pattern might change. If this is so, then there will be a very definite trend, as in Thompson, for a decentralized locally financed and self supporting community, in contrast to Inuvik. If this takes place there will inevitably follow subtle political pressures for cheaper construction methods which will again make even wider demands on the limited fund of expertise. This should be borne in mind.

CONCLUSIONS

1. Distinction can and must be made between geotechnology and geomorphology in permafrost research. The latter through inspection may give guidance to problem areas but the application of soil mechanics and foundation design to resource development must rest on the proper application of geotechnical principles.

2. There has been and there will be even greater increase in resource development in the permafrost region in the next decade.

3. There will be a multi-fold demand for trained senior engineers and scientists to solve the problems which are likely to be encountered, and many of the problems will be multi-disciplinary. The present level of activity will be totally inadequate for the future.

4. While there will obviously be an increase in research activity and therefore funds, it is not clear at the present moment as to whether this research will be within industry or within government laboratories.

From the above some policy recommendations can be drawn. These are:

1. In view of the fact that the major economic development in northern Canada will, in all likelihood, be related to the oil and gas industry, it follows that:
   - (a) A constant watch on expenditure in this industry must be made by the various research groups in the government and in particular by the National Research Council. From this it must not be concluded that this is not already being done but is put forward once again to emphasize the urgency of the matter.
   - (b) Liaison with the resources industries should be maintained at all costs.
   - (c) Requests must be made continuously to the industries for information as to research requirements.

2. Consequent on 1. above, research expenditures must be adjusted to fit the economic returns to the Canadian government.
3. A decision will have to be made as to whether to increase intramural or extramural research and which agency will oversee the research program.
4. Increased emphasis will have to be placed on training at lower levels than at present particularly in the high schools.
5. There will have to be an enlarged research program and as stated in 2. above this program must have some well defined relationship to the economic returns.

APPENDIX

The following program of permafrost research requirements was prepared by the Permafrost Subcommittee for submission to the Associate Committee on Geotechnical Research.

PERMAFROST RESEARCH REQUIREMENTS RELATED TO THE EXTRACTION INDUSTRIES

The Permafrost Subcommittee recognizes that the extraction industries, comprising mining and the production of oil and gas, and the necessary transportation and communication facilities to support these operations, are the most important economic activities in the development of northern Canada. Problems caused by permafrost in these activities are judged to be of prime importance in the consideration of research needs prepared by the Subcommittee for presentation to the Associate Committee on Geotechnical Research.

I. Mission-Oriented

1. Design Criteria
    - a. Oil and gas pipelines, service lines.
    - b. Roads, railroads, airstrips, dams.
    - c. Disposal of surficial waters, industrial wastes, including mill slimes, refinery wastes, nuclear wastes.
    - d. Groundwater, water supply and the disposal of wet wastes such as sewage.
    - e. Foundations such as piles and anchors.
    - f. Excavation and handling of frozen materials.
    - g. Cementing materials in freezing conditions.

II. Techniques (Research and Development)

2. Properties of Permafrost
    - a. Thermal studies related to aggradation and degradation of permafrost due to natural and/or artificial changes.
    - b. Physico-mechanical properties such as adfreezing strength, volume changes and pore water supercooling.

3. Application of ground and airborne geophysical methods for measuring the depth of the active layer and thickness of permafrost, and the effect of permafrost on geophysical prospecting methods.

4. Development of inexpensive insulating materials, including wood chips, for pipelines, roads, etc.

III. Inventories

5. Inventory of gravel deposits and/or other construction materials because of special requirements in permafrost regions.

6. Compilation and summary of borehole information in permafrost areas to confirm geophysical observations by remote sensing methods.

7. Monitoring of foundation movements - building, roads, airstrips, etc.

8. Inventory of permafrost and groundwater supply in permafrost regions.

9. Engineering site investigations and monitoring of present developments in permafrost.

Subsequent comments on this document by members of the Permafrost Subcommittee include the following suggested areas of essential permafrost research submitted by R. A. Hemstock, Imperial Oil Limited, Calgary. It appears to be more suitably oriented to the extraction industries' requirements although both programmes have virtually the same content. This arrangement is in order of priorities as seen by the industry.

Mission-Oriented Research Related to Permafrost

1. Winning of Resources
    a. Excavation and handling frozen materials.
    b. Drilling and completion of oil and gas wells through permafrost.

2. Transportation
    a. Oil and gas pipelines, and service lines.
    b. Roads, railroads, airstrips.

3. Construction
    a. Foundations.
    b. Excavation and handling of frozen materials.
    c. Cementing materials in freezing conditions.
    d. Development of insulating materials or techniques.

4. Pollution Control
    a. Disposal of domestic and industrial waste, mill slimes, etc.
    b. Groundwater, water supply.

Basic Research, Development and Inventory Needs Having to do With Permafrost

1. Aggradation and degradation of permafrost either natural or artificial.
2. Physico-mechanical properties such as adfreezing strength and pore water supercooling.
3. Ground and airborne geophysical methods for mapping permafrost.
4. Effects of permafrost on prospecting methods.
5. Inventory of permafrost, areal extent and thickness.
6. Inventory of groundwater supply in permafrost.
7. Inventory of gravel and construction materials.
8. Monitoring of present developments in permafrost.

MUSKEG

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DEFINITION

The terrain of Canada includes a minimum of 500,000 square miles of muskeg or organic terrain which by definition is constituted of peat (fossilized plant remains) and the living cover with which the peat is botanically associated. The expression 'muskeg' also implies that water is normally abundant in the terrain and that there are characteristic edaphic and geomorphic associations between the organic and the underlying mineral terrain.

Muskeg is not a single phenomenon; its aspects are multiple. It may be densely wooded or "barren". It occurs where permafrost is continuous, discontinuous or absent, and the association suggests relationships that are not yet properly understood. It may be potentially highly productive in an agricultural sense, or markedly unproductive. It may be either yielding or resistant to loading forces, and highly variable in the texture of its materials. It appears to associate in characteristic ways with hydrological features and in central Canada, when free water is most plentiful, muskeg is usually the most prominent terrain.

In consideration of the biotic and abiotic factors in the muskeg environment one must expect variation in terrain condition and type. It is this circumstance that has precipitated a basic and challenging complex of major problems which, should they remain unsolved, will prevent understanding of an important element of our Canadian terrain.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT

Peat deposits provide a fossil record of recent environmental development. They provide a historical background which helps to account for the present environmental state and aids prediction of future ecosystem changes when environmental factors are altered either naturally or artificially. Investigation of these phenomena relates to matters of national development as well as to fundamental enlightenment. It is in this two-fold implication that there is special significance to research and development in muskeg studies.

The research, if pursued on a broad and intensive basis, facilitates development of systems of access, mobility and transportation within a nation-wide zone of difficult terrain. It enables prediction to be made concerning the best use of muskeg for agriculture, forestry, and wildlife. It contributes to understanding the behaviour, conservation and exploitation of our remaining water resources. Finally, if affords an approach to finding best industrial use for peat and peat products.

The nation-wide zone in which muskeg often predominates, approximately coincides with what has been called the "Mid-Canada Development Corridor". Muskeg is found in every province of Canada and predominates in the northern regions. It is a common feature of the headwaters of many rivers. The various types of muskeg suggest characteristic association with the behaviour of gravitational water and thermal conditions including permafrost. These suggested relationships imply the significance of muskeg to pipe-line technology, road design, dam-site development and head-water distribution. Pipe-lines and off-road transportation routes are affected by erosional patterns in the muskeg foundations when permafrost prevades it.

Research and development on off-road vehicles must accommodate to the trafficability limitations in muskeg types. Optimized vehicle design in this context affect not only off-road transportation but also the peat mining industry, as well as agricultural and silvicultural operations.

The cost of road construction and maintenance for inorganic terrain is doubled for muskeg. Costs of oil exploration in muskeg increases by many millions of dollars per oil field and the costs of drilling are doubled. Reductions in cost hinge on further research and development on muskeg, especially relative to transportation. Research supported by the Muskeg Subcommittee and Division of Building Research of NRC has resulted in the saving of over $2, 000, 000 in the construction of 11 miles of dyke for the Brazeau Power and Water Conservation Project.

Interpretive research in the muskeg environments especially when aerial interpretation is utilized, contributes to wise land use, to understanding of biological productivity leading to improvement of forest and agricultural crops, and to appreciation of management needs for water resources especially those within and immediately south of the discontinuous permafrost zone. Without muskeg investigation, national development of transportation schemes will encounter limitations and the off-road vehicle industry will face basic difficulties through lack of design criteria. This point has been made in the past largely in connection with development of military vehicles but it now also pertains to civilian transport and forestry equipment. In military technology there is a current effort directed to development of "terrain trafficability maps" related to the mobility of specific off-road vehicles. Such maps are based on quantitative descriptions of terrain features processed by computers and appropriate descriptions of muskeg conditions will be required for this application. Finally, the research leads to guidance for the peat products industry which is much in need of help in Canada at the present time.

HISTORY OF RESEARCH AND DEVELOPMENT IN MUSKEG STUDIES

In 1945, the Muskeg Subcommittee of the Associate Committee on Soil and Snow Mechanics (now known as the Associate Committee on Geotechnical Research) of the National Research Council, was formed, largely as a result of engineering problems involved in the variability of muskeg and in the operation of tracked military vehicles on soft ground. The initial objective was to provide a useful interpretation of "Muskeg" to assist military and civil investigations having to do with organic terrain. In 1957, following its sponsorship of three annual Muskeg Research Conferences dealing primarily with access over muskeg by petroleum, mining, utilities and military groups, the Muskeg Subcommittee was formally designated as the convenor of a continuing series of technical sessions dealing with engineering problems on muskeg. In 1967, the Subcommittee's terms of reference were expanded, giving it responsibility for delineating problem areas in its own field, advising the Associate Committee on research priorities, encouraging and monitoring the solutions of the research problems, and assisting in the publication and utilization of research results.

Continued attention was given at McMaster University to the paleobiological relationships in muskeg to reveal the basis of variability and organization in the terrain. This led to development of a classification system which incorporated physiographic features that could be identified from high altitude aerial photographs. In the latter connection the Defence Research Board supported the work. A classification system summarized in NRC Tech. Memo. 44, "Guide to the Field Description of Muskeg", is oriented towards engineering use. The programme on investigation of structural differentiation in muskeg and peat was extended at McMaster University, and field investigations ranged from the far arctic to southerly latitudes.

Starting in 1954 this work was paralleled by work in the Division of Building Research of the National Research Council. The solution of actual engineering field problems was sought through application of knowledge acquired on the engineering properties of muskeg and peat. This work is being continued largely by one full-time civil engineer, augmented from time to time by the work of a geographer interested in the inter-relations of permafrost with muskeg, and another civil engineer interested in the thermal properties of peat.

In the early sixties, an interdisciplinary approach to muskeg studies was commenced with the establishment of the Organic and Associated Terrain Research Unit at McMaster University. Faculty from biology, geography, mathematics and engineering departments associated, on a consulting basis, in problem solving and in graduate programmes. There was emphasis on terrain-vehicle studies as applied to muskeg.

In 1968 the active nucleus of the McMaster University group transferred to the University of New Brunswick to establish the Muskeg Research Institute with a staff of five: an engineer specializing in vehicle design systems analysis, instrument design and development, two biologists working on muskeg methodology for data survey, muskeg and peat properties for applied requirements, a geobotanist engaged as an airphoto interpreter and emphasizing permafrost-muskeg relations, hydrological classification of muskeg, and a geologist studying permeability relations in muskeg and peat. The Institute is also developing an internal consulting system which has an on-campus and inter-agency (government-industry) off-campus structure.

During the past 10 years the system of classification of muskeg has broadened, become more sophisticated and more widely applicable. The research required to establish the system is being extended to effect interpretation of muskeg states in connection with user requirements. In addition, knowledge has been gained about trafficability prediction, design of high mobility vehicles, peat sampling techniques, the successful design, construction, and performance of engineering structures on muskeg, and the usefulness of such instruments as the cone penetrometer, shear vane, and nuclear density meter. This experience is recorded along with international contributions in a large bibliography.

The culmination of the first phase of interest of the Muskeg Subcommittee is expressed in the forthcoming publication of a Muskeg Engineering Handbook (University of Toronto Press). Energy normally expended on Annual Muskeg Conferences was most recently invested instead in organizing the Third International Peat Congress in Quebec City and the printed Proceedings are soon to be released.

PRESENT LEVEL OF ACTIVITY

There are four Federal Government agencies engaged in research on peat. The Department of Energy, Mines and Resources is concerned with the mining techniques and processing of peat for the domestic and export market. The Department of Agriculture evaluating peat deposits for agricultural use, primarily in consideration of reclamation of land and productivity potential. Its programme is incipient but nation-wide in scope. The National Research Council is examining the mechanical properties of peat. Emphasis is on frozen and unfrozen peat, and on thermal properties. The main approach is to gain understanding of the strength-deformation characteristics of peat. The Department of Fisheries and Forestry is conducting investigations according to a systems analysis approach to evaluate the significance of the muskeg factor in vehicle design for summer operations and is interested in the reclamation of muskeg for higher timber and pulpwood yield.

From time to time the provincial research agencies attempt ad hoc investigation. Newfoundland has been very active in this respect and is now engaged in a limited programme of enquiry into what might be done with the vast expanses of muskeg with which they are endowed. The Manitoba government, agitated by the affects of muskeg on development north of Lake Winnipeg and west of the edge of the Canadian Shield, is concerned about land use classification and the segregation of muskeg resources into agriculture, forestry and woldlife applications. The concern in that province is to enhance the airphoto interpretation approach. The wetlands investigation in Alberta is attempting to assess the characteristics of water behaviour and resources in foothill country. The Ontario government, principally through the Departments of Lands and Forests and Agriculture, is concerned with problems relative to the development of forested muskeg and to cultivation management (with University of Guelph) of peatlands, of which the Holland Marsh is a salient example.

Probably the broadest and most critical activity concerning muskeg research and development is underway at the Muskeg Research Institute of the University of New Brunswick. Research and development is progressing at this centre which has been humbly but effectively endowed as a temporary facility. Its programme includes research in the measurement of physical properties of peat, vehicle mobility, airphoto interpretation of muskeg for user requirement, muskeg hydrology, land use, peat utilization and muskeg ecology and paleoecology.

Age relationships in peat deposits and the post-glacial history of the land have received the attention of the Department of Energy, Mines and Resources and some of this work is being continued at Brock University.

THE NEED FOR INCREASED ACTIVITY

Other countries with a similarly high incidence of muskeg (USSR 10 per cent, Ireland 15 per cent) expend far more man-hours on research and development on muskeg than does Canada. In the USSR about 400 professionals and over 2,000 students are involved. Ireland employs about 30 professionals through the equivalent of a "Crown Corporation". Canada has about 15 identified with muskeg investigations. Despite the present national contribution which comes from different disciplines and continues with healthy enthusiasm the demands are not being met.

Forested muskeg is sometimes thought to provide the area for re-emphasis in research and development. The export of forest products from Canada will be very high partly because of growing deficiencies in Europe. At the moment the demand is being met through the attractive rates of forest regeneration in the southwestern United States. The lands involved, however, agricultural have a greater potential to meet the pending food shortage from the world's rapidly rising population. If they are connected to this purpose, Canada would be left as the most significant supplier of wood pulp for the future. There is therefore a need to extend our knowledge of engineering and biological principles which will bring bigger yield from forested muskeg. Drainage has been applied to forested muskeg in the past without regard to muskeg type and effect on the hydrology of the forest environment. Harvesting machinery has been designed and introduced to the market before development programmes elucidating terrain-vehicle relationships have made their contribution. In the process of forest harvesting, the peaty foundation is remolded and this hampers forest regeneration. A serious concern is the absence of a national or provincial inventory of the various classes of muskeg, each of which requires different management.

Most of our knowledge about agricultural crops on peatland has arisen from empirical experience gathered in the Holland Marsh area in Ontario. But this knowledge is based on one kind of peat, and without further research it is not possible to effectively predict the safe development of other peatlands. Much could be learned from intensive research into the productivity of adequately classified Newfoundland muskeg and its relationship to ionic transfer from the underlying mineral terrain.

On both the Pacific and Atlantic coasts there are extensive expanses of highly homogeneous peat almost pure in Sphagnum moss. The peat product industry needs constant support from research to assist in wise exploitation of these deposits - if indeed they should be exploited from the total land use point of view. Imaginative proposals for utilizing this peat for manufactured agricultural commodities are not yet based on research experience that will safeguard this developing industry.

The mining of peat in sufficient quantity to supply today's market requires new research and development. This is partly due to the need for economic improvement in mining and processing, as well as additional research on the properties and best use of the different peat structure types. As well, the peat mining industry has not learned to develop its product selectively.

Development of the north is best approached in relation to knowledge of the land and the distribution of its predictable conditions. The new Canadian industry producing off-road vehicles has had to accommodate to muskeg as a limiting factor in transportation. Success in transportation over muskeg is a function of adequate terrain interpretation. The vehicle industry requires continual environmental analysis of the zone of muskeg, which is now regarded as critical for transportation routes.

With the recent growing emphasis on national water supply, research on the relationship of muskeg types to control of the supply is pressing. Groundwater is a major component in the delicately balanced system of biotic and abiotic factors contributing to the composition of muskeg and its environment. In the absence of sufficient quantitative knowledge regarding the interaction of these factors, there is grave danger that if man tampers with any of the system components, such as groundwater, the present balance will be irretrievably lost. The long range effects on climate, ultimate water supply, survival of plant and animal communities, and the eventual benefits or loss to mankind, resulting from such action cannot be adequately assessed with the information now available. It is in the national interest to conduct further research on this problem.

TRAINING

Because of the multidisciplinary nature of muskeg research, university postgraduate training is necessary. At the same time, cooperation between universities and government agencies offers potential advantages which could be attained at the "Institute" or equivalent level including coordination of training. The northern universities have an important contribution to make.

IMPORTANT OBJECTIVES AND FUTURE TRENDS

There are many indications that resource development and population growth will demand that muskeg become an increasingly prominent and significant part of man's environment. The delineation of national need and the identification of broad problems for muskeg research require investigation by a high level national committee. The committee should be broad in its representation of disciplines and provision should be made for frequent liaison with provincial units of interest.

Research is required to extend the basic system of natural classification to the point where reference categories are quantitatively expressed and meaningful, not only in terms of organizational entity in the muskeg but also in relation to user requirements. Thus the classification of muskeg character for agriculture, engineering, and hydrology might differ according to purpose, but should be relatable to a natural system common to all, and by which valid prediction of the effects of technology can be made.

A stage in muskeg studies has been reached which suggests that beyond classification, research should be further encouraged on the automatic mapping of natural configurations of muskeg from airphotos so as to develop a national inventory of the classes of muskeg. The inventory should be relatable to land-use alternatives, resources development, and engineering problems.

The orientation of research might now be in response to *ad hoc* requirements in hydrology, engineering application, military uses, enhancement of biological productivity (forestry and agriculture), off-road transportation and vehicle design and the development of peat products.

CONCLUSIONS

1. (a) The expanded Muskeg Subcommittee should be recognized as the multidisciplinary national group concerned with muskeg studies.
   (b) All research and development concerned with muskeg and organic terrain should be encouraged and coordinated through the expanded Subcommittee.

2. A fund of not less than $500,000 per year should be provided to institutes, universities and government agencies for urgent national requirements such as: problems in access, transport, water-resources control, peat utilization, land-use, productivity (forestry and agriculture) and all bio-engineering studies that facilitate solutions to these problems (e.g. pipeline technology).

3. Immediate steps should be taken to recognize and support the work and potential of existing organizations with long experience in muskeg studies to commence:
   (a) an inventory, by modern methods, of the kinds of muskeg in Canada;
   (b) analysis of the Mid-Canada Zone relative to the muskeg factor as it impinges on development planning;
   (c) systems analysis applied to the interpretation of muskeg areas and user requirements;
   (d) data collection, storage and coordination pertinent to muskeg properties across Canada, including information on thermal hydrological and biogeochemical cycling;
   (e) extension services on the development of research results.

4. More financial support should be given to the teaching of trainees in muskeg studies in order that national and provincial needs can be handled adequately. Industry as well as Government should be asked to provide funds.

5. The establishment of priorities for the support of research and development should not be confining, in order that existing capability can be exploited and encouraged to expand where reasonable.

REFERENCES

Proceedings Eastern Muskeg Res. Meet., N. R. C., Tech. Mem. No. 42, 1956.

Proceedings 3rd Muskeg Res. Conf., N. R. C., Tech. Mem. No. 47, 1957.

Proceedings 4th Muskeg Res. Conf., N. R. C., Tech. Mem. No. 54, 1958.

Proceedings 5th Muskeg Res. Conf., N. R. C., Tech. Mem. No. 61, 1959.

Proceedings 6th Muskeg Res. Conf., N. R. C., Tech. Mem. No. 67, 1961.

Proceedings 7th Muskeg Res. Conf., N. R. C., Tech. Mem. No. 71, 1961.

Proceedings 8th Muskeg Res. Conf., N. R. C., Tech. Mem. No. 75, 1962.

ENGINEERING AND ENVIRONMENTAL GEOLOGY

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DEFINITION

Engineering Geology is the branch of applied geology that requires the application of geological observations and measurements, together with reasoning and judgment, to the problems pertaining to earth materials and processes encountered in engineering practice. Engineering geology is not a division of the earth sciences. It is rather the technique or art of applying the methodology and data derived from earth science and engineering disciplines, principally stratigraphy, structural geology, petrography, hydrogeology, geophysics, soil mechanics and rock mechanics, to the problems of civil and mining engineering.

Environmental geology is also a branch of applied geology rather than an earth science discipline _per se_. The term "environmental geology" was originally proposed (2) to describe those activities concerned with the integration and synthesis of earth science data for the use of planners and administrators in the management of terrains, water resources and subsurface fluids, waste disposal, and usable rock and mineral materials. As stated by Frye (2), the term means:

> "... an attitude of mind, an orientation, the application of the best and most sophisticated scientific work we are capable of doing to the problem of accommodating a rapidly shrinking living space to the needs of man."

A further branch of applied geology which encompasses many of the elements of both engineering and environmental geology is Urban Geology. Urban geology relates to the additional problems imposed by the presence of structures and vast areas of concrete and asphalt. For the purposes of this paper, urban geology, although recognized as a separate entity, is included within the scope of engineering and environmental geology.

These branches of applied geology span the full spectrum of geological materials that exist in a complex variety of Canadian environments.

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SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

It has been estimated on the basis of present population trends that the earth's population will probably double by the year 2000. It is possible that Canada's population growth rate during the next 30 years may be less than the growth rate of the world as a whole, but it is certain that, barring catastrophic events, a substantial population increase can be expected which will require the construction of almost double the number of buildings and public facilities that now exist. Many of the new buildings and structures will occupy lands formerly considered, from the geological point of view, as either undesirable or unfeasible as construction sites. In addition, the size and complexity of engineering structures, both on surface and below ground, will continue to grow, thereby requiring a greatly increased capability to evaluate the interactions between structures and foundation materials and to assess and evaluate in situ rock stresses both under natural conditions and under conditions imposed by rock excavations.

The significance of research in engineering geology, therefore, is to enable the construction and mining industry to economically and safely construct on, or excavate within, the terrain with a full understanding of the reactions of earth materials to the imposed changes in regime.

Within urban and interurban areas, the increasing complexity of social organization has produced a need for improved planning, at various levels of government, in the management and utilization of natural resources. Environmental geology, therefore, becomes particularly significant in the application of geological information to the efficient management and utilization of land, mineral and water resources.

Information on the geology and hydrogeology underlying urban areas is of fundamental importance for the design of building foundations and underground facilities. Data obtained from urban geology studies is thus of direct economic benefit in the engineering design process by greatly increasing the efficiency, and thereby reducing the cost, of foundation investigations.

PRACTICAL APPLICATIONS

Costs of preliminary explorations, including geological and geophysical surveys, test borings and sample analyses, are a necessary and integral part of the cost of engineering structures. The exploration costs are commonly of the order of 1 or 2 per cent of the total cost of the project (4). These percentages are relatively small, however, when compared with the 10 per cent allowance for "contingencies" which is commonly calculated in civil engineering estimates, to allow in part for uncertainties that thorough subsurface explorations might eliminate. The practical applications of research in engineering geology, therefore, are directed toward ensuring that the exploration costs related to a construction project achieve reductions in the over-all project costs.

In the field of urban geology, the systematic recording and synthesis of geological information derived from construction activity can result in substantial savings in the costs of planning and execution of engineering works. Similarly, environmental geology studies can materially assist in overcoming the all too prevalent contamination of the physical environment by waste products, loss of property and life through development of unstable slopes or flood plains, and the loss of valuable mineral resources through planning or zonation based on inadequate or non-existent geological information.

HISTORICAL DEVELOPMENT

The early history of the development of engineering geology dates back to the 1790's when William Smith, of England, one of the fathers of modern geology, applied geological reasoning to the construction of canals and the draining of agricultural lands. During the next century, the growth of engineering geology was extremely slow, although there were significant applications of geology to the construction of railway tunnels in the Alps and in England.

In North America, the first substantial use of engineering geology occurred in 1905 with the appointment by the Metropolitan Board of Water Supply, City of New York, of a panel of consulting geologists to advise on the construction of dams and aqueducts. Other important contributions of geology to engineering followed in the next two decades, highlighted in 1911 by the appointment of C. W. McDonald as resident geologist on the Panama Canal project.

In 1928, the failure of the St. Francis Dam in California as the result of poor quality foundation rock, focused attention on the need for the utilization of geological information in the design and construction of engineering works. This event might be regarded as the beginning of modern engineering geology in North America.

Throughout the 1930's, the development of engineering geology was accelerated through the contributions of engineering geologists to the investigations for hydraulic structures conducted by such American organizations as the U. S. Corps of Engineers, Bureau of Reclamation, and the Tennessee Valley Authority. During the same period, developments in other disciplines provided quantitative methods of great value in engineering geology. Two of the more notable developments were the emergence of soil mechanics as an important and separate field of engineering, due primarily to the extraordinary contributions of Karl von Terzaghi and the development of analytical techniques for evaluating groundwater flow as, for example, by C. V. Theis.

A significant Canadian contribution to engineering geology was made by R. F. Legget with the publication in 1939 of his book Geology and Engineering. This book (4) has become an international reference text.

During World War II, geology was widely applied to military operations by all countries. However, the greatest development of engineering geology has been in the postwar period of accelerated construction activity. In this period, the impetus for development in engineering geology has been provided by the necessity of solving the constructional problems encountered in civil and mining engineering. Consequently, many of the significant developments that have furthered the understanding and measurement of the engineering behaviour of earth materials have been contributed by engineers and are recorded in such journals as Geotechnique and the Journal of the Soil Mechanics and Foundations Division of the American Society of Civil Engineers.

Within the geological profession, the growing importance of engineering geology has been recognized by such events as the formation in 1947 of an Engineering Geology Division within the Geological Society of America, the formation of an Association of Engineering Geologists in the United States in the early 1960's, and the organization of the International Association of Engineering Geologists during the period 1964-68.

Engineering geology in Canada has been advanced in the past two decades largely through the medium of the annual Canadian Soil Mechanics Conferences sponsored by the National Research Council, Associate Committee on Soil and Snow Mechanics. The proceedings of these conferences, held in various Canadian cities from 1947 to 1962, contain important contributions on the geological factors that influence the engineering behaviour of such typically Canadian soils as lacustrine and marine clays, tills, and the complex soils of the lower mainland of British Columbia. Since 1962, the Soil Mechanics Conferences have been sponsored by the Geotechnical Engineering Division of the Engineering Institute of Canada, which has provided a forum for the interchange of information between engineers, geologists and others concerned with earth sciences in Canada.

Other significant Canadian developments in engineering geology in the last two decades have been the organization of geological departments within the Hydro Commissions of Ontario and Quebec, the employment of increasing numbers of geologists in consulting engineering firms, the application of air photo analysis techniques for engineering purposes, notably by Dr. J. D. Mollard, of Regina, and the growing awareness of the engineering profession of the significance of geological information in construction.

Environmental geology is a relatively new term which serves to emphasize the requirement for earth science studies in the planning and management of the terrain and its resources in areas of population growth. Much of the basic geological development in environmental geology, however, stems from classical geological studies of bedrock and surficial geology and groundwater resources.

Since 1965 the Illinois State Geological Survey has conducted environmental geology studies, particularly in the Chicago area. These studies, apart from their local usefulness, have served to focus attention on environmental geology and to demonstrate the significance of an integrated earth science approach to planning in areas of population growth.

Urban geology studies have been carried out in only a few of the major cities of the world. In Moscow, Prague, Paris, London and Tokyo, for example, notable achievements have been made in the recording of borehole data and in the publication of urban geology maps. Similarly, in the United States, the U. S. Geological Survey has carried out continuous studies of the urban geology of Washington, Boston, San Francisco and Portland (Oregon), based on natural exposures, borehole data and foundation excavations.

In Canada, the surficial geology of the Montreal area has been mapped at a scale of 1 inch to 1, 500 feet as a co-operative project between the City of Montreal and the Geological Survey of Canada. Contributions to the urban geology of Ottawa and Vancouver have also been made by the Geological Survey of Canada.

During the planning and construction phases of the Yonge Street subway in Toronto, the geology of the subway route was carefully studied (3) both by pre-excavation borings and by detailed examination of the geology during construction. This study, which involved personnel from the University of Toronto, National Research Council, Geological Survey of Canada, Ontario Department of Mines, and the Royal Ontario Museum, served not only to assist materially in subway construction but also capitalized on an otherwise unavailable opportunity to study the subsurface geology within the centre of the city. Similar geological studies were also made during the construction of extensions to the subway system. Surficial geology mapping programs of the Ontario Department of Mines have further contributed to the knowledge of urban geology of parts of Metropolitan Toronto.

The Alberta and Saskatchewan Research Councils have been active in urban geology studies in Edmonton, Calgary and Saskatoon. A study of the geology and groundwater of the Metropolitan Winnipeg area has been made by the Water Control and Conservation Branch of the Manitoba Department of Mines, in connection with the construction of the Red River Floodway.

PRESENT LEVEL OF ACTIVITY

Almost all of the activity in engineering geology in Canada at the present time is devoted directly to geotechnical investigations for the design and/or construction of major engineering projects such as hydroelectric developments or tunnels. The engineering profession has clearly recognized the need for geological and hydrogeological information at the project sites; consequently, geological and groundwater investigations are conducted at every major project.

The level of activity in urban geology in Canada can only be described as either very low or nonexistent. With the exception of Montreal, none of the municipal engineering departments or regional planning commissions employ a full-time geologist or systematically record the vital geological information in existing excavations for the benefit of future construction projects. In Montreal, a technician is employed to collect geological data and update the existing geological maps of the city, and a continuing computer-based program has been established at McGill University, under the direction of Professor R. H. Grice, to develop methods of storage and retrieval of urban geology data.

Current mapping programs of the Ontario Department of Mines, Saskatchewan Research Council, Alberta Research Council, and the Geological Survey of Canada are directed in part toward the surficial geology, construction materials and groundwater resources of populated areas, and hence constitute significant contributions to Canadian environmental geology studies. These programs, however, are but a very small proportion of the total geological mapping effort in Canada.

From the standpoint of research relating to the engineering behaviour of the terrain of Canada, most effort is directed toward soil and rock mechanics and is centred in the Civil and Mining Engineering Departments of Canadian universities, in the National Research Council, and in the Mining Research Centre of the federal Department of Energy, Mines and Resources. The level of activity in engineering geology research is relatively low among geological groups in universities and governments. The latter, however, make very significant indirect and direct contributions in the form of the analysis and description of geological materials and in the interpretation of the geological history of these materials as a basis for the determination of their engineering significance.

NEED FOR INCREASED ACTIVITY

In the field of engineering geology related directly to construction, it is possible to recognize two levels of activity which, for descriptive purposes, are designated herein as local and regional.

At the local level, the engineering geologist is concerned with the geological detail at a particular construction site. Although the geologist may know the critical geological parameters of the site from his general experience and knowledge, in many instances these details may not be directly revealed during the site investigations because of the lack of geological exposure or poor core recovery in boreholes. The lack of such detailed information can have serious consequences on the ultimate performance of the structure.

The development of the NX-size borehole camera has provided a means of increasing the information obtained from boreholes. However, limitations on the usefulness of the instrument are caused by drill-hole casing, opaque fluids in the borehole, and the subjective methods of film interpretation. There is, therefore, a requirement for the development of reliable, small-diameter borehole instruments analogous to those presently in use in the petroleum industry, to assist in the detection of such geological details as fractures or clay seams. Further advances are also required in the development of in situ test techniques for both soil and rock, as well as drilling and sampling technology, to permit the recovery of undisturbed large-diameter samples from soft ground and to improve the drilling rates and sample recovery in tills and granular materials.

Improvements in the quality of geological data for engineering purposes, however, is not an end in itself. In order that these data may be of maximum value in the design of engineering structures, the development of analytical techniques is required so that the geological data may be incorporated directly in the calculation of design parameters.

At the regional level, Canada possesses vast areas of geological materials which create engineering problems. These include "sensitive" marine clays, varved clays, tills, swelling shales, unstable jointed rock slopes (particularly in the Cordilleran region), and vast permafrost areas in the Canadian north. While significant contributions have been made on the various engineering aspects of these materials, a synthesis of the geological factors that underlie their engineering behaviour has hardly been touched. Thus, the challenge for Canadian engineering geologists to master their own environment through an understanding of the engineering significance of geological materials and processes remains largely unfulfilled.

Almost 70 per cent of Canada's population are urban dwellers, and it can logically be expected that the present patterns of population density will continue and that the anticipated increases in population will occur within the urban centres. Approximately 60 per cent of the incorporated cities in Canada with populations of 50,000 or over lie within a relatively narrow corridor that extends from Quebec City to Windsor. Elsewhere throughout the country, the population tends to be concentrated in the rather more widely separated major centres of the Atlantic Region, Northern Ontario, the Prairies, and southern British Columbia. It is, therefore, obvious that these are the areas where vastly increased activity in urban and environmental geology is required if these important aspects of geology are to serve the economic and social development of Canada, and if geologists are to avail themselves of the rich harvest of geological information afforded by construction activity in the urban centres.

TRAINING NEEDS

Until very recently, Canadian universities have displayed a singular lack of interest in providing training in engineering geology related to the construction industry, with the consequence that many Canadian engineering geologists have found it necessary to obtain training at the postgraduate level in American or other foreign universities.

At present, 12 of 25 departments of geology at Canadian universities (1) offer one or more undergraduate courses in engineering geology. Only six Canadian universities, however, offer a degree program in engineering geology or geological engineering at the Bachelor's level or higher, and where such a program is offered it is usually through a department of engineering rather than a department of geology.

As with most interdisciplinary fields, logical arguments can be advanced by both engineers and geologists to support claims that their particular branch of learning should form the principal basis of training, but with a substantial input from the other field. The significant fact is, however, that a substantial co-operative effort is required between departments of geology and departments of engineering. Engineering geologists, soils engineers and rock engineers all require a background of mathematics, applied mechanics, groundwater hydrology and theoretical soil and rock mechanics as a part of their academic training and, most important, extensive geological experience in the field.

It is unlikely that any one person will have the aptitude and experience to be competent in all aspects of engineering geology. Hence, a most important attribute of the practising professional is his ability to co-operate and communicate with his colleagues in other disciplines and to respect their efforts in the attainment of common objectives.

MAJOR OBJECTIVES AND FUTURE TRENDS

Some of the outstanding problems of engineering, environmental and urban geology in Canada have been outlined above; thus the most important objectives relate to the ways and means whereby solutions to these problems can be attained.

Since trained personnel engaged in scientific activities are the key to the solution of these problems, the primary objectives are as follows:

1. Attraction of top-quality students to the geological sciences through modern field- and laboratory-oriented earth science programs at the secondary school level. An equally important objective of a secondary school earth science program is to increase the over-all awareness of the general public of the earth sciences and to emphasize the significance of these sciences in the economic development of the country.

2. Development of co-operative attitudes and research projects between Departments of Geology, Engineering, Geography and Soil Science in Canadian universities to actively demonstrate to both staff and students the interdisciplinary aspects of engineering, environmental and urban geology.

3. Development by federal and provincial government agencies and industry of opportunities for the field training of students in the fields of engineering, environmental and urban geology. In this regard,

an immediate objective should be the initiation of urban and environmental geology projects in all of the major urban centres of Canada, involving both mapping and data storage and retrieval systems.

The future trends in engineering geology are bound to be closely related to advances in engineering technology. As examples, the peaceful uses of nuclear energy are in the late stages of development, hence future engineering geologists will be increasingly concerned with the problems of radioactive waste disposal and with the effects of using nuclear devices for large-scale excavations.

Exploration and exploitation of mineral resources from the continental shelves and from the Arctic regions will provide challenges to the engineering geologist both in these phases of endeavour and in the construction of access routes to these resources. In the field of construction materials, the declining supply of concrete aggregates and granular materials in the rapidly developing urban areas may very well require the development of techniques to utilize "low grade" granular material such as till, for aggregate purposes.

CONCLUSIONS

1. Since mineral resources and urban affairs are in the domain of the provincial governments, pilot projects for urban and environmental geology studies of the major Canadian cities should be initiated as co-operative ventures between provincial government agencies and one or more university Departments of Geology. Such studies, utilizing existing 1:25,000 scale topographic maps as base maps, could serve as models for continuing programs that would involve participation at the municipal level of government.

2. Co-operative programs involving engineering geologists and engineers from universities, government departments and industry should be established for a concerted attack on the engineering geological problems of a region. The relative priorities for such programs might be determined through studies sponsored by the Associate Committee on Geotechnical Research, or by the Geotechnical Engineering Division of the Engineering Institute.

3. Industry participation in education, at both the undergraduate and graduate levels, should be encouraged by such means as special lecture series or personnel exchange arrangements that would permit prominent practising engineering geologists or geotechnical engineers to present their knowledge directly to students.

4. In view of the extensive distribution of Quaternary deposits in Canada, and their significance to almost all Canadian engineering projects either as foundation or construction materials, a substantial proportion of the research effort in engineering geology in Canada should be directed toward an understanding of the engineering behaviour of these materials, both in their natural environment and under the altered conditions imposed on them by construction activity.

REFERENCES

1. Directory of geoscience departments in the colleges and universities of the United States and Canada. Am. Geol. Inst. 1968.

2. Frye, J. C., 1967. Geological information for managing the environment. Illinois State Geol. Surv., Environmental Geol. Notes, No. 18.

3. Legget, R. F. and Schriever, W. R., 1960. Site investigations for Canada's first underground railway. Civil Eng. Public Works Rev., vol. 55, pp. 73-80.

4. Legget, R. F., 1962. Geology and engineering. 2nd ed., McGraw-Hill Book Company Inc., New York.

SOIL MECHANICS[1]

DEFINITION

Soil mechanics forms the basis of the geotechnical sciences. During many years, both terms 'soil mechanics' and 'géotechnique' were used to name that part of geotechnical sciences which is now called 'soil mechanics'. With continuing development of geotechnical sciences during the last two decades in Canada, the term 'géotechnique' has recently been defined by the Associate Committee for Geotechnical Research of the National Research Council of Canada as 'the study of the properties of soil, rock, peat, snow and ice, the influence of environmental factors on such properties and the application of this knowledge'.

As for Soil Mechanics, it could be defined as the study of the chemical, physical, hydraulical and mechanical properties of soils in their natural or disturbed state.

On the basis of the two above-stated definitions, it may be realized that the scope of soil mechanics is very wide and that the term 'mechanics' is somewhat restrictive and should be taken in its very general physical meaning.

In order to determine soil properties the engineers have to resort to many physical and engineering sciences. Once these properties and the main factors (geological, climatological, etc...) influencing them are known, the major problems which soil mechanics engineers deal with fall into one of the following five classes:

1. Slope stability in all kinds of soil deposits.
2. Earth retaining structures.
3. Construction of fills (for roads, dykes, dams, ...) on different kinds of soil deposits (sand, clay, peat, frozen soils...[2]).
4. Foundations for various engineering works.
5. Groundwater and groundwater control.

Two other specialized classes of problems which soil mechanics engineers may be concerned with are: seasonal frost in soils, and soil dynamics.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT

Canada's surface includes a wide variety of particular soil deposits whose characteristic properties need to be studied to assess their behaviour under different loads and climatic conditions. It is well known that many important structures (dams, for example) which have been built in the last few years in Canada would not have been economically or even technically feasible, had it not been for the results of extensive research programs

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[1] Prepared by the Soil Mechanics Subcommittee of the N.R.C. Associate Committee for Geotechnical Research, Pierre La Rochelle, Chairman.

[2] The Associate Committee for Geotechnical Research of the National Research Council of Canada having realized, some years ago, the importance and extent of muskeg and permafrost areas in Canada has formed separate subcommittees to deal with the relevant problems.

performed in the last few decades in Canada and elsewhere. Millions of dollars are saved annually, by the refinements in construction and design of foundations and earth structures which are made possible mainly as the result of research and development into new construction techniques. Many more millions will be saved as research and development allows the present empirical approach to be replaced by more rational and economical designs.

Although Canada can borrow R and D results from other countries, we have our own particular soils and climate problems which no other countries will solve and which will have to be dealt with by our own engineers if Canada is to receive the full potential benefits.

PRACTICAL APPLICATIONS

The Canadian Section of the International Society of Soil Mechanics and Foundation Engineering is publishing an Annual Report including a complete listing of all R and D activities in Canada. A reading of this listing gives an idea of the tremendous diversity of problems being studied by our engineers and it becomes quite obvious that the practical applications of soil mechanics are too numerous to be listed. In fact, all kinds of structures, from residential homes to aircraft, bring at one moment or another some foundations or stability problems which have to be dealt with by geotechnical engineers. Soil mechanics and géotechnique as a whole is the basis of the construction industry and is essential to both the exploitation of our natural resources and our industrial development.

The Soil Mechanics Subcommittee of the above-mentioned associate committee was established around 1946 with the primary responsibility of organizing the annual Canadian Soil Mechanics Conferences and screening papers for the International Conferences of Soil Mechanics and Foundation Engineering. At the same time research activities in Canadian universities started to grow under the stimulus of research grants from the National Research Council of Canada, and development activities increased as Canadian soil mechanics engineers became involved in increasingly complex construction problems mainly in relation to the exploitation of our natural resources. In fact, due to the tremendous variety and importance of soil problems in our country, Canadian engineers had no choice but to get deeply involved in soil mechanics in order to help accomplish the economical growth of Canada.

PRESENT LEVEL OF ACTIVITY

Canadian Soil Mechanics engineers are now considered to form, in relation to population, one of the most active groups of all countries in this field.

The annual Canadian Soil Mechanics Conferences, now organized under the sponsorship of the Engineering Institute of Canada, yield many important papers each year; one research seminar and two Trans-Canada lecture tours by eminent soil mechanics engineers are yearly sponsored by the Associate Committee for Geotechnical Research in cooperation with Canadian Universities; the 'Canadian Geotechnical Journal', which was first published five years ago by an independent group of Canadian engineers, has earned a high reputation in this field in the world and is now published by the National Research Council.

All the main Canadian universities are actively engaged in research in soil mechanics and many of our soils engineers enjoy an international reputation; indeed, many of our structures and earthworks designed and built by Canadian engineers are considered to be engineering feats.

NEED FOR INCREASED ACTIVITY

The Soil Mechanics Subcommittee has recently attempted to define areas to which research priorities should be given in Canada. Firstly, considering the influence of the winter climate on our construction operations and design criteria, it was agreed that considerably more research should be undertaken on problems involving frost action. Secondly, although research on soil samples in the laboratory is useful and fills certain purposes, we have now reached a state where more work should be done on soils in their natural environment, taking into account the numerous natural factors which might influence their behaviour.

Consequently, priority in Canadian soil mechanics research should be given to: 1. Cold temperature engineering design and construction. 2. Study of the behaviour of soils in their natural environment.

There is also a need to encourage studies in the following specific fields: (1) Frost action; (2) Winter construction; (3) Ground water pollution; (4) Field research with regional cooperative program; (5) Engineering geology; (6) Urban geology with respect to environmental planning; (7) Earth pressures; (8) Rock mechanics (with reference to geotechnical works); (9) Soils stabilization; (10) Earthquake engineering; (11) Construction equipment; (12) Underwater geotechnics; (13) Shore line geology.

For some years, the Subcommittee members have been convinced that there was a need for urban geology in Canada. An enquiry made in the main cities of Canada in 1968 showed that the very few cities possessing geological maps have them in constant use. Other cities lacking such maps can do little about it since it is geologists who have conducted or are conducting the urban geology work that is being done. As most consulting firms have good records and would readily yield such information for an urban geology project, it is considered that some Federal Agency could sponsor work in that field, with little expense, and with much benefit for the economy of our urban areas.

TRAINING NEEDS

The great majority of Canadian universities offer a Civil Engineering curriculum which includes an adequate soil mechanics course at the undergraduate level. However, satisfactory engineering education in soil mechanics can only be obtained at the graduate level. At the present time, all the main Canadian universities are offering M.Sc. and Ph.D. degrees in that field and most of the research work is subsidized by grants from the National Research Council.

At the technician and labourer level, there seems to be a complete lack of training facilities in some parts of our country, and the Soil Mechanics Subcommittee considered that these needs would be greatly helped if reading and visual aids for training purposes in the field of soil mechanics were prepared and made available through some federal agencies.

MAJOR OBJECTIVES AND FUTURE TRENDS

The most important objective for soil mechanics specialists, in relation to their involvement in the construction industry or the exploitation of our natural resources, is to try to make the best out of the cold climate in which we live. It is a well known fact that the winter season has a damping effect on the development of our economy and that, with more research, our technology could be improved in order to lengthen the season during which construction involving soils (roads, dams, etc...) may be undertaken. This factor is still more critical as the need increases to develop the North. Hence we think there is a great need for increased research on cold temperature engineering design and construction.

Up to now, most of the research work performed in Canada has been done by university professors who confine themselves to the laboratory for, amongst other reasons, financial limitations. Soil mechanics which, in large measure, is still basically an empirical science can be better developed by field observations and structures performance data. Hence, we have now reached a stage in Canada where it is most important for our research scientists and engineers to orientate their work towards the behaviour of soil in its natural environment. This implies also a thorough evaluation of the geological factors which might influence this behaviour and which could be achieved by better collaboration between geologists and geotechnicians at the research level.

We contend that better progress would be made if we could reach a more complete integration of the studies of engineering materials involved in géotechnique, that is: soils, rocks, ice, frozen soils and muskeg. Indeed, much can be learned on the mechanical and rheological behaviour of one of these materials from the knowledge of the behaviour of other ones. Engineering education should be thought of more in terms of geotechnique as a whole rather than in terms of soil mechanics.

CONCLUSIONS

1. Topic-oriented research grants should be offered to foster research in areas of particular interest to Canada, that is, cold temperature engineering design and construction, and the behaviour of soils in their natural environment.

2. More substantial research grants should be given to projects involving extensive field work and the collaboration of geologists, consulting and construction companies, in order to study the soil in its natural environment.

3. Considering that much can be learned from field or structure performance records which are usually in the hands of the industry or consulting

firms, some method should be devised to make possible the publication of these case histories and even to cover a part of the cost of instrumentation and performance observations. If it took the form of grants though university professors, this scheme would benefit also the research scientists and engineers in allowing them to keep close contact with practical problems.

4. Better liaison should be established between geologists and geotechnicians so that both these groups of scientists can fulfill their respective needs.
5. An effort should be made through a federal agency to facilitate the improvement of the training of technicians and labourers in the field of géotechnique.

ACKNOWLEDGEMENT

The Subcommittee members wish to express their appreciation to all the members of our profession who have commented on the brief and have sent useful suggestions.

Section II

GEOPHYSICS

EXPLORATION GEOPHYSICS*

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DEFINITION

Exploration geophysics is the application of the methods of physics to petroleum and mineral prospecting in order to obtain surface and subsurface geological information. A nearly synonymous term is "applied geophysics", although the latter includes engineering geophysics which is not generally considered as a part of "exploration geophysics". Geophysical prospecting for groundwater aquifers on the other hand is considered to be within the field of exploration geophysics. It is from the basic research activities of earth physics that exploration geophysics derives most of its methods, although by no means exclusively. Exploration geophysics deals with macroscopic rather than microscopic properties of the rocks. Thus, force field methods, radiative emission or absorption, properties of rocks in bulk and in place come within the scope of the term "exploration geophysics". The subject involves the accurate measurement of physical parameters of the underlying rocks in bulk and demands an interpretation of these measurements in geological terms.

INTRODUCTION

Calgary, Alberta, the centre of Canadian petroleum exploration, is perhaps the second most important city in North America in terms of the number of petroleum exploration specialists. Toronto, Ontario, is regarded as the most important mining exploration city in the world in terms of mineral exploration and finance. Exploration geophysics is much more important to petroleum exploration than it is to mineral exploration. The cost of drilling for petroleum exploration is approximately three orders of magnitude greater than that for mineral exploration so there is more incentive to spend money on petroleum exploration geophysics than for mineral geophysics. Petroleum exploration has long since exhausted the possibilities of drilling for petroleum on surface evidence, whereas the mining industry was able and is still sometimes able to make significant discoveries based on surface evidence. These circumstances forced the petroleum industry to search for a means of understanding the subsurface and to delineate traps which could not be inferred from surface information. This need caused petroleum exploration geophysics to develop very rapidly. The development of mining exploration geophysics has been somewhat slower.

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* This report has been prepared under the auspices of the Subcommittee on Exploration Geophysics, Associate Committee on Geodesy and Geophysics, National Research Council of Canada. Initial preparation was by L.W. Morley, Chairman of the Subcommittee. Useful comments were received from a number of geophysicists and particular contribution was made by the Canadian Society of Exploration Geophysicists, Calgary. Final editing was by L. S. Collett, M. S. Reford and D. W. Strangway.

Prior to the development of the reflection seismograph, the success ratio for petroleum exploration holes was 1:20, while after the wide acceptance of the method, the ratio has increased to approximately 1:7. In petroleum exploration geophysics, the seismic method completely dominates the field in terms of usefulness and consequently the amount of money spent on it. The other methods, largely gravity and magnetic, are regarded as supplementary and find use more in the initial exploration of a basin than for later detailed work. In mineral exploration, the magnetic method is the most useful general reconnaissance tool while the electromagnetic method and the induced polarization methods are considered to be the most diagnostic for the exploration of metallic sulphide mineralization. There has been little geophysical exploration for groundwater in Canada, but special needs in some areas have recently led to test surveys using seismic, electrical and airborne electromagnetic methods. This promises to be of increasing importance.

The Society of Exploration Geophysicists compiles comprehensive information on the use of geophysics throughout the world (Tucker, 1967 and 1968; Allen, 1969; Elliot and Kellogg, 1967; Hood and Kellogg, 1968 and 1969). The following statistics show the magnitude of expenditures on exploration geophysics in Canada.

EXPLORATION EXPENDITURES IN CANADA - 1966 to 1968

(A) Petroleum Exploration Geophysics

Methods	Cost ($'000)			Crew Months (Line Miles)		
	1966	1967	1968	1966	1967	1968
Seismic	53, 149	54, 654	70, 655	997	1, 048	848
Gravity	1, 004	930	2, 065	42	107	122
Air Mag	1, 047	562	1, 196	(129, 000)	(110, 100)	(87, 000)
Total	55, 200	56, 146	73, 916	1, 039	1, 155	970

These figures include only the costs of contract services. The Society of Exploration Geophysicists suggests that the costs should be increased by 2.5 times to cover data processing, overhead charges, interpretation, etc. A realistic estimate of petroleum geophysical expenditure is $185 million in Canada in 1968.

(B) Mining Exploration Geophysics

Type	Cost ($'000)			Man Months (Line Miles)		
	1966	1967	1968	1966	1967	1968
Ground Methods	6, 944	5, 637	6, 331	2, 537	1, 551	2, 886
Air Methods	2, 424	4, 101	6, 161	(319, 688)	(540, 916)	(754, 218)
Research	1, 066	2, 034	2, 944	843	843	1, 364
Total	10, 434	11, 772	15, 436	3, 016	2, 394	4, 250

Similarly this figure is estimated to be $38 million for 1968 when all charges are accounted.

It is interesting to note that 12 per cent of the petroleum geophysics in the noncommunist world and 34 per cent of mining geophysics is done in Canada.

In 1967 the United Nations Development Program awarded contracts for geophysical work in mineral exploration totalling $1, 348, 500. Canadian contractors obtained 49 per cent of this business pointing up the fact that this is an industry in which Canada does have a favourable world position. This position is however tenuous as aggressive groups are being built up in other parts of the world and everything possible must be done to maintain this position.

The petroleum exploration industry, including both the contractors and petroleum exploration companies themselves, spend a large amount of money on instrument development and to investigate new exploration methods. Very little of this, however, is spent in Canada although the application of these methods to Canadian exploration is both vast and speedy through operating offices set up in Calgary. In contrast to this, the amount of money spent on research and development of instruments for mineral exploration by the mining companies is very small. It has been left to the instrument and geophysical contracting companies to finance this development in any way they could. Happily this situation is somewhat alleviated, although not completely, because instrument development companies are able to get a modicum of government support through the National Research Council Industrial Research Grants and the PAIT program of the Department of Industry. In a few cases the Geological Survey of Canada has given contracts for test surveys using new methods. Yet some mining companies will spend literally millions of dollars on routine prospecting surveys but do not consider spending $100, 000 on researching the very same methods they are using, to confirm that they actually do work.

REFLECTION SEISMIC METHOD

Reflection seismic surveys have overwhelming importance in the overall picture of Canadian exploration geophysics, both in terms of employment and expenditures. These surveys, which yield considerable structural information, have been successfully used to delineate the complex folds and overthrusts of the western margin of the Western Canada basin. Drilling based on this work has discovered and developed large natural gas reserves and some oil. The reflection seismograph has also been used successfully in western Canada to locate reefs by using suggestions of reef isochron and character changes, the continuity and lack of continuity of reflections, and indications of dip. The successful use of the reflection seismograph in the search for productive porosity in reefs accounts for a substantial part of the known petroleum resources in western Canada. These include the Leduc field and many other reef fields in the same geological configuration - the Swan Hills complex of reef and reef platform production, the Windfall group of productive reefs, and, more recently, the Rainbow and Zama reef swarms. The delineation of productive areas at or near unconformities is a difficult problem, but again the reflection seismograph has proved of great value in many plays, including the Souris Valley of Saskatchewan and the Mississippian productive area of central Alberta.

Reflection seismic methods have been in effective use as an exploration tool for less than 40 years, and the technology of these methods has recently shown a rapid acceleration. Efforts to control the form of transmitted seismic energy have resulted in the development of new sources for generating elastic waves. Mathematical developments such as the statistical theory of communication provide the means for analysis of signal and noise. Modern filter theory offers an approach to solving the problem of recognizing significant events in the presence of noise. In order to utilize these developments to the best advantage, the primary information is recorded in the field in digital form to take advantage of the greater available dynamic range.

A problem in applying these new techniques is to develop economical methods for processing the vast quantity of data obtained in every mile of coverage. A seismic record usually contains 24 channels, and if the data were sampled every thousandth of a second for 3 seconds, a total of 72,000 numbers would be recorded. A mile of line may have 9 records, or 648,000 sample points. It is only recently, with the advent of large digital computers, that the mass-production capability has been available to apply these techniques routinely. The total seismic exploration system, using digital technology and digital computers, provides a revolutionary extension of the reflection seismic method which should markedly improve its application to structural and stratigraphic geology and, hence, to petroleum exploration.

IMPACT OF AERIAL GEOPHYSICAL METHODS

The enormous speed and economy of the aerogeophysical methods as compared with the ground methods is so attractive in a large relatively unexplored country like Canada that there has been a tendency to rely very heavily on these methods in mineral exploration. The airborne magnetometer has been particularly useful in assisting geological mapping over the Precambrian shield, and still more important where the basement is hidden by a thin layer of sediments or overburden. In the present stage of development in Canada, it is very difficult to decry this philosophy. However, the result is that most of the deposits which have been discovered in Canada are ones which are amenable to these particular methods, namely massive sulphides and magnetic iron formations. While the effect of aerogeophysics on exploration has been generally good, there are also some resultant bad side effects. For example, no reliable geophysical methods have been developed for the exploration for gold or diamonds, and it may be that the art of prospecting for gold is being lost in Canada. Another tendency has been for geologists to rely too heavily on geophysical indications and not enough on their geological wits. For example, it is quite a triumph for aeromagnetic mapping to hear from even the most traditionally minded geologists that it is uneconomical to conduct standard geological mapping until such time as aeromagnetic data has become available for the area. As true as this is, one wonders whether or not too much stress is placed on the need for geophysical data.

The economic impact of the application of the airborne magnetometer, by both government and industry in Canada, over the last 20 years or so, has been enormous. Morley (1969) has briefly described this work. With the combined efforts of federal and provincial governments and the aerial survey contractors, more than 5,000 individual aeromagnetic sheets (3,527,567 line miles to 1969) have been published in Canada, mostly in the last 10 years. It is the cheapest way of obtaining complete coverage with preliminary subsurface information of an area of igneous and metamorphic rocks. Canadian geologists and prospectors have become almost as familiar with the use of magnetic contour maps as with the standard geological maps. Canadian expertise on aeromagnetics is recognized world wide, and indeed Canadian aerial survey companies have worked on aeromagnetic programs on all continents, in petroleum as well as mineral exploration.

The development of the airborne electromagnetic detector was one of the most significant advances in the history of mineral exploration-greater than the development of the airborne magnetometer because it is a more direct detector of ore than is the magnetometer. Without this instrument, the dire predictions of the Paley Report, published in the United States in 1952, of world-wide shortages of copper, lead, zinc and nickel would be in great danger of coming true. This one instrument, which was a Canadian invention, had the effect of keeping Canada in the forefront of the production of these metals. In spite of its success the method still has great potential for further development.

"The airborne scintillation counter developed in 1949 in Canada did not discriminate against high K counts and therefore was not particularly effective in mine finding until the late sixties when the gamma-ray spectrometers came into widespread use. In 1962, Dr. Arthur Lang pointed out that of approximately 10,000 discoveries of radioactive occurrences in Canada, only about 10 could be attributed to the airborne scintillometer. Most of these occurrences, however, were originally detected with the ground geiger counter which was very inexpensive and easy to operate and hence found wide use as compared to the airborne method. This may have accounted for the small success of airborne prospecting, but other reasons also contributed. By virtue of the geometry involved, airborne radiometric surveys are much more susceptible to the detection of relatively large areas of medium activity such as can be caused by radioactive potassium in ordinary rocks. Most surveys were over the Canadian Shield, where potassium and economically insignificant amounts of uranium and thorium all tended to swamp significant anomalies. With the development of the gamma-ray spectrometer for field use in the late 1950's, it was considered that this weakness would be cured. It was in 1967 that a gamma-ray spectrometer survey led to the discovery at Wollaston Lake, Saskatchewan, on which Gulf Minerals Company is shortly going into production."

All the airborne methods are presently undergoing a major revolution. Recording methods are being changed from the traditional analog or strip chart methods to IBM compatible digital magnetic tape. The sensors themselves are being improved considerably. The high-sensitivity airborne magnetometer has a sensitivity approximately 50 times greater than the conventional fluxgate or proton magnetometer. The combination of increased sensitivity and digital processing has revealed a new range of magnetic features for geophysical and geological study. Development of new techniques in field operations and data processing is proceeding to realize the full potential of these instruments. Additional work will be needed to determine the physical causes of some of the minor magnetic features discovered.

Several more new airborne EM developments are under way using a much wider spectrum of frequencies than heretofore. Like the airborne magnetometer, recording is being done on magnetic tape, making the method much more amenable to quantitative interpretation with the use of the computer.

The change-over in aerogeophysics from analog to digital recording is very similar to the revolution which is still taking place in the seismic method from analog to digital recording. Apart from financial considerations, experience shows that the greatest difficulty in this conversion is the retraining of personnel - all the way from data compilers to geophysicists who are doing interpretation. Training requirements are more stringent for the handling of this type of data than they were for the analog data. Development of the new methods of data processing requires a thorough understanding of computer programming on the one hand, and of the geophysical data and problems on the other. To make use of the new methods, geophysicists must become familiar with much more sophisticated mathematical treatment of data than was required ten years ago. The result is a tendency towards increased specialization. Whereas one geophysicist trained in instrument interpretation and geology could handle all the methods previously used, he may be replaced nowadays by three different types - the instrument specialist, the data analyst and finally the geologist/geophysicist trained in the interpretation and integration of geophysical data. The place of the old exploration geophysicist is now in question, unless his knowledge is broadened to include an understanding of digital instrumentation, computer processing of data and up-to-date geologic concepts. There is an increasing need for inter-disciplinary training and retraining.

DRILLHOLE GEOPHYSICS

The future of mineral exploration rests increasingly upon the discovery of concealed deposits. Subsurface physical measurements from drillholes become increasingly important, and any technique which provides more information at less cost should be used. The oil industry makes extensive use of drillhole logging methods, but these are not often applied in mining exploration. In Canada, there is a very great need for the development of all types of borehole geophysical methods and hardware for small diameter holes. One particularly neglected field is nuclear geophysics, including neutron activation techniques. Because of the importance of the mineral industry to Canada, it would seem that drillhole geophysics is one of the activities that should be strongly developed in this country, with benefits to both mineral exploration and to Canadian instrument manufacturers.

OPERATIONS RESEARCH APPLIED TO MINERAL EXPLORATION

As in many other fields, most of the important decisions involving vast expenditures of money are made by senior executives employing 'feel and flair' acquired by experience. In mineral exploration, a beginning is being made to try to apply the methods of operations research to decisions involving the types, sequence and degree of detail of the various kinds of surveys, as well as the manner in which they relate to discoveries of mineral deposits and cost effectiveness. Research into this subject should be encouraged at universities and should be supported by mineral exploration companies and government; it is a critical factor for the success of exploration geophysics in foreign aid programs.

INSTRUMENT DEVELOPMENT

There are four phases of instrument development, namely, conception and laboratory testing; construction, testing and proving a field system; the carrying out of test surveys for the purpose of determining the geological significance of the data; and, the development of data collection, processing, and interpretation routines for production surveys. Significant advances are made by those who are able to span all four of the specialties mentioned above. If electronic capability alone determined success in this field, successful development would have been made by a different group of people. In actual fact, geophysical instrumentation progresses by adapting new developments from the physics and electronics fields for geophysical purposes. The vast amount of research and development done in connection with the American space and defence programs forms a particularly good source for new developments in geophysical instrumentation. Exotic new sensors in miniaturized and compact packages are being developed for space research that can readily be adapted for geophysical use either on the ground or in the air. We can hope that methods equally as significant as the airborne EM and the airborne magnetometer will be lurking unrecognized in the plethora of electronic instrumentation.

The history of the successful development in geophysical instrumentation shows that it is necessary for a geophysicist or geologist to work in very close association with an electronic engineer or physicist. The incentive for such effort is greatest in the instrument development company which specializes in geophysical instrumentation. In such companies, earth science expertise is brought in contact with electronic development engineers with the possibility of realizing profit through patents and contract surveys.

The NRC Industrial Research Assistance grants and the Department of Industry PAIT schemes are of great value in assisting geophysical instrument development. However, these assistance programs do not cover the fourth stage mentioned above, in bringing the instrumentation into routine use for exploration surveys. Obvious examples occur in adapting new instruments for airborne survey use. Means of expanding and improving these assistance schemes should be pursued most actively.

GOVERNMENT PROGRAMS IN EXPLORATION GEOPHYSICS

The role of government programs in Canadian exploration geophysics warrants particular attention. The federal and provincial governments of Canada have been directly responsible for geophysical development and surveys. The work has not been restricted to Canada alone, for major survey programs have been undertaken overseas to assist developing nations through the Canadian International Development Agency. Also, the work done by the Geological Survey of Canada, the Bedford Institute of Oceanography, the Observatories Branch, and the National Aeronautical Establishment in examining the continental shelves of Canada will likely prove to be of tremendous economic impact to the Canadian economy. For instance, these studies in offshore areas and the Gulf of St. Lawrence have advanced in the exploration of these areas by many years. The oil industry has under lease over 400 million acres of sedimentary areas as a result of these investigations and is committed to the expenditure of hundreds of millions of dollars. In fact, several hundred million will be spent by industry in exploration geophysics in the foreseeable future.

Yet there is controversy over the role which government should play in Canadian exploration geophysics. Different points of view have been expressed by various groups and individuals as this report was prepared and some attempt must be made to present them. The question is: "At what stage in any program should government work cease and industry take over?" Misunderstandings arise due to the fact that the phases and purposed of the program are not always spelled out in sufficient detail at its commencement and that any program usually has multiple purposes. Considering the variety of purposes, a number of problems exist. When testing methods, at what stage is the testing complete? When collecting basic scientific data, what account should be taken of similar surveys undertaken by industry? How long should publication be delayed while the data are studied by government scientists? When surveys are made to spur economic development of a particular region, at what stage has enough work been done?

These questions are particularly delicate in Canada, where each exploration group in industry is competing with many others in seeking new ore bodies or oil fields, and where many survey organizations compete for the opportunity of performing each survey. The resolution of the arguments will also have a direct effect on the government establishment, determining its capability to carry out its own surveys with its own staff, or to supervise surveys done by contract, or simply to observe the work done by industry.

All groups recognize the obligation of the government to collect scientific data. It is very difficult to contract out certain types of surveys such as geological mapping because of the enormous difficulty in inspecting and accepting work in return for payment, but some geophysical surveys are relatively easy to contract out and some involve only a minimum of inspection. A prime example is the federal/provincial aeromagnetic survey program in which about $1.5 million dollars has been spent annually since 1962. A plan for a similar but less extensive program is presently being formulated for airborne EM. It is considered quite feasible that a similar scheme could be worked out for more detailed gravity surveys. It is more difficult to make a case for seismic surveys because so much is already done on a private basis that in many cases it would amount to duplication. The Geological Survey of Canada finds that while it has great need of extensive seismic information, the cost of contract work is so great as to be considered to be beyond the means of the public purse. In almost any area in Canada in which the government might choose to work, it would find that it would be duplicating private work.

Under federal and provincial government regulations, exploration companies are required to turn over copies of all the factual information and the basic geophysical data taken within permit areas. Because of shortages of staff to handle this large volume of data, many government departments are only storing reports. These data now have a total value in the hundreds of millions of dollars for the land areas and continental shelves around Canada. In the interests of future generations of Canadians, these data should be collected and retained. Yet this is not enough. New regulations should be enacted allowing the eventual release of these data to the public after a confidential period.

Returning to those geophysical surveys for which extensive contract work can be economically justified, there is the matter of laying down specifications and of contracting the work. These matters should not be left entirely in the hands of administrators, who are primarily responsible for minimizing costs without being able to judge the bewildering questions of quality in geophysical surveys made by all sorts of organizations with all sorts of instrument specifications. Such administrators must rely on geophysicists for professional advice, and this is difficult to obtain on a continuing day-to-day basis outside the public service, although consultants and university professors can certainly be involved.

For those responsible for the administration of large amounts of public funds in the technical field, it is necessary that they should have available to them a cadre of well-qualified government specialists for consultation and advice. The necessity for this is recognized in many technical fields and is sometimes referred to as 'the technical interface' between government and industry.

If it is granted that such technical advice is best supplied from within the public service, it then follows that the government must attract and hold good engineers and scientists to ensure competent advice on a continuing basis. To date, this has been done by offering them the opportunity of doing research and development directly, rather than vicariously through contractors. This is not to say that all research should be done in-house. An attempt should be made to place particular research projects with the most competent group available whether it be within the government or outside.

In a field such as mineral resources which is so vital to the economy of Canada, it is important that the most modern and powerful exploration tools be available at fair and reasonable prices. In the event, for reasons in the interests of privately-owned foreign corporations or foreign governments, that such tools are not made available in Canada, it is the duty of the government's technical arm to see that steps are taken for the government to acquire such instruments. There is evidence, at the present time, that some instruments are not commercially available in Canada because of supposed foreign military restrictions, while the same instruments are available to commercial companies within the country of origin.

Governmental R and D or geophysical instrumentation constitutes only a small proportion of the total Canadian effort. Government laboratories offer little or no competition to private industry because they are not in the business of making and selling instruments. Frequently the instrument companies will, at nominal cost, take out licences to manufacture equipment invented in the government laboratories. A normal growth rate within the government should be allowed to continue.

MANPOWER, TRAINING AND THE ROLE OF THE UNIVERSITIES

In the post-war years, considerable emphasis was placed on applied geophysics in Canadian universities and many of the present leaders in exploration geophysics in Canada are graduates of these programs. Since the mid-1950s, however, the interests of incoming students have gradually shifted from applied problems to problems of a more fundamental nature. As oil companies initiated widely publicized layoffs of geologists and geophysicists, more students remained in graduate schools and turned away from positions in industry. At the same time the federal government, following the example of other countries, made more funds available for research of a fundamental nature. It became increasingly difficult to attract university faculty who were interested in the problems of applied geophysics. As a result, many high-calibre students who might otherwise have been attracted into Canadian industry simply moved into the fields of pure science where funding and job opportunities were much more abundant. Others moved into the glamorous field of space science.

In the last two or three years, this trend has been reversing slowly. The reasons for this are clearly the increased awareness that people have for the environment and the very important role that geophysics has to play. Unfortunately there is still little concerted effort by either the government or industry to stimulate and encourage the universities to attack problems in applied geophysics. One of the recommendations of this brief is clearly that industry and government should work together to increase interest and support in applied geophysics at the universities. This can only be done by making exciting opportunities available to graduates and by encouraging research in applied geophysics at the universities. Otherwise it will be impossible to attract students or faculty into the field.

With support of this kind available, the universities could certainly make a greater commitment to the field of applied geophysics. Additional faculty members could be attracted and more specialized curriculums could be introduced. Cooperative programs with industry could introduce students to the problems of the mineral industries and to the excitement and challenges of the profession.

The Canadian Society of Exploration Geophysicists estimates that approximately 600 professional earth scientists are employed in oil exploration geophysics. A breakdown by degree would be - B.Sc. - 510; M.Sc. - 70; Ph.D. - 20. More than 100 professional personnel would be employed in the mining industry. The Universities are graduating approximately 50 students in solid-earth geophysics each year including all degree levels. This number does not begin to satisfy the demands of industry, government and university.

RECOMMENDATIONS

In preparing this brief it has become clear that there are three basic groups with a deep interest in exploration geophysics in Canada. These are the exploration industry itself, the governments and the universities. It is almost impossible to write a single set of recommendations with which all groups can agree in detail, but it is certain that Canada is presently a world leader in the field and everything possible must be done to maintain and enhance this position. There are strong signs that unless action is taken on the following recommendations we shall be in danger of losing our present position of world prominance.

1. The Federal government should continue the present Federal/Provincial program of aeromagnetic surveys in Canada and should initiate similar programs in aeroelectromagnetic surveys and other techniques with regional applications. This work of course includes research into new techniques and the conduct of research to fully exploit existing techniques. A portion of this work would include the development of an ability to

acquire data for regional studies from exploration companies and to make use of these data by appropriate storage and handling techniques.

2. Research in applied geophysics should be encouraged in every possible way. This could be done by:
   (a) Expanding the present industrial research assistance programs of the Federal government to spur the development of techniques of surveying, data processing and interpretation as well as instruments to permit Canadian companies to compete favourably with foreign organizations.
   (b) The granting of increased funds to universities and individual researchers for work in applied geophysics.
   (c) The establishment of institutes funded by government and industry to investigate problems to be defined by the exploration industry. These could operate in cooperation with existing university facilities.

3. Particular attention should be paid to problems which may have a particular Canadian significance. These include, among others
   (a) Problems of exploration in the Arctic and permafrost,
   (b) Rapid coverage techniques to exploit large areas and determine the mineral potential,
   (c) Drillhole geophysical methods and in particular the technology of nuclear geophysics,
   (d) Groundwater exploration with particular emphasis on Arctic and Prairie environments,
   (e) The usefulness and cost effectiveness of using different methods of geophysics as phases in overall exploration programs,
   (f) Continued expansion and development of a saleable and exportable technology.

4. Federal and provincial regulations requiring exploration companies to supply copies of all factual information, original interpretation and basic geophysical data taken within permit areas should be enforced. Staff should be recruited to handle and interpret the data. Regulations allowing for the eventual release of these data after a confidential period should be enacted.

CONCLUSION

The role of exploration geophysics in Canada's economic development is more complex than might first appear. The development of an exportable knowledge and competence through a strong geophysical industry will be of greatest benefit. The natural resources of the country will be discovered in time, whether Canadian competence is maintained or not. But it must also be recognized that discovery leads to ownership, and that Canadian competence in exploration geophysics has a relationship with control of Canadian resources.

REFERENCES

Allen, S.J.
1969: Geophysical activity in 1968; Geophysics, vol. 34, No. 6, pp. 821-847.

Elliott, C.L., and Kellogg, W.C.
1967: Mining and geophysical activity; Geophysics, vol. 32, No. 6, pp. 1065-1072.

Hood, P.J., and Kellogg, W.C.
1968: Geophysical activity in 1967 applied to mining exploration; Geophysics, vol. 33, No. 6, pp. 903-910.

1969: Mining geophysical activity in 1968; Geophysics, vol. 34, No. 6, pp. 848-858.

Lang, A.H., Griffith, J.W., and Steacy, H.R.
1962: Canadian deposits of uranium and thorium; Geol. Surv. Can., Econ. Geol. Ser. No. 16, 2nd edition, pp. 71 and 116.

Morley, L.W.
1969: Regional geophysical mapping; mining and groundwater geophysics/1967; Geol. Surv. Can., Econ. Geol. Rept. No. 26, pp. 251-255.

Paley, W.S.
1952: Resources for freedom; a report to the President; U.S. Gov. Printing Office.

Tucker, L.R.
1967: Geophysical activity in 1966; Geophysics, vol. 32, No. 6, pp. 1047-1064.

1968: Geophysical activity in 1967 applied to petroleum exploration; Geophysics, vol. 33, No. 6, pp. 885-902.

REMOTE SENSING AND THE SOLID-EARTH SCIENCES

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DEFINITION

Remote sensing is not a new concept although the diversity and power of the technology has only recently accelerated. Strictly speaking, all extensions of man's senses are remote sensors. However, there are physical limitations that have restricted the use of some sensors to observations at relatively short distances. Accordingly, remote sensing has come to imply the sensing of certain electromagnetic radiations that penetrate deeply into the atmosphere and resolve detail to an acceptable degree.

The methods of remote sensing are divided into two broad categories by basic physical principles. Force-field sensing is concerned with the Earth's natural and spontaneous fields of gravity and magnetism. Electromagnetic sensing is concerned with a broad spectrum of radiations emitted, reflected and absorbed by all materials. The electromagnetic methods may be arbitrarily grouped into three classes. These classes are suggested by the major interactions of electromagnetic radiations with materials comprising the Earth. Thus a total of four classes of remote sensing methods may be recognized:

(1) force-field sensing (gravity and magnetic surveys);

(2) electromagnetic sounding, or sensing in depth below the surface of the Earth (audio and radio frequency surveys);

(3) remote electromagnetic sensing of the surface of the Earth with atmospheric transmission (microwave; infrared, optical and ultraviolet surveys); and,

(4) proximal electromagnetic sensing of the surface of the Earth with limited atmospheric transmission (X-ray and gamma-ray surveys).

Of the four classes of remote sensing, only the methods of remote electromagnetic sensing have the optimum characteristics of atmospheric transmission and good resolution that make them useful for sensing detail at great distances. Accordingly, these remote electromagnetic methods are commonly, though more restrictively, considered as Remote Sensing. It is in this qualified sense that the term is used hereafter.

The force-field and electromagnetic sounding methods have best resolution at relatively short distances and also have capability of penetrating into the Earth. Proximal electromagnetic sensing is useful at short distances only. Thus, when applied to the study of the Earth, these three classes of sensing are broadly grouped as methods of Exploration Geophysics.

Remote sensing (in the qualified sense) is inherently multidisciplinary in application because the pertinent electromagnetic radiations are variously attenuated by materials with which they interact, e.g., atmosphere, vegetation, water, rocks, cultural features, snow and ice, and a host of others. Remote sensing can be conducted from a variety of airborne and space platforms. The technology utilizes both active sensing systems such as radar, which transmits radiation and measures the return from the object, and passive systems such as the camera, which records radiation reflected or emitted by the target. Careful selection of target parameters, sensors and platforms will provide optimum data for remotely defining the target. Unfortunately, there are vast gaps in our knowledge of the properties that affect the response of materials to electromagnetic radiation at various frequencies. This subject has been under increased study in the last few years and these gaps are gradually being closed. Related advances will further the development of a practical remote-sensing system for surveying the Earth. Such a system will co-ordinate ground, airborne and satellite surveys, with automated processing and analysis to provide a fuller understanding of the human environment. In the meantime, man must rely on his own assisted powers of discrimination to achieve optimum contemporary use from remote sensors.

SIGNIFICANCE OF REMOTE SENSING TO GEOLOGY

Research and development in remote sensing has great significance to both the science and practice of geology. Of paramount importance is the requirement for fundamental research into the radiative properties of rocks and soils. Only a major research effort will make significant and timely progress toward this knowledge that is essential to the interpretation of remotely-sensed data. Without this increase in understanding, the flight of more refined sensors will be of limited value.

Whether or not all the predicted applications will be achieved from space, many will certainly be feasible from aircraft. Airborne surveys using other sensors incompatible with space operations will also present supplementary data from other parts of the electromagnetic spectrum. Future applications of remote sensing to resource missions will not require a decision of space or airborne, but, rather, the judicious blending of space and airborne surveys. The decision of whether to use remote sensors in aircraft or satellites is based primarily on (1) the scale of the problem, (2) the spatial resolution required to achieve useful data, and (3) the temporal resolution required for fuller understanding. World-wide coverage, synoptic views of large areas at small scales, repetitive observations and special lighting conditions are requirements that can best be met with spaceborne sensors. On the other hand, sensors in aircraft can provide information on small areas at larger scales for more detailed studies.

It is possible that, as a result of research in remote sensing, the approach to geological mapping and prospecting may be greatly influenced. For example, portfolios of maps portraying interpretations of remotely-sensed data and geophysics will be assembled for a given map area and studied by the geologist, prior to his field program. The geologist will then validate or modify the general interpretations and spend most of his time resolving problems of special concern and/or unanswered by the assembled data. Sophisticated systems, including specialized sensors and computer programs are being conceived, planned and developed to perform many functions of observation, compilation and interpretation now done by man, plus many other functions beyond man's inherent capabilities. It remains for scientists and engineers to select and adopt the techniques that are most likely to be economically reliable.

Because of the radiation frequencies employed, the application of remote sensing in geology is limited to surficial materials. Essentially, no data is provided with respect to the third spatial dimension of depth. Repetitive and economical surveys, however, do introduce a time dimension to the survey of the Earth's surface. The benefits of such remote sensing will have greater significance in agriculture, forestry, hydrology, oceanography, and geography than in geology and geophysics.

PRACTICAL APPLICATIONS IN GEOLOGY

Aerial photography is the most useful contemporary system of remote sensing. Its major contribution lies in the presentation of a familiar image that is useful to record, map and study an object or phenomena. Commonly, overlapping photographs are viewed stereoscopically to obtain a three-dimensional view. Such photographs are invaluable aids to the inventory, planning, development, utilization, and conservation of our mineral resources. Among their many applications are included:– the definition of geologic structure for mineral exploration and geologic mapping; location of construction materials, such as sand and gravel; route investigations for transportation and transmission of energy; site surveys for dams, bridges, buildings; and the recognition of geologic hazards for urban planning. The high quality topographic maps and thematic surveys resulting from aerial photography are essential to the orderly and economic development of Canada. Space photography has established a similar potential for regional or small-scale planning and mapping.

The relative proliferation of remote sensors in recent years has expanded the means available to earth scientists for acquiring data about the terrain. Remote sensors of interest and presently available include: panchromatic, colour and colour-IR photography combined with appropriate filters; SLAR*; remote vapour detectors; microwave radiometers; and optical-mechanical line-scanners imaging selected parts of the visible and IR spectra. Excepting photography, most remote sensors cannot yet be considered economic for systematic surveys because of the high cost of data acquisition and a lack of interpretative skills. SLAR, because of its ability to penetrate clouds, has immediate airborne application for obtaining good quality images of topography and structure where obscured by persistent cloud cover. Surveys with infrared scanners have established applications for locating surface features with contrasting temperatures and/or emissivities.

A most intensive study of geological applications of remote sensing is being conducted by the U.S. Geological Survey in their EROS (Earth Resources Observation Satellite) program. The work to date suggests that three types of geological benefits can be expected:

1. Benefits related to the extension of known techniques to new problems:-
    (a) inductive, small-scale thematic mapping of gross soils and lithologies, major structures, mineral provinces, alteration zones, land use, etc. Rapid and economic regional mapping, independent of many detailed studies, is feasible with synoptic, orthographic photography obtained under uniform conditions of observation from space.

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* Side Looking Airborne Radar

Comparable areal coverage might take years or decades to obtain by nonspace methods.

(b) synoptic and timely observations of dynamic geologic processes such as coastal erosion and sedimentation. The high-altitude, narrow-angle views of space observations allow the mapping of bottom features in waters to depths of 100 feet or more, depending on the transparency of the water. Such mapping will further the understanding of currents, tides and sediment distribution and may lead to the discovery of placers and other valuable deposits of sediments.

2. Benefits related to the introduction of new techniques of remote sensing:-
   - (a) determination of gross mineralogical and/or chemical composition of surface materials with spectrometers and multi-spectral scanners. Gross lithologies in simple distributions have been mapped experimentally with automated airborne systems.
   - (b) mapping of thermal infrared (IR) contrasts indicative of volcanic and geothermal areas, fresh-water springs, bedrock versus soil, and other differences in physical properties.
   - (c) location of buried karst topography using microwave radiometers.
   - (d) terrain mapping through persistent cloud cover with SLAR (side-looking airborne radar).
   - (e) night-time observations with suitable sensors (IR, SLAR, etc.).
   - (f) photography with low angles of illumination (and more expensively, SLAR) provides new data on texture and structure of surface materials.
   - (g) mapping of evaporites, phosphate and carbonate rocks using ultraviolet (UV) surveys.
   - (h) temporal resolution based on repetitive surveys of dynamic geologic processes such as erosion, landslides, volcanism, sedimentation, pollution, earthquakes, and for the monitoring of pertinent relief operations.
   - (i) in the more distant future, it may be possible to map vegetative stress resulting from geochemical anomalies related to ore deposits.
3. Benefits derived from improved planning based on remote sensing:-
   - (a) timely gross inventories can be made rapidly with the aid of synoptic space photographs, e.g., regional or national inventories of surface water, open-pit mining, tailings, dumps, etc.
   - (b) use of synoptic photographs or gross inventories to identify areas of change or interest, and thence to guide detailed analyses by airborne or ground methods, e.g., the geologist can see at a glance the relation between the area of interest and its regional setting, and thus optimize his selection of localized targets for detailed exploration.
   - (c) analysis of contemporary terrain conditions, freeze-up and break-up, etc., in planning field work, construction, transportation, land use, etc.
   - (d) synoptic orthophotographs can be used as small-scale base maps with high information content.

HISTORY OF CANADIAN DEVELOPMENTS IN REMOTE SENSING

Remote sensing has long been used by many government agencies, industries, and universities in the study of resources and the physical environment. Aerial photography has been the primary application, if exploration geophysics is excluded. Myriad applications are found in the practice and research of scientific disciplines ranging from archeology to zoology.

The late Professor H. L. Cameron was one of the first Canadian geologists to become aware of the possibilities of synoptic, high-altitude photography and other methods of remote sensing. By the early 1960's, he was using synoptic and time-lapse photography to measure the velocity of water currents, clouds and ice packs using photographs obtained from high-altitude aircraft and satellites. About the same time he used SLAR (side-looking airborne radar) and PPI (plan position indicating) radar for mapping geological structure. He later studied early space photography for NASA and was responsible for awakening the interest of Canadian geologists to the potential of remote sensing. Canadian support for his work was irregular, being distributed through several provincial and federal agencies. Casual interest aroused therein grew into a few fuller programs of research, especially in the federal government. With the notable exception of Barringer Research Ltd., of Rexdale, Ontario, there has, until recently, been little pertinent research in Canadian industries and universities.

In the federal government, remote sensing was fostered by the resource-oriented agencies that made extensive use of aerial photographs and by those agencies concerned with satellite photography. Geologic applications were investigated primarily by the Geological Survey of Canada. In 1965, the Survey contracted with H.R.B. Singer Inc. of State College, Pennsylvania for an experimental survey of parts of southeastern Ontario with a then-classified airborne IR scanner. The results of this confidential survey were most encouraging for the mapping of water phenomena such as currents, ground-water outflow and thermal effluents. In 1967, through cooperation of the Defence Research Board, the National Aeronautical Establishment and the Geological Survey of Canada, an airborne infrared scanner was purchased for experimental surveys. Initially, the whole operation was classified but most of the imagery was declassified subsequently. Cooperative investigations of water, soil, forest and rock phenomena were then carried out in a developing program with several government agencies and universities.

The Geological Survey attempted to obtain, through military channels, high-resolution space photography of Canada. However, the only return was limited U-2 coverage of parts of southern Ontario which was poor in quality and extensively obscured by cloud. In addition, 70-millimetre photography was obtained using CF-100 aircraft at altitudes of about 45,000 feet. These photographs served to emphasize the value of synoptic, high-altitude coverage. They also pointed out the fact that the Canadian military and space authorities were unable to provide the technologic impetus that was fostering the rapid development of remote sensing in the United States.

At present (1969-1970), the federal government is attempting to plan and coordinate Canadian research in remote sensing. In 1969, under the direction of Cabinet and the chairmanship of Dr. J.M. Harrison, an Interagency Committee on Resource Satellites and Remote Airborne Sensing was established to focus the pertinent interests of all the different agencies and departments in the federal government. It is supported by a Program Planning Office (PPO), directed by Dr. L.W. Morley. The PPO is an interim organization that will submit, in 1971, a report and recommendations for a national program to meet government, industrial and academic needs for remote sensing in Canada. To further this objective, the PPO has set up technical working groups (including a Geology Group) with appropriate and broad representation. In addition, the PPO will manage certain urgent projects to help prepare Canada for the launch of NASA's Earth Resources Technology Satellite in 1972.

PRESENT LEVEL OF ACTIVITY

A well-established industry based on aerial photography has been operating for many years in Canada and around the world. Air photos are widely used by Canadian geoscientists for planning, locality recognition and base maps, and for mapping the more obvious geological phenomena. However, there is little contemporary research directed to the interpretation of subtle geologic features, e.g., reflective characteristics of rocks, effects of the geometry of viewing, etc.

While interest in other methods of remote sensing has increased in Canada, especially since 1965, there has not been a concomitant rise in related geologic research. The few contemporary research projects concerned with geologic interpretation of remotely-sensed data are inadequate, despite some sizeable investments. This inadequacy results primarily from a restriction in funding. Thus, one of the early leaders, the Geological Survey of Canada, has reduced its involvement in this field of research.

With respect to sensor technology, the level of activity is increasing. One of the most advanced private Canadian developers of remote sensors is Barringer Research Limited. Their imaginative ideas and developments in the field of remote sensing and monitoring of air pollution have been supported in part by NASA.

Because of the rapidly increasing interest in remote sensing, it would be unwise (for fear of significant omissions) to attempt to list here all the organizations that are concerned with or engaged in remote-sensing research. Such a review of Canadian capabilities is one function of the Program Planning Office referred to previously.

Much of the Canadian knowledge and expertise about remote sensing is due to the considerable help and interest of the United States Geological Survey and NASA. A major technical input is provided by the meetings and published proceedings of symposia on 'Remote Sensing of Environment', which have been presented periodically since 1962 at the University of Michigan.

WHERE IS INCREASED ACTIVITY NEEDED MOST?

Major benefits from remote sensing have been predicted by many diverse and knowledgeable technologists. These judgements are based on two, as yet unvalidated, assumptions:-
(1) the availability of a reliable, economic, nonphotographic, remote sensing system; and (2) the availability of automated facilities and techniques for

processing and interpreting the data. In these areas, it is not possible to separate the geologic aspects from the inherent, multidisciplinary totality.

A reliable, economic, remote sensing system depends on significant, but feasible, advances in interpretation and use as well as in sensor design and development. The need for fundamental research into the radiative properties of rocks, soils and the atmosphere has already been mentioned. Equally important is increased thorough flight-testing of the sensors over calibration sites, i.e., test-areas that have been intensively studied on the ground. Without this increase in understanding, the sensing systems will be of little value to potential Canadian users, despite important advances in instrumentation.

The requirements for automated processing and interpretation are poorly defined. The analog format of photographs temporarily reduces the data-handling problem compared to digitization because a vast amount of data is compressed into a single image. Further, compared to conventional aerial photography, small-scale photographs from space and hyperaltitudes will require less rectification and mosaicing, resulting in significant cost reductions. A large volume of analog data is expected to follow the introduction of systematic remote-sensing surveys. Severe constraints to the program can be foreseen in a world-wide scarcity of skilled interpreters and a need for additional training and facilities. Ultimately, the volume of analog data will necessitate the incorporation of automated procedures for processing and interpreting data into the survey system.

Other sensors, and perhaps ultimately the imaging sensors, will generate data in digital form. For such data, a highly sophisticated technology has already developed to meet many processing and handling requirements although, again, the volume of data may cause severe blockages.

The full realization of benefits from aerospace surveys will require a major program of research and development in the area of data processing and interpretation. NASA and other user agencies are supporting American studies to define pertinent techniques, hardware and software, and to estimate costs. Enormous quantities of data are expected from Earth-orbiting satellites. Clearly, much must be done to develop the sophisticated systems to filter out the useful data and interpret it for the optimum management of the human environment.

Thus, the two major areas requiring increased activity are:-

(1) development of fundamental skills in interpretation;
(2) development of automated facilities for processing and interpreting large volumes of data.

Other related needs are:-

(3) acquisition or development of relatively inexpensive platforms for testing and operating sensors, e.g. aircraft, ballons or drones;
(4) coordination and training of ultimate users and recognition of new applications;
(5) conception, development and testing of new or improved sensors and systems;
(6) application of remote sensing to further economic and social development around the world.

TRAINING REQUIREMENTS

A major constraint on the application of remote sensing technology is the relative scarcity of interpreters in Canada and abroad. Most contemporary airphoto interpreters are already employed in ongoing programs of resource agencies. These same agencies will also be major users of other remotely-sensed data. Their interpreters could be trained to handle the new data, but only at some sacrifice to the agencies' ongoing missions.

Few, if any, educational institutions in Canada are planning the multidisciplinary programs that are essential to training interpreters of remotely-sensed data. A few centres are developing in American universities. Canadian progress in aerospace surveys will require many special interpreters with a strong background in several resource-based disciplines. In addition, a lesser number of sensing specialists will be required with a strong background in engineering physics.

The essential education and experience takes years to attain, and the development of a fully operational cadre of specialists in remote sensing is likely to require a decade or more. A need for personnel in development studies already exist, requirements for airborne remote sensing are imminent and will increase when experimental space surveys of the Earth take place in two or three years. The time for training is now. Schools of geology and geophysics, as well as of agriculture, forestry, hydrology, and other resource disciplines should include these broadly-based needs in their curricula.

MAJOR OBJECTIVES AND FUTURE TRENDS

For Canada, a most important and urgent objective is the application of remote sensing to geological mapping and mineral exploration in the vast, poorly-known northern lands, especially the 'barrens' where remote sensing of geology would be most effective.

The great distances between sensor and the Earth are inherent limitations on spatial resolution and recovery of detail. For example, remote sensing from satellites will have little application to direct prospecting for minerals. However, the synoptic views of satellites will comprise a major input into initial reconnaissance, regional exploration and ultimate management of mineral resources. A consequent demand for detail and data from ground and airborne surveys can be expected to increase with the introduction of space surveys.

Aerial and ground surveys are essential to our understanding of the remote sensing systems and the significance of the observations. In preparing for space flights, airborne tests are used to select useful parameters, to assess techniques of observation, to define applications and to prove sensing systems under operational conditions. The glamour of the space age has glorified the acquisition of data by satellites. But the real benefits of Earth-oriented space surveys will be achieved only through interpretation of the data in terms of the earth's surface. Here, in the near future, man will systematically use aerial and ground surveys to follow up space data in the same way that he now uses ground surveys to verify aerial observations.

The future application of these space-related technologies will assuredly contribute to the welfare of mankind through a better knowledge of many environmental problems. In just the past decade, meteorological satellites have improved weather forecasting, and communications satellites have brought a new dimension to human relations. In a similar way, earth resources satellites will be the future stimuli for economic and social development. The achievement of such benefits, however, will depend on advances in remote sensing technology, on the skills of interpretation and perhaps most important of all, on human cooperation.

CONCLUSIONS

1. The present level of research into the geoscience aspects of remote sensing is inadequate; forecasts for the immediate future are equally dismal. For several decades, Canada has been a leader in the development of airborne geophysics. Thus, Canada has the interests and capabilities to make significant advances in remote sensing and feedback to geophysics. It is particularly distressing, therefore, to observe that previous leaders, such as the Geological Survey of Canada, are reducing their participation in remote-sensing research because of austerity.
2. The predicted geological benefits of remote sensing are sufficiently great and varied to warrant a more thorough evaluation in the Canadian context. Involvement of industry in contemporary remote sensing undoubtedly will lead to the development of industrial capabilities and expanded use, despite the major geological constraint of sensing only the surface of the Earth.
3. There is a very urgent need in Canada for policy formation and organization of the research directed toward remote sensing from aircraft and satellites. Remote sensing is inherently multidisciplinary and thus cuts across accepted boundaries of knowledge and organization. A national plan and policy is therefore essential in order to consider the means of focussing effort, centralizing major facilities for sensing, flight and processing of data, and of minimizing the overall cost.
4. There are many needs and great opportunities for Canadian research into the interpretation of remotely-sensed data. Interpretation is the key to the application of remote sensing in the vital national interests of resource exploration and management.
5. Canadian scientists and engineers should prepare themselves, individually and collectively, for pertinent participation in remote sensing activities. Airborne remote sensing is on its initial upsurge and space surveys are but a few years away. Many more scientists and engineers need to acquire a fuller understanding of the problems and potential of remote sensing so that Canada will obtain a maximum benefit.
6. Remote sensing is but one example of the need for educational institutions to experiment with multidisciplinary curricula and research. While there will be no lessening in the need for discipline-oriented specialists, e.g., geologists, physicists, chemists, etc., there will be an increasing need for problem-oriented specialists with a broader base in one or more related disciplines, e.g., geologists with a working knowledge of forestry and/or hydrology. Consideration should be given to the means

of achieving and recognizing multidisciplinary education in both the science and the art of resource management.

RECOMMENDATIONS

As a consequence of the above conclusions, the following actions are recommended:-

1. The level of geological research pertinent to remote sensing should be increased enormously. The most important areas for investigation are:-
   - (i) radiative and absorptive properties of rocks, soils and the atmosphere;
   - (ii) establishment and intensive study of calibration sites, or test areas;
   - (iii) automated techniques of processing and interpreting data, especially for large volumes in both analog and digital format;
   - (iv) the development of computer-graphics techniques to portray the parameters of geoscience. Manual drafting methods cannot cope with the magnitude and many forms of data displays;
   - (v) definition of geologic needs for remote sensing and development of pertinent sensors and systems.

2. Remote sensing centres should be established at selected locations across Canada to provide for optimum exploitation of national capabilities and to meet requirements for regional uses. Because of the multidisciplinary aspects and the expense of remote-sensing research, the team approach is essential.

3. The application of remote sensors to geological problems should be considered on a systems basis, and not as an isolated tool. Most sensors are an integral part of a system that involves specific platforms and special techniques of processing and interpreting the data. As in the case of geophysics, visual interpretations will provide information about gross contrasts and phenomena, but there is a greater need for intrepretation of subtle features.

MARINE GEOPHYSICS

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DEFINITION

Marine Geophysics is the study of the physical properties of the material forming the earth's crust and mantle in the marine environment. It encompasses the complete field of geophysical investigations, including -

(i) Seismology. Refraction, reflection and dispersion wave measurements are made to determine the structure of the crust and upper mantle beneath the oceans. The first two can be carried out at sea but the last requires fixed land-based stations studying the propogation of waves through oceanic crust and mantle.

(ii) Gravity. Both continuous shipborne measurements and bottom gravimeter measurements provide important information for the interpretation of seismic data and the mapping of crustal structure variations.

(iii) Magnetism. Underway measurements of total field provide important clues to the history of the ocean floors and evidence for theories of ocean floor spreading and continental drift. Station measurements of the temporal variations in the earth's field provide information on the conductivity structure of the crust and upper mantle.

(iv) Bathymetry. Precision sounding provides much information on the ocean floor. Micro-topography can be studied through the use of deep-sea photography.

(v) Bottom sampling. Although perhaps better included under marine geology, bottom sampling provides rock and core samples, the analysis of which provide information on the physical properties of the rocks of the crust. These properties are used in interpreting gravity, magnetic and seismic data.

(vi) Heat Flow. Oceanic heat flow measurements provide information on the heat transfer processes occurring within the earth. They may provide evidence to support or refute such ideas as convection currents within the mantle used to explain sea flow spreading theories.

The marine environment has imposed serious limitations on the methods of direct sampling so that the studies have necessitated considerable development and adaptation of the conventional geophysical techniques employed on land. It has also emphasized other problems easily overcome on land, such as navigation and stabilization of the measuring platform. The high cost of ship time has required considerable research into efficient data acquisition and processing techniques.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Marine geophysical studies are of vital importance to an understanding of the planet on which we live since more than 70 per cent of the earth's surface is covered with water.

Probably the most significant fact which emerged from research in the Earth Sciences was the discovery that the crustal structure beneath the continents was markedly different from that beneath the oceans. This was first deduced from seismic refraction investigations and verified with gravity measurements. This, plus the discovery that, on the average, the heat flow through the oceanic crust appeared to be the same as that through the continental crust, led to greatly increased interest in oceanic crustal studies.

The development of equipment for making accurate geophysical measurements at sea led to the description of the major morphological divisions of the ocean floor, and the discovery of the continuity of the mid-ocean ridge system. Further study of the mid-ocean ridge system, using available geophysical techniques, has shown it to play a fundamental role in the evolution of the earth's crust. Deep seated processes within the earth seem to be fundamentally associated with this ridge system. How these influence the formation of the deep ocean floor, the interaction of the oceanic and continental crust, and the possible differentiation of the continental crust, remains to be clearly defined. Marine geophysics will continue to play a major role in better understanding these fundamental problems.

The immediate importance of research and development for Canada is the discovery and development of mineral resources on the continental margins. As of February 28, 1969, a total of 5,194 Canadian oil and gas permits involving 370,428,851 acres were held off the east and west coast, and in the Hudson Bay. Eventually, as deep sea mining techniques become economical, these interests will extend off the continental shelves into the deep sea areas. A clear understanding of world tectonics, and particularly the relationship of the mid-ocean ridges to the continental masses, is important to fully develop these offshore resources. Data obtained by marine geophysics research groups is very highly sought after by commercial exploration companies. For example, the extremely good geophysical data provided by the combined hydrographic/geophysical surveys conducted by the Bedford Institute provides very detailed information on the eastern continental margins. The quality of this data is probably not bettered anywhere in the world.

Measurements over deep ocean regions help define the earth's gravity and magnetic fields. The former is vital for the accurate prediction of satellite and rocket orbits. Magnetic field measurements supply new data for the evaluation of theories on continental drift and ocean floor spreading. Data is also supplied to the World Magnetic Survey to provide information for the description of the earth's magnetic field and its secular variation.

Detailed surveys over deep ocean features such as the Mid-Atlantic Ridge provide vital information on tectonics of these regions necessary for a detailed understanding of the earth's crust. This in turn provides information on the formation of the continents and the processes occurring within them with applications to earthquake prediction and an understanding of volcanic activity.

HISTORICAL DEVELOPMENT

Although a considerable amount of earlier work had been done over the oceans, mainly in the disciplines of gravity and magnetics, marine geophysics in its present form only developed after the Second World War. The need to detect submarines led to the development of the fluxgate magnetometer. This made continuous magnetic measurements possible at sea. Development of sonar equipment led to the construction of accurate deep sea sounders and equipment for seismic refraction and reflection work. Gravity measurements at fixed stations had been carried out some twenty years earlier using pendulum instruments in submarines, but not until the late 1950's was it possible to make continuous measurements from a surface ship underway. Geological sampling of the sea floor has been carried out for several centuries. With the increased interest in the ocean crust, some effort has been made to improve the techniques to obtain samples of rock in situ, and longer sediment cores. Heat flow instrumentation was developed because of this technique's direct relevance to proposed deep seated processes within the earth, e.g. convection currents. Seismic techniques have always played an important role in geophysics and some of the strongest evidence for theories of oceanic crustal structure has come from the seismic work carried out at sea.

In all aspects of marine studies two major problems have had to be overcome because of the hostile environment. Equipment to carry out the measurements has had to be developed to a greater sophistication than that required for land geophysics. This development has then led to the need for more sophisticated data handling and processing procedures to efficiently use the data produced. One outcome of this has been the adaptation of the small computer for use at sea and the development of software for on-line data processing. All these developments have been essential to the efficient use of research vessels.

Marine Geophysics is a very new field for Canada. Research and development began with the magnetic surveys off the East Coast carried out by the Geological Survey. Industry became involved in offshore mineral exploration in the early 1960's. University activity commenced on the East Coast around 1963 and some time later on the West Coast.

In 1963 the Canadian Government initiated a continuing marine geophysics program on the East Coast with the formation of the Bedford Institute. The program at the Bedford Institute has developed along two main fields of study. The first of these involves the study of the continental margin of eastern Canada. This work has been closely integrated with the bathymetry surveys of the Canadian Hydrographic Service, greatly increasing the value of the hydrographic surveys and providing comprehensive data for commercial offshore exploration companies.

The second field of study has been that of the deep ocean structure, and particularly the Mid-Atlantic Ridge. This project has been carried out with the cooperation of a number of universities and other government agencies. Because of the wide range of disciplines involved in such a project, close cooperation with other institutions is of vital importance.

University and other government agencies have been involved in seismic studies of the eastern continental margin, studies in Hudson Bay and in the Gulf of St. Lawrence. More detailed investigations of mainly local importance have been carried out by the provincial research establishments.

University research in marine geophysics has increased through the support offered by the federal government in terms of ship time and loan of equipment. Research on the Great Lakes has been in progress for some time, particularly in university programs. This work will increase with the development of the Canada Centre for Inland Waters. In recent years, marine geophysics has been introduced to the West Coast of Canada. Some seismic and magnetic work had previously been done, but the first attempt at detailed survey work was probably that of Dominion Observatory in 1968.

Many mineral exploration companies are involved in geophysical surveys of the continental margins. The approximate expenditure by industry in the search for oil and gas offshore in 1968 was over 60 million dollars. However, the data obtained by exploration companies is of a proprietory nature and not generally available till long after the survey is completed. This seriously limits the usefulness of the data for scientific purposes.

PRESENT LEVEL OF ACTIVITY

Present studies can be subdivided into surveys of continental shelf areas to provide information about potential resources; research in regions where active formation of ocean bottom may be occurring, such as the Mid-Atlantic Ridge; and the design and evaluation of new methods to be used in gathering, processing and interpreting data. To aid in these studies further development of equipment for continuous underway geophysical measurements, seismic reflection and refraction investigations, and deep-sea navigation is in progress. The problem of accurate deep-sea navigation is probably the most important factor in the continuing effort of providing more accurate geophysical data. In an attempt to answer this problem, research into the capabilities of long range navigation aids such as VLF-OMEGA and satellite navigation is in progress. Techniques to make measurements of the fluctuations with time of the electric and magnetic fields of the earth at the bottom of the ocean are being developed. These measurements are to provide information on conductivity and temperature distribution within the deeper layers of the earth. Trial experiments with the equipment have been carried out over the last two years.

Although there has been an increase in interest among commercial firms within Canada to develop geophysical techniques the major part of this research is being carried out by universities and government agencies.

With the development of the small computer which can be installed and operated on board ship it has become possible to carry out preliminary processing of geophysical data on board within a few hours of data acquisition. This has increased the efficiency of surveys and enabled preliminary corrected profiles and contoured charts to be made available immediately for interpretation on return of the ship to port. A further development to use small computers for on-line control of geophysical data acquisition for a number of specialized projects is underway.

The problem of storage and retrieval of geological and geophysical data has received considerable attention in the last few years. With the common use of automatic data logging equipment for collecting geophysical data at sea there has arisen the major problem of storage and retrieval of data for subsequent analysis, and the associated problem of data exchange between institutions. This is a particularly important problem for the coordination of research carried out by government agencies and exploration companies on the continental margins. There is a very definite need for the establishment of regional data banks which are accessible by institutions concerned with research in the fields concerned.

Studies on the continental margins has increased enormously in the last few years, particularly among the exploration companies and government agencies. Universities on both the east and west coasts are becoming increasingly involved in marine geophysics programs. On the east coast at least, this involvement has been at a high level for some years.

Integration of geophysical survey techniques into the hydrographic survey program on the east coast has ensured continuing high quality geophysical surveys of the eastern seaboard of Canada. The data provided by these surveys will be of considerable value both for scientists concerned with geological interpretations of the eastern regions of Canada, and exploration companies concerned with resources on the continental shelf.

Studies of the mid-ocean ridge system have caused widespread interest among earth scientists. Expeditions to the Mid-Atlantic Ridge have always attracted scientists from a number of institutions both inside and outside Canada. There are presently a number of research projects within universities and other Federal Departments which have resulted from these expeditions. A wealth of knowledge can be gained from this type of coordinated effort spread over a number of disciplines, in different institutions.

NEED FOR INCREASED ACTIVITY

The greatest need at present is to develop sophisticated data handling techniques to ensure that the full potential of existing data collection machinery is realized. Two immediate fields of development are necessary.

1) Increased sophistication of shipboard data processing techniques to provide facilities for 'on the spot' assessment of data and to reduce the time lag before the data is available.

2) Development of efficient shore-based data storage and retrieval systems so that any portion of available data can be quickly, efficiently and routinely disseminated. With the rate at which data can now be collected through the use of automatic data acquisition systems it is essential that even a small geophysics group have access to a computer-based data storage system.

To ensure that the high quality of data presently available on off-shore surveys will also be obtained on future deep-sea and Arctic surveys it is imperative that more effort be put into developing a sophisticated navigation system using satellite navigation to provide absolute control for referencing other aids used for on-line survey control. Such a system would improve the accuracy of measurements on deep-sea surveys to that obtainable on off-shore surveys controlled by accurate short range navigation aids.

An important addition to the integrated hydrographic/geophysical survey program would be continuous seismic reflection profiling. For this to be incorporated on such surveys requires a considerable improvement in the present techniques to enable good penetration to be obtained at the required survey speeds of 13 knots. This is a field where the use of a computer for on-line correlation analysis should prove very useful.

Although the immediate commitments should be directed towards the above objectives continued research on all levels of marine geophysics is necessary if Canada is to provide a major contribution in this field.

TRAINING

A marine geophysicist is an oceanographer and training of oceanographers can be carried out only at sea. The successful member of the team (be he a technician or scientist-in-charge) must have a peculiar blend of special attributes: technical competence and confidence in his own ability to solve problems under difficult environmental conditions, deep involvement with the subject which will sustain him through periods of hardship while working at sea, pleasant and cooperative personality which will make him a cheerful companion during prolonged confinement on board ship, a broad knowledge of auxiliary subjects from meterology to seamanship which distinguish an ocean-going scientist from a land-based scientist. There are very few opportunities in Canada for formal training and development of these skills. The Institutes of Oceanography at Dalhousie and the University of British Columbia can train professional researchers of Masters and PhD levels. The operating personnel at the BSc level can be occasionally developed by follow-up of summer student employment. More direct involvement of university graduate students in continuing research projects would provide some of this training, and at the same time, relieve some of the shortage of junior scientific personnel in most research institutions.

The greatest need is at the technician level where there is no potential source of personnel. At the present time, all the technicians must receive on-the-job training. Technical Institutes are a source of technologists who have pursued specialized courses, for example, in electronics, chemical and mechanical technology. As a result of this specialization it has been found that technologists recruited into the marine geophysics research area lack sufficient interest in, and are not easily adapted to, the broader scientific work. However it is encouraging to note that the Community Colleges of Applied Arts and Technology in Ontario are considering offering a course in physics technology.

MAJOR OBJECTIVES AND FUTURE TRENDS

The most important objective is to develop efficient data storage and retrieval facilities for marine geophysical data collected by government, university and commercial agencies. If maximum benefit is to be obtained from the enormous amount of data that can now be obtained on survey operations, and "ships of opportunity", it is imperative that this data be available to interested earth scientists. Such facilities would enable maximum cooperation with universities. It seems logical that these facilities can be housed within government institutions, but this will require considerable increase in personnel.

Future developments in equipment design will be to use digital techniques at earlier stages of signal processing and to provide on-line control of data acquisition through the use of specialized computers. Three fields in which this type of approach is immediately necessary are in the automatic acquisition of gravity, bathymetry and seismic data.

The greatest single problem in geophysical research in deep sea regions is the lack of navigation control. An important objective in the immediate future should be to develop a sophisticated navigation system utilizing a variety of navigational sensors and calculating the best approximation to the true track by sophisticated filtering techniques. With satellite navigation commercially available it is now possible to consider such a system. Both hardware and software will be very complex. Considerable research into the precise needs of the oceanographic community, and the available systems, is required before development of such a package is possible.

CONCLUSIONS

1. More effort should be made to coordinate offshore surveys being carried out by Government agencies, Universities and Industry. A first step would be accomplished by reducing some of the artificial barriers existing which limit the exchange of data.
2. The integration of geophysical surveys with the bathymetry surveys carried out by the Canadian Hydrographic Service has proved very successful. Expansion of the geophysical program to include seismic reflection profiling and time for refraction measurements should be encouraged. To ensure that the most efficient use can be made of the survey time available, it is important that hydrographic personnel be trained in the requirements of geophysical surveys. The data obtained on these surveys must be made available to all interested institutions within a year of the survey being completed.
3. The development of regional data centres for marine geophysics data should be encouraged. These centres would be capable of supplying data to outside organizations through a national data bank.
4. The expansion of marine geophysics in Canada and the establishment of an active Federal Laboratory on the West Coast is recommended. Such a laboratory would provide an expansion of marine research on the West Coast and could promote coordination of programs of interested Institutions. The introduction of government facilities would provide support for the precise surveying required in much geophysical work.
5. Marine geophysics is an expensive field of research because of the sophisticated equipment involved and the requirement of ship time. Support for university programs must come from Federal Institutions. It is important that personnel and funds be available for this support.
6. Because of the international nature of marine geophysics, it is important that support for overseas travel to conferences and meetings be maintained.

SEISMOLOGY AND PHYSICS OF THE EARTH'S INTERIOR

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DEFINITION

Seismology is the study of earthquakes and the earth by means of mechanical waves from earthquakes and other energy sources. Since the study of elastic waves from earthquakes has been in the past the principal contributor to our knowledge of the earth's deep interior (its mantle, core and inner core), seismology is inseparably related to the physics of the earth's interior. The International Association of Seismology and Physics of the Earth's Interior (of IUGG) reflects this close association. All the university departments and government bodies in Canada and abroad use the broader definition in their thinking.

Accordingly, in this brief report I make no distinction between "Seismology" and many aspects of the "Physics of the Earth's Interior", except for geothermal studies for which a separate background report is being submitted. It should, however, be clear that studies of the earth's interior are by no means the exclusive domain of seismologists: for example, isostatic studies are undertaken by geophysicists specializing in gravity studies and geomagneticians are vitally concerned with the earth's outer core. Nevertheless, the principal advances in the past have been derived from or in association with seismology, and there is no evidence to suggest this will change if a sufficiently broad view of the earth is taken. The relation with tectonophysics is of course extremely close: seismology is an important contributor to the new global tectonic picture which is now emerging.

Reflection and refraction seismic methods dominate petroleum exploration geophysics. Although a separate background paper is being prepared in exploration geophysics, this most important economic application of seismology is also treated herein within the context of the scientific discipline as a whole.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

The continuing study of seismicity is a social and economic requirement because of the considerable loss of human life, extensive property damage, and long-term political, economic and social effects produced by devastating earthquakes. A recent estimate showed that during the last 160 years, 13,000 people per year were killed by earthquakes and the annual property damage for the same period was $1.5 billion.

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Documented studies of the Seismology Division, Observatories Branch, incorporated in the National Building Code Revision of 1970, indicate that the earthquake risk is high in important areas of both eastern and western Canada. Rapid economic development and high-rise construction in Quebec City, Vancouver, Victoria and Montreal, and the construction of dams, bridges, nuclear and other power plants, port facilities, etc. demand an increasing body of knowledge concerning the activities and characteristics of Canadian earthquakes to avoid or minimize national disasters. Canada also contributes to the Pacific Tsunami forecasting system: the last major tsunami striking Canada in March 1964 did more than $5 million of damage. Furthermore, evidence in recent years from experience in Rhodesia (the Kariba Dam) and in India (the Koyna Dam) suggests that incipient seismicity in a region can be triggered by crustal loading from artificial lakes. This is a subject of considerable economic concern in western Canada.

An important political problem between nations involves the reaching of agreement on measures of controlled disarmament. One of the problems most discussed is the question of a ban on further underground nuclear explosions as an essential first step in armaments limitation. Failure to agree on a test-ban treaty is largely a consequence of failure to agree on acceptable methods of verification. The only techniques for the detection and identification of underground nuclear explosions are seismological. A continuous R&D program into the problems of detection and identification of underground nuclear explosions is under way in many of the technologically advanced countries of the world, with some impressive results to date. Such a program is required in Canada for purposes of national security. It can be regarded as a moral obligation of a government committed to seeking agreement in the field of disarmament.

Since the scientific problem is partly one of distinguishing between the signals from earthquakes and explosions, almost any activity in seismology is more or less germane to the problem: the enormous expansion of seismological effort in the United States and elsewhere in the last 10 years owes much to funding supplied because of this political problem.

In Canada, an active program in this field has been promised by the government in international negotiations in the Eighteen-Nation Disarmament Conference in Geneva, and elsewhere. This arises from the need for independent expert advice from countries not producing nuclear weapons, from the government's expressed interest in promoting measures of controlled disarmament, from the availability of talent, experience and technical infrastructure to make a worthwhile contribution, and from the excellent geographical position of Canada. It undoubtedly is an extremely significant feature of R&D in seismology in this country.

Many modern studies in seismology involve modern techniques of handling vast amounts of data by digital techniques and the tricks of extracting low-level seismic signals from ambient natural noise. R&D in this field has considerable economic application in seismic prospecting for petroleum. The converse is of course true: R&D in seismic petroleum exploration can often usefully be applied in the pure aspects of seismology.

In Canada in 1967, seismic exploration in the petroleum industry comprised 1,048 seismic crew-months, 14 crew-months being offshore seismic work. The estimated cost for contract services was $67 million, of which 7.5 per cent was for marine work. This figure should be increased by about two and a half times to cover data processing, overhead charges, interpretation, etc. The expenditures in seismic petroleum exploration are approximately five times larger than those in all other petroleum and mining exploration geophysics fields. The procedures are becoming more sophisticated, and digital recording and data processing are becoming increasingly essential. For example, data processing costs alone for 1968 for oil exploration data obtained in Canada can be estimated at $8.5 million; all but about $1 million of this was spent in Canada, and the estimates exclude R&D costs.

Comparable sophistication in university and government R&D programs is essential in order to provide adequately trained manpower and to offset and balance the fact that most of the major petroleum companies maintain their research laboratories outside Canada. Although some research is done on Canadian problems in the United States, there is a tendency to apply the solutions to American problems to the Canadian scene, and this can often be ineffective.

R&D in seismology can and will further contribute to our understanding of the structure of the earth's interior. From the details of boundary layers inside the core, to a major understanding of crustal units, all parts of the earth can be probed by naturally or artificially generated seismic waves. It is probably fair to state that the major features of the earth models have now been defined and can often be explained; however, surprises still await us, and in recent years lateral variations to depths of a few hundred kilometers have been discovered and in some cases well explored.

Seismic results need integration wherever possible, both within the discipline and with the results and observations from other geophysical disciplines. Some slow but steady progress in this area can be noted.

The upper mantle and crust are studied actively by seismologists using a variety of techniques. R&D in seismology is essential to an understanding of three-dimensional geology beyond shallow depths, which is of long-range economic significance. It is certain that seismic R&D will continue to contribute to the evolution in geological concepts arising from present studies of convection, ocean floor spreading, and continental drift, i.e. all lithosphere mechanics.

R&D in seismology is extremely significant in the study of the ocean floor, the oceanic crust and mantle, the distribution of sediments, and the structure of the continental shelf. Studies at sea using sophisticated equipment and techniques represent one aspect; the study of earthquakes, location, energy and mechanism, which occur under the ocean and island areas are also fundamental. The continental shelves with their potential resources are of the greatest economic importance to Canada.

PRACTICAL APPLICATIONS

The practical applications of seismology may be briefly summarized as follows:

1. To minimize the effects of earthquakes on the Canadian people and economy, to provide practical advice on earthquake risk in Canada, and to provide basic scientific data for improved earthquake engineering studies.

2. To develop methods of detecting and identifying underground nuclear explosions.

3. To explore Canadian petroleum resources.

4. To contribute to an understanding of the evolution of the earth (particularly its crust and upper mantle) as a fundamental aid in all resource development including resources under the sea or ice cover.

5. To so understand the dynamics of earth processes that earthquake prediction may ultimately be possible, and possible methods of earthquake prevention usefully explored. In this area, most geophysicists are undoubtedly motivated by curiosity to increase understanding, which may lead to these practical results.

HISTORICAL DEVELOPMENT

Earthquakes were known and feared by ancient man. Early historical records contain references to earthquakes as far back as 1800 B. C. In the second century A. D. , the Chinese had an official earthquake observer (Chang Yen) and had a crude strong motion seismometer. In the mid-1870's John Milne designed the first seismographs, and by the beginning of the 20th century a few seismographs were in operation throughout the world (in the British Empire, Japan, Italy and Germany). United States development was rapid in the first 10 years of this century.

By 1965, more than 500 seismic observations of varying capability were in operation throughout the world, and today there must be at least 600.

The first continuously recording seismograph was introduced into Canada at Toronto in 1897 by the Meteorological Service. In 1906 the Dominion Observatory began a seismic network, and in 1936 took over the remaining Meteorological Service functions in this field. By 1923, insensitive instruments (by modern standards) of one kind or another were operating in five locations in Canada. In 1928 the first seismographs were installed in the Lower St. Lawrence Valley for detecting local shocks. By the mid-1950's there were about 10 stations, mostly along the southern border of Canada but including the then most northerly station in the world at Resolute, on Cornwallis Island in the Northwest Territories. Instrumentation was not homogeneous, and few adequate long-period instruments existed.

In 1959, the federal government approved a plan to install about 25 first-order stations at intervals of approximately 500 miles throughout Canada, and this plan is now completed. The equipment and procedures are standardized and are entirely compatible with other major networks of the world. It provides a rich source of data on the seismicity of Canada, and meets Canada's international obligations very effectively in the exchange of seismic data including data from underground and underwater explosions.

In 1967, a program of updating and reassigning four second-order short-period stations in the active seismic regions of Canada began. In early 1969, only one station remains to be converted, and there are plans to extend and improve this local seismicity coverage.

In the period from 1963 to 1968, a network of strong-motion seismographs has been installed at 14 sites in the earthquake-prone zone of western Canada. This network is complemented by the installation of more than 40 seismoscopes in Vancouver and Victoria schools, across the sediments of the Fraser River, and in support of the strong-motion stations. In the eastern Canadian zone of high earthquake risk, the Division of Building Research of the National Research Council installed a network of six strong-motion seismographs and nine corresponding seismoscopes during 1966-68. Both networks are expected to expand in coming years to meet the requirements for adequate and economic earthquake-resistant dynamic design of structures, and to understand better the role of foundation materials in the earthquake engineering problem.

The medium aperture seismic array in Yellowknife, N. W. T., was brought into operation by the Dominion Observatory in co-operation with the Atomic Weapons Research Establishment of the United Kingdom Atomic Energy Authority between 1962 and 1964. The purpose was largely to undertake research into the detection and identification of underground nuclear explosions, though array seismology also provides a powerful tool for pure research studies in seismology. Between 1965 and 1968, a Canadian research group in this field has been established at the Dominion Observatory and, following early successes with a new concept of data processing, is now equipped with a modest in-house analog-digital-analog facility for array seismic research. It is planned to upgrade the array as personnel and funds permit, and a modest start has been made.

The determination of the structure of the earth from seismological studies of elastic waves (initially often the travel times) is an achievement of this century. Some milestones were the discovery of a crustal layer and the M (Mohorovicic discontinuity) in 1909, the publication of the Jeffreys-Bullen travel time curves (1939), and the discovery of the inner core in 1936. In addition, a fuller understanding of the mechanism of earthquakes has been reached, a number of magnitude scales devised and their relationship to energy release understood, dispersion has been explained and turned to good account in the determination of upper mantle structure, and the complexity of the upper few hundred kilometers of the real earth clearly proved by a variety of studies. Fundamental oscillations of the earth were first detected as late as 1957, and zero frequency seismology is only now leading to an appreciation of mass redistribution inside the earth, either following or partly preceding very large earthquakes. The first underground nuclear explosion took place as recently as September 1957; these, plus the digital computer, have ensured continuous and accelerated progress. Prior atmospheric explosions also contributed to seismological progress. Current studies of the entire character of the seismogram and anelastic studies are leading to a deeper understanding than can be achieved purely from travel times.

Reflection seismic methods have been in effective use as an exploration tool for less than 40 years: recent important and fundamental advances relate to the development of new sources for generating elastic waves, the application of statistical communication theory and filter theory to the problems of extracting useful signals from ambient noise, the development of digital recording techniques to take advantage of the above methods and the widespread and essential application of digital computers to process the data. The reflection seismic method has been successfully used in Canada to delineate folds and overthrusts of the western margin of the western Canadian basin, to locate reef fields, and to investigate productive areas at or near unconformities. The measure of success and rapid development can easily be seen in the figures quoted in the previous section.

University research in seismology has steadily expanded since the war, with a considerable increase in the early 1960's being attributed to the stimulus of the Upper Mantle Project and the support thereby generated. The present widespread level of activity is summarized below.

PRESENT LEVEL OF ACTIVITY

A review of the current Canadian situation in 1968 is as follows.

Considerable competence has been developed in the Observatories Branch in seismicity and microearthquake studies, in earthquake mechanism studies, in many aspects of array seismology including research into the detection and identification of nuclear explosions, in surface wave dispersion studies, in the synthesis of seismograms and crustal deconvolution, in instrumental systems development, in studies of the earth's core, in long-range refraction and deep reflection crustal studies (including theoretical studies), and in synoptic interpretation. Significant advances produced by this group include the concept and validation of multiple real-time processing of seismic-array data, the investigation of a body-versus-surface-wave criterion for the positive identification of nuclear explosions, the application of probability theory to seismic zoning, the evaluation and combination of P and S wave studies of earthquake mechanisms, the invention of the time-term method of seismic refraction surveying, and the extension of velocity profiles to great depth by a variety of interacting techniques, thereby illustrating lateral changes in the earth to a depth of some 500 kilometers.

In the Geological Survey of Canada, competence exists in shallow and intermediate range seismic exploration techniques and interpretation both on land and at sea, and well-logging activities. In addition, longer range seismic crustal studies have been undertaken.

At the Bedford Institute, competence is found in marine seismic studies, both shallow and deep, and this is strengthened by close working relations in the field of seismology with Dalhousie University.

In the Defence Research Board, strong particle motion studies are made near large explosions, cratering studies are undertaken, and the seismic properties of ice explored. The Board co-operates with the Dominion Observatory by operating a standard seismic station at Suffield, Alberta.

In the Division of Building Research of the National Research Council, earthquake engineering studies in a broad sense are undertaken by a small but expert group.

At least seven universities have appreciable and significant seismic programs of research under way. They have made significant contributions to the new tectonics and the theory of faulting, the extensive series of crustal studies off the eastern seaboard of Canada, in the Canadian Shield, and in the Prairies, elastic dislocation theory, the theory of seismic attenuation mechanisms, the excitation of the Chandler wobble by large earthquakes, deep seismic reflection studies, crustal deconvulotion studies on teleseisms and marine seismic studies. An incomplete listing of programs under way in 1968 is as follows.

1. Dalhousie University: marine and land shallow, intermediate and deep seismic sounding, studies of synthetic seismograms, theoretical studies on body wave propagation, a crustal tilt program, direct measurements of stress and synoptic geophysical interpretation.

2. Laval University: shallow and intermediate seismic exploration, and microearthquake research.

3. University of Toronto: marine and land shallow, intermediate and deep seismic sounding, seismic measurements on rocks, earthquake mechanism studies, model studies on fracturing, experimental and theoretical anelastic studies, dispersion studies, studies

of icequakes, studies of convection and synoptic geophysical interpretation including most important contributions to lithosphere dynamics and the new tectonics.

4. University of Western Ontario: seismic exploration, seismic refraction studies, earthquake probability studies, earthquake mechanism studies, the excitation of the Chandler wobble and predictive studies on large earthquakes, model studies on dispersion, studies of convection, synoptic geophysical interpretation and high pressure physics of rocks.

5. University of Manitoba: seismic exploration and deep seismic sounding techniques and interpretation.

6. University of Alberta: research into digital data acquisition, including a digital seismic observatory, crustal refraction and deep reflection studies, long-range mantle P wave studies, microseismic research, research into crustal loading and the possible generation of earthquakes, crustal deconvolution and synthetic seismogram studies.

7. University of British Columbia: interpretation of crustal seismic studies, sparker surveys, studies of the coda of P wave arrivals, crustal deconvolution, magnitude studies, studies of specialized filters, the excitation of the Chandler wobble, and predictive studies on large earthquakes, microseismic studies, earthquake engineering studies.

NEED FOR INCREASED ACTIVITY

Increased activity is desirable in local seismicity studies, in the study of the detection and identification of underground nuclear explosions, and in crustal seismological studies leading to a better understanding of the evolution of the crust and a better synoptic understanding of three-dimensional geology for resource development.

From the viewpoint of pure science, increased activity in the recording of earthquakes and research into the deeply persisting lateral variations within the earth will improve the accuracy of hypocentre locations. With an increased understanding of earthquake focal mechanisms (stress drop, slip, orientation of principal stresses) and anelastic studies (including fault creep), this will improve our knowledge of lithosphere mechanics and contribute invaluably to the new global tectonics.

A considerable Canadian contribution to most of these activities is being made by government agencies and universities, with adequate co-ordination ensured through a strong Associate Committee on Geodesy and Geophysics of the National Research Council, and through the Canadian National Committee on Earthquake Engineering. Given the financial sources, adequate increased activity in the above fields would inevitably follow.

The author believes that increased research activity in seismic exploration in Canada by the petroleum industry could reasonably be expected and should be encouraged. Although seismic exploration is partly universal in invention and application, and although problems in Canadian operations are often found elsewhere, Canadian R&D should increase in the petroleum exploration field because of the economic significance of this field to Canada and the occasional inadequacy of an imported technology and experience. Research into seismic energy sources and their evaluation, into the design of field experiments for difficult problem solutions, into communication and filter theory and into digital processing generally are all required.

TRAINING NEEDS

The government agencies have traditionally recruited research staff from both Canadian universities and abroad; demonstrated ability to conduct first-class research in geophysics and the general training received in graduate geophysics have in general been more important than the details of graduate training in seismology available at any one university. Some government agencies have given specialized training in various seismological areas to foreign government employees under the aegis of External Aid.

Approximately 600 professional earth scientists are employed in oil exploration geophysics in Canada, or at least a factor of ten times more than the number employed in government and universities. The author understands that the universities are sometimes criticized by the oil industry on the grounds that present methods of teaching geophysics are too traditional, and that much more practical and interpretive geophysics should be included in laboratory or field programs. However, any industry with a rapidly changing technological base will inevitably have to provide in-house postgraduate training more or less continually to professional staff. Since I understand these in-house training programs have been successful, and the results in western Canada certainly suggest this, this appears to reflect favourably on the grasp of fundamentals and basic geophysical training acquired by geophysical graduates from Canadian universities. It therefore appears to the author that the relative lack of facilities and perhaps encouragement to undertake postgraduate university research in exploration geophysics is a more serious criticism, which the industry itself might cure by a positive program of financial support to universities and by presenting the picture of a good potential employer.

MAJOR OBJECTIVES AND FUTURE TRENDS

The most important objectives are a full understanding of the physics of the earth's interior which would:

1. Explain global tectonics (i. e. the fundamental processes which have shaped and are shaping the crustal features of interest to geologists).

2. Explain the mechanism of earthquakes and, hopefully, lead to the prediction or prevention of earthquakes, most probably in partial combination with other geophysical disciplines. I include in this the very important problem for Canada of explaining patterns of seismicity (which can include occasional large earthquakes) in western and eastern Canada and parts of the Northwest Territories.

3. Allow increased and more effective petroleum and mineral resource development by increasing the efficiency of techniques of determining subsurface structure.

4. Explain the lateral variations of the lithosphere and asthenosphere and its relation to (1) above, and the complete internal structure and evolution of the earth and other planets.

Future general trends will undoubtedly include increased emphasis on obtaining a wider frequency band of elastic wave information (from zero frequency seismology to high frequency volcanic tremor work) and increased theoretical and experimental emphasis on such parameters as attenuation, strength, creep viscosity, temperature and so on(anelastic phenomena and high pressure and temperature geophysics). Immediate specific trends can be seen in (a) the emphasis on treating both teleseismic and explosion seismic signals as a whole, rather than travel times only, with increased understanding of the real earth, (b) the digital approaches becoming more and more common in research and exploration to increase the efficiency of expensive techniques and thereby allow studies of a kind impossible only 10 years ago, (c) the accelerated interplay between seismology and other geophysical disciplines and geology in synoptic understanding of the earth and its earthquakes.

CONCLUSIONS

Canadian responsibilities are proportional to the area of the country and its potential economic resources, rather than its present wealth or population. The nature of the different active seismic regions in this country, its geographical location, its tectonic variability and the existence of the Canadian Shield as a low-noise environment for seismic research offer unique opportunities for basic seismology and suggest that the per capita investment in seismological research in this country should exceed that of most other technologically advanced countries. The level of petroleum exploration seismic expenditures is 10 per cent of the world activity, and increased research to strengthen this considerable economic effort is amply justified.

Government Agencies

The author suggests that the role of the government agencies should continue to cover:

1. National seismic networks (teleseismic, local seismicity and strong motion), the data processing and international exchange involved and appropriate support laboratories. In this way efficiency, uniformity and economy can be practised. The frequency band covered in some stations of the national network should be increased with ultra-long-period instrumentation, and local seismicity and strong motion coverage expanded. The networks must be maintained at an advanced level and not allowed to become equipped with obsolescent equipment.

2. The estimation of seismic risk in Canada, the provision of building code information appropriate to the risk, the work of a regional centre for Canada and appropriate levels of research into seismic regionalization, Canadian earthquakes, microearthquake studies and earthquake engineering. Seismic catalogues of Canadian earthquakes should be brought up to date and maintained on a current basis.

3. Research into the detection and identification of nuclear explosions, including the operation and modernization of arrays, an appropriate digital data reduction centre, and support laboratories. Long-period capability in this field should be improved by the implementation of a suitable array and other specialized instrumentation.

4. A broad spectrum of fundamental wave and mechanism research conducted at an advanced level plus research activities deriving from their service responsibilities such as instrumental development and data processing techniques. All these are essential if the agencies are to remain distinguished research organizations in their own right, which is necessary in order to maintain high service standards: of course these agencies should also be in a position to undertake longer term projects than are often possible for universities. Higher levels of technical support should be provided to make their work more efficient.

5. Regional seismic surveys of the earth's crust and upper mantle which provide basic data for research into the development of the earth's crust and upper mantle, including marine and other surveys requiring logistical support beyond the capabilities of universities.

6. Some basic research into the evaluation of techniques of seismic exploration on both land and sea, and seismic exploration activities for non-commercial basic research: much of the latter should be contracted by government agencies to commercial contractors.

7. Co-operation with active university groups particularly in making available special data-handling facilities with a short half-life - time of obsolescence and some extensive data, and in seismic

crustal programs on both land and at sea, where government agencies must increasingly be prepared to implement and co-ordinate expensive shot programs conducted jointly by government agencies and universities.

Universities

1. The role of the universities should be to continue to teach and conduct broad programs of fundamental research into seismology and the physics of the earth's interior. University activity in this field has increased very remarkably in the last few years, although much excellent university effort in seismological fields may suffer from the dispersion of professional staff through many centres. Perhaps the encouragement of a limited number of centres of excellence by grant policies would be wise, and should be at least considered.

2. It is also considered important that at least some universities maintain and increase research activities in applied exploration seismology to ensure adequate and relevant basic training for resource development. Suggestions have been made that a Research Institute of Exploration Geophysics should be established at one or more Canadian universities conducting industry-sponsored research, and presumably with joint industry and government financial and personnel support. An experiment along these lines is now an urgent necessity.

3. It appears important that granting agencies recognize the need for a mechanism for planning and conducting some joint university projects in which government agencies are not involved, and recognize the increasing cost and rate of obsolescence of specialized seismic equipment and digital facilities required by universities in their pursuit of research excellence.

4. Another area of potential development in universities would be the funding and development of centres of excellence with rather more specific aims. Such aims could include experiments on the physics of earth materials at the high temperatures and pressures found in the mantle, or investigations into crustal loading problems.

5. The proportion of university to government research effort (excluding data collection) should remain essentially unchanged. The present balance is both efficient and fair, since the government agencies are in general far more efficient than universities in data gathering and processing and network operation.

Industry

1. The scale of petroleum exploration in Canada and offshore areas is so large it is difficult to understand why more basic research in exploration is not undertaken in Canada both by industry

(encouraged by increased financial incentives if necessary) and by universities in some such arrangement as that discussed above.

2. If industry is prepared to support a Research Institute with open contracted research and staff support, government should provide the necessary support to nourish the Institute in its formative years.

Earthquake Engineering

The application of seismological information and concepts to earthquake engineering can pay important dividends in the Canadian economic environment. The interaction of seismology with earthquake engineering is a close and complex affair involving structural and material properties, soil mechanics, and the character and duration of input seismic accelerations. It is recommended that the university research effort in earthquake engineering be strengthened, and that the continuing interdisciplinary approach between engineers and seismologists, as seen in the present National Committee structure, be encouraged and strengthened both nationally and in individual universities.

General

The increasing importance of interdisciplinary approaches and projects suggests that the present National Committee structures and their comparative accessibility to younger scientists in universities, government and industry must be maintained and strengthened, and national policy should encourage the attendance of scientists at national and international meetings to present their work, discuss international activities in their fields of interest, and contribute fully to the future development of the science.

It is difficult to put cost figures on the above recommendations. To maintain the present balance between government and universities, and to maintain the present technological level of government services and data collection, the costs can be expected to rise at an average annual rate of about 9 per cent during the next five years. This figure excludes government commencing any significant new programs. The capitalization of a number of university centres and excellence suggests that university grants probably need to rise at twice this rate, or 18 per cent in the next few years.

No cost figures can be given for the proposed strengthening of seismic exploration research by means of a Research Institute: presumably if the Institute is to excuse industry from doing basic research in Canada, it should be largely self-supporting on industrial research contracts, and eligible for present industrial research incentive schemes.

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GEOMAGNETISM

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DEFINITION

Geomagnetism is the branch of geophysics dealing with the study of the earth's magnetic field, its origin, its time variations, its present and past configuration, and the magnetization of the rocks of the crust and upper mantle.

The research activities in this discipline are monitored on a worldwide basis by four Commissions within the International Association of Geomagnetism and Aeronomy (IAGA).

Commission I (Observatories and Instruments) deals with all problems related to the operation and instrumentation of magnetic observatories (permanent, temporary or satellite) which are essential in providing standardized basic data for the study of the present configuration and variations of the earth's field.

Commission II (Representation of Main Magnetic Field) advises on methodology, equipment and other technical matters pertaining to land, sea, air and space surveys and provides a medium for data exchange between nations.

Commission III (Magnetism of the Earth's Interior) deals with observations, analysis and theoretical interpretation of all phenomena relating to the magnetism of the earth's interior, including the main geomagnetic field and its secular variation, electromagnetic induction within the earth, archeomagnetism, paleomagnetism, rock magnetism, electrodynamics and geomagnetic anomalies.

Commission IV (Magnetic Variations and Disturbances) deals with the study of transient magnetic variations and their origin, and with the development of precise definitions of the various indices introduced to characterize certain features of magnetic activity. Aspects of geomagnetism considered by this Commission include daily variation, equatorial electrojet, special disturbance events, micropulsation, magnetospheric field variations, and conjugate point studies.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Research in geomagnetism can be (i) directed toward improving the presently available instruments and techniques for measuring the earth's magnetic field, and (ii) directed toward understanding the origin and variations of the present and past magnetic field.

Because of the presence of the north magnetic pole, Canada has a particular opportunity and responsibility to provide fundamental data of value to the study of the geomagnetic field. This can be effectively achieved if Canadian scientists are involved in research to improve the instrumentation and technology of data acquisition and processing. Research in this area is closely related to magnetic prospecting, so that advances are quickly translated into improved methods of magnetic exploration for minerals and oil.

Research to understand the origin of the earth's field has resulted in general agreement that it is due to a rather special dynamo action in the fluid core of the earth, but a precise description has not been produced. Such is the complexity of the problem that progress toward a solution will be slow. It is important that research in this area proceed in conjunction with the collection of magnetic field measurements. The data collected are essential to research into the origin of the field, and it is certain that a better understanding of the origin will result in more efficient measurement of the field.

Paleomagnetism, which provides a history of the ancient field through studies of the remanent magnetization of rocks, has contributed to both of the above areas of research. Knowledge that, in the past, the field has reversed its polarity and varied its intensity many times is also important to research in the origin of the field. Paleomagnetic investigations assist in the interpretation of aeromagnetic surveys by providing data on the remanent magnetization which, in the Canadian Shield rocks, can be as large as the induced component.

One of the most significant new concepts in earth science relates to global tectonics and involves continental drift, movement of segments of continents, and sea floor spreading. Much of the evidence for these hypotheses has come from an unexpected combination of geomagnetic research. The significance of research in geomagnetism is well illustrated by its contribution to these new concepts of global tectonics. Research on the origin of the earth's magnetic field by a fluid dynamo has shown that the dipole axis of the field must lie close to the axis of rotation of the earth. Paleomagnetic studies have permitted the establishment of the ancient geographic latitude of continents and segments of continents by calculation of former magnetic pole positions, and have thus contributed to concepts of polar wandering and continental drift. Airborne magnetometer surveys have revealed large-scale geological features that mark major crustal blocks. Airborne and shipborne surveys over the ocean basins have outlined magnetic patterns in the sea floor that correlate remarkably well with the pattern of recent reversals of polarity of the paleomagnetic field. These studies have considerably strengthened the theories concerning the opening up of the ocean basins by spreading of the ocean floor from the mid-ocean ridges. Thus, geomagnetic research is making a significant contribution to the substantiation of these hypotheses.

PRACTICAL APPLICATIONS

The following list of applications of geomatnetism should be considered as illustrative rather than exhaustive.

Navigation

Accurate geomagnetic charts are necessary for navigation by ground parties, aircraft, ships and satellites. Demand is growing from a number of users for charts that show more detail.

Communication

Radio communication is affected by phenomena associated with fluctuations in the earth's magnetic field. A better knowledge of the field and its fluctuations is a basis for improved radio communications.

Mineral Exploration

Aeromagnetic maps do not directly indicate mineral deposits other than iron and titanium, but they delineate geological structure which is important in mineral prospecting. Aeromagnetic maps can show boundaries between different rock types and outline dykes, faults and fold structures, even where there is a cover of overburden and muskeg. Most geologists consider them a prerequisite to mapping an area geologically. Simple correlation between ore zones and structural features such as faults, contacts, etc. on aeromagnetic maps has led to the discovery of several mines. The value of the Marmora mine, which is one example of such a find, is probably greater than the total investment Canada has made in geomagnetism hitherto.

Petroleum Exploration

Aeromagnetic maps have an application to oil exploration in the reconnaissance phase by delineating sedimentary basins and providing an estimate of the thickness of sedimentary rocks in them. It is apparent that high resolution magnetic surveys will provide more useful geological information.

Methods based on time-varying magnetic fields may also have applications to measuring the thickness of sediments.

Paleomagnetic studies can establish whether sedimentary formations have been laid down in equatorial latitudes and thus have a higher probability of containing oil. The Paleozoic formations of Hudson Bay and the Yukon are good examples of sedimentary rocks that were deposited near the equator but now are in a polar region.

Mineral Exploration on the Continental Shelves

Magnetic survey methods can be usefully employed in coastal regions and over the continental shelves in delineating the underlying geology, since they are not adversely affected by the conductive sea water and because they can be carried out from aircraft and ships.

Iron Ore Concentration and Mineral Separation

Rock magnetism provides basic data on the magnetic properties of rocks and minerals upon which the magnetic techniques of ore concentration and mineral separation are based.

Stratigraphic Correlation

Paleomagnetism can provide a means of correlating lavas, sills and dykes by the direction and polarity of their remanent magnetizations. In some cases it is also possible to give reasonable estimates of relative and absolute age of such bodies.

Tectonics and Structural Geology

Large-scale magnetic map compilations and the techniques of magnetic anomaly filtering can outline major structural blocks and provide a method for detecting large-scale tectonic movements.

Upper Mantle Structure

Induction studies, or magnetic deep sounding, are the only method other than seismology that can probe the upper mantle. The magnetic method provides additional information to that available from seismology and, as such, is very valuable in those regions where it is applicable.

Continental Draft, Polar Wandering and Sea Floor Spreading Studies

Paleomagnetism provides information upon which the ancient geographical location and arrangement of the continents can be determined. Magnetic surveys of the oceans are now providing information from which the age and the sequence of ocean floor spreading can be inferred. As these concepts are further developed, they should provide a more rational basis for mineral and oil exploration on continental margins and in ocean basins.

HISTORICAL DEVELOPMENT

The magnetic field of the earth was the first geophysical parameter to be measured in Canada on a regular basis. The first magnetic observatory was established in Toronto in 1840. J. H. Lefroy, its Director from 1841 to 1853, also made a remarkable magnetic survey of the Canadian Northwest during 1843-44 which, in addition to making possible the first magnetic maps of Canada, provided the earliest studies of magnetic disturbance in the auroral zone. With the establishment of the Dominion Observatory in 1905, magnetic field measurements were expanded. Garland (1) describes further developments as follows:

> "Canadian research in terrestrial magnetism formed a logical extension to the early measurements of Lefroy, and continued to benefit from the importance of mapping the magnetic field in a region close to the north magnetic pole - originally because of the use of the magnetic compass in navigation. Undoubtedly, however, the single outstanding characteristic of Canadian research in geomagnetism over the past century has been the development and application of the airborne magnetometer.
>
> "Although the original total-field airborne magnetometer was developed elsewhere, its application by the Geological Survey of Canada over the past 20 years to the systematic mapping of the country has been of tremendous value. Canadian surveys have shown, better than any other published work, the detailed nature of the magnetic field over a continental block. The use of aeromagnetic maps to determine major geological trends, to delineate the borders of formations in the Precambrian Shield, to determine the depth of sedimentary cover over the concealed Shield, and to locate magnetic ore bodies has been highly developed in this country. When magnetic surveys of the ocean floor first became available, it was largely as a result of this knowledge of the field over a continent that it was possible to recognize immediately the contrasting magnetic nature of the ocean floor. While the Geological Survey extended its measurements of total magnetic field, the Dominion Observatory designed and constructed the first successful airborne magnetometer for the absolute measurement of the field components. With this magnetometer, it has made internationally recognized contributions to the knowledge of the earth's field as a whole, by a grid of flight lines over North America, the North Atlantic Ocean, Scandinavia, and parts of the Pacific Ocean. The Observatory has also pioneered in the study of the intense and complicated variations of the magnetic field in the regions of the auroral zone and north magnetic pole."

University involvement in geophysical prospecting, and geophysics in general, dates from the late 1920's with the work of Eve at McGill and Gilchrist at Toronto. One of the most outstanding contributions of the Toronto group was the training during the 1940's of a whole generation of Canadian geophysicists who have been largely responsible for the development of geophysics programs at a number of Canadian universities, government laboratories, and geophysical companies. The impact of the second generation of geophysicists, trained by this expanded number of university geophysics programs, is now being felt throughout Canadian geophysics. While the first work at McGill and Toronto was oriented to geophysical prospecting, university research in geomagnetism is now of a more fundamental nature. Significant contributions have been made by universities in most research areas that do not require extensive data collection. The universities have not as yet made very extensive use of the data collected by the government agencies.

Magnetic prospecting by dip needle, ground magnetometer and, now, the airborne magnetometer have formed a major part of geophysical prospecting. Canada has led in the commercial exploitation of the airborne magnetometer as a mineral exploration tool. The Marmora iron deposit is a good example of direct discovery of a mine by the method, but perhaps the most widespread contribution of airborne surveys has been in the delineation of geological structure. Large areas of Canada have now been aeromagnetically surveyed by the Geological Survey of Canada, and the resulting maps are so useful in delineating the geology of a given area that aeromagnetic coverage is now considered a prerequisite for the geological mapping of new areas.

PRESENT LEVEL OF ACTIVITY

The magnetic field over Canada must be measured on a regular and continuing basis. To this end, the Dominion Observatory operates 10 permanent magnetic observatories, several temporary observatories, and maintains a network of 103 repeat stations that are occupied every five years to record secular variations. Geomagnetic charts for navigation are published at regular intervals. Aeromagnetic maps on a scale of 1 and 4 miles to the inch are being systematically published in order to provide complete coverage in the near future. These low-level aeromagnetic surveys are contracted out to industry under a joint federal-provincial program. Shipborne magnetometer caps giving total field values over the continental shelves are now published by the Marine Sciences Branch of the Department of Energy, Mines and Resources, and used by companies for exploration purposes.

Activities associated with the interpretation of magnetic maps are carried out in various branches of the Department of Energy, Mines and Resources, provincial government departments, earth science departments of universities, geophysical exploration companies, and resource-based industries. Most of this work is directed toward the solution of geological and mineral exploration problems but a part of it is directed toward the development of improved interpretation techniques.

Magnetic exploration by commercial exploration companies is at a high level. There are nine airborne geophysical survey companies based in Canada which offer aeromagnetic surveys as a contract service. These form a substantial proportion of the worldwide industry (2). Most of these companies also carry out contract surveying throughout the world as well as in Canada. Research to improve magnetic exploration equipment and techniques is conducted on a modest scale by industry.

Research on the magnetism of the earth's interior, and on magnetic variations and disturbances, is conducted in universities and government laboratories. Research is under way in eight or nine university departments, where groups vary considerably in size and scope of their interest. This research is related to the teaching-through-graduate-research function of universities. Research in government laboratories is closely related to the scientific data collection functions of these laboratories.

In assessing the level of activity in geomagnetism in Canada, the international reputation of its quality is of primary importance. On this basis, Canadian scientists are making leading contributions in the modern technology of geomagnetic field observations and in the development of a superior airborne instrument for worldwide geomagnetic surveys. Numerous requests have been received from international agencies for Canadian scientists to advise on aeromagnetic surveys, and the services of Canadian-based exploration companies are in constant demand. Publications of geomagnetic research by Canadian scientists are frequently cited in the international literature. Another of the indicators of the high standard of Canadian geomagnetic research is the considerable number of Canadians who have served in responsible positions in the International Association of Geomagnetism and Aeronomy.

NEED FOR INCREASED ACTIVITY

Magnetic Observatories and Charts

In most areas of data collection, activity is adequate for the preparation of the present geomagnetic charts. A demand is developing, however, from airlines and the forestry and mining industries for more detailed geomagnetic charts which, if met, will require increased activity.

Aeromagnetic Surveys

The present aeromagnetic program is excellent and proceeding at an adequate rate. It should, however, be extended in some form to completely cover Canada's continental shelves and adjacent ocean basin regions.

Systematic surveys with the new high-resolution airborne magnetometers should be made over sedimentary basins at first and extended to other areas as experience dictates.

Geomagnetic surveys are carried out by five federal government agencies: Bedford Institute, Dominion Observatory, Geological Survey, National Research Council, Polar Continental Shelf Project. There is a definite need for more co-ordination among these groups, especially between the marine and airborne surveys. This co-ordination should involve selection of areas to be covered and forms of data presentation (including scale and projection). At present, contour maps are produced on different scales and even different projections, making it very difficult to work across survey boundaries. There are considerable demands from the exploration industry for data in its original form (analog or digital records) and the methods of releasing this data are variable and require review.

Analysis of Data

Data collection by airborne and shipborne methods is producing a volume of information that taxes the present data processing techniques. Continuing improvements are being made, but research directed to increase the efficiency is required. Increased effort should be made to exploit the magnetic data that is already available. This will require improved techniques of analysis as well as data processing.

Time-varying Magnetic Fields

Research on magnetic field variations and disturbances is, in general, outside the scope of this report but has a direct bearing on many solid-earth magnetism studies. Rapid changes in the magnetic field due to extraterrestrial sources must be measured systematically to provide corrections for magnetic observations and magnetic surveys. The limiting factor in the production of more detailed magnetic maps may be the efficacy with which rapid variations in the field can be monitored.

Induction Studies

Studies of perturbations in time-varying magnetic fields, due to electromagnetic induction in regions of anomalous electrical conductivity in the crust and upper mantle, have produced a technique that is becoming known as magnetic deep sounding. This technique is very promising and, along with studies in magnetotellurics, deserves greater study to develop potentially valuable geophysical tools based on time-varying magnetic fields.

Main Geomagnetic Field and Its Secular Variations

The level of activity is limited by the relatively few people with the background and interest in this area of research. Better liaison between researchers and those collecting geomagnetic data may be the most efficient means of improving progress in this very basic and vital part of geomagnetism.

Paleomagnetism and Rock Magnetism

With four major paleomagnetic laboratories and some smaller ones in Canadian universities, and two laboratories within the Department of Energy, Mines and Resources, it is doubtful if there is justification for additional major laboratories at this time. There is a continuing need to acquaint earth scientists with rock magnetic and paleomagnetic information, and for arrangements whereby the resources of existing laboratories can be made available to Canadian earth scientists in institutions, laboratories, or companies lacking such facilities.

Research by Industry

Research activity by exploration companies is modest but increasing, whereas that of mining and oil companies in Canada is almost non-existent. When one considers the great value of magnetic methods to mineral exploration, and the potential future value of high-resolution surveys and methods based on time-varying fields, the relative paucity of industrial research in magnetic methods in Canada is most regrettable.

TRAINING NEEDS

Most Canadian geophysicists, including those working in geomagnetism, receive their graduate training in a geophysics department which is either separate from or attached to a physics department, after an undergraduate degree in physics or geophysics. The resultant physics association produces earth scientists who are very competent in the necessary technical and theoretical aspects of geomagnetism but are less familiar with the geological implications. This situation also results in geology graduates who are often insufficiently aware of magnetic map interpretation and paleomagnetic techniques. The advantages and disadvantages of specialization and diversification in education can be argued endlessly, but what is important is to recognize that efforts must be made to improve the liaison between the geological and geophysical branches of earth science.

In common with other branches of earth science, geomagnetism does not attract many Canadian graduate students. A considerable number of the students are from outside the country. Some of these intend to stay in Canada but others intend to return to their home country. Support for the latter group is a worthwhile endeavour for Canada, but the cost should be recognized as aid to the developing nations. A recognition of the foreign aid role of Canadian graduate schools, and a rearrangement of financial support, would provide a more realistic picture of graduate training. It would make an objective appraisal of the adequacy of Canada's graduate training program more feasible.

Geomagnetic research of a high quality in the universities is an essential requirement for training graduate students of the calibre Canada requires. Valuable contributions to graduate training could be made by arranging leave for members of government and industrial laboratories to accept teaching and research appointments in a university for short periods. Additional benefit could be obtained by co-operation between university, government, and industrial laboratories in research projects, including thesis research, and in the use of facilities, equipment and data.

At present, no French-speaking Canadian university offers a graduate degree in geophysics. Whereas a number of French-speaking students do take degrees in English-speaking universities, an important source of Canadian geophysicists is not being tapped adequately.

It was disturbing to find in one of the major contributions to this report comments on training and objectives which display an almost vindictive view of university research workers coupled with a lack of sympathy with, and possibly a lack of understanding of, the university role in the national interest. While many ideas from this contribution have been incorporated in the report, I am convinced that the views expressed about university people are not shared by many other government scientists, and so they have been omitted.

MAJOR OBJECTIVES AND FUTURE TRENDS

As an advanced industrial nation with special requirements in transportation and communication, and as one having a major economic base in natural resource industries, Canada requires a comprehensive geomagnetic program. Such a program must have three interdependent sectors: efficient government geomagnetic data collection and research agencies, thriving graduate training research groups in a number of universities, and an applied-research-oriented group of commercial companies engaged in mineral and oil exploration.

Canada must continue to fulfill her international obligation to monitor and survey the earth's magnetic field over her territory and adjacent ocean areas, to make such data available to other countries, and to take part in international magnetic studies. The government departments must have the chief responsibility in this area and should be able to draw upon the personnel and facilities of universities and industry, particularly for special projects which may require an increased number of participants and equipment for a short period.

Fundamental research in geomagnetism must be supported and encouraged as the basis for increased understanding of this major geophysical phenomenon and the source of new and improved applications. University laboratories should have the prime responsibility in this area, but the co-ooeration of government laboratories and industry is essential where special facilities, or special data acquisition and analysis capability, are required. Research projects requiring such co-operation would be stimulated by government and industry scientists spending periods in university laboratories, and vice versa.

Applied research in geomagnetism is a continuing necessity to improve existing applications and to exploit the findings of fundamental research. This area should be mainly the concern of exploration, mining and oil companies. However, many of these companies are reluctant, or financially unable, to invest substantial amounts of money in research and may require government-inspired incentives to set up their own facilities or to establish industry research consortia. Government research laboratories should be encouraged to continue to play a significant role in applied research.

The co-operation among the three sectors that is outlined is not just a pious hope but a quite feasible program to increase the effectiveness of the money Canada invests in geomagnetism. There have been a number of instances already of co-operative involvement of personnel from one sector in another: several universities and government laboratories have co-operated in induction studies; at least one scientist from a government laboratory has spent a period of several months in university geomagnetic laboratories; university scientists have used facilities at a government laboratory; and graduate students have been allowed to use data, from summer field work with the Department of Energy, Mines and Resources, for theses. Most Canadian scientists working in geomagnetism are personally acquainted through the efforts of the Subcommittee on Geomagnetism of the National Research Council's Associate Committee on Geodesy and Geophysics. All that is required is a climate of co-operation and encouragement from senior people in the various sectors. Friendly competition between laboratories is a stimulus to good research but unnecessary rivalry between groups can be destructive.

In addition to co-operation within all sectors of geomagnetism, there must be more co-operation among the different branches of solid-earth science in the form of integrated surveys of particular regions.

There have been valuable examples where magnetic, seismic and gravity surveys have been used in an area, but the integrated approach must be expanded to include more techniques.

CONCLUSIONS

The following conclusions are listed in the order of their appearance in the text of this report and not in order of importance.

1. The program of preparation of geomagnetic charts must be continued and an investigation into the benefits versus costs of more detailed charts should be carried out.

2. The program of airborne and marine magnetic surveys must be continued and should be extended to cover the continental shelves and deep ocean regions.

3. Co-ordination is necessary among the agencies conducting surveys in the selection of areas to be covered and in the forms of data presentation.

4. High-resolution surveys should be conducted on a trial basis over sedimentary basins and evaluated for possible extension to other areas.

5. More effort must be made to exploit the vast amount of information available in existing aeromagnetic maps.

6. Research in the potential of induction studies, magnetotellurics and other geophysical methods based on time-varying magnetic fields should be encouraged.

7. Studies should be made to improve methods of compensating for time-varying fields in magnetic surveys conducted in the magnetically disturbed auroral zone and during magnetically disturbed periods.

8. Research on the origin of the main geomagnetic field and its secular variations should be pursued, in consultation with the government agencies which obtain geomagnetic data, with the aim of improving the applicability of the data to such research without impairing the primary function of monitoring the field.

9. Arrangements should be made to make the facilities of existing paleomagnetic laboratories more widely available to research workers lacking such facilities.

10. At least one French-speaking university should be encouraged to set up a graduate program in geophysics.

11. Liaison between geologists and geophysicists should be encouraged by joint committees of the Advisory Committee on Geodesy and Geophysics and by the arrangement of yearly symposia that would attract both groups.

12. Arrangements should be made whereby geophysicists in government and industrial laboratories could participate in graduate teaching and research at the universities for periods of a few months to a year.

13. Training of graduate students from the developing nations, and assistance with magnetic surveys given to the developing countries, should be classed as foreign aid and financed as such.

14. Fundamental research in all aspects of geomagnetism should be expanded to improve our understanding of this phenomenon.

15. Applied research, particularly by commercial companies or industry research consortia, should be encouraged by government to improve the applications of geomagnetism and to exploit new discoveries made by expanded fundamental research.

16. Integrated geophysical surveys, combining the techniques of geomagnetism with other geophysical methods, should be organized in particularly interesting areas, such as the Pacific coast region, where an oceanic ridge system intersects the continental shelf.

ACKNOWLEDGMENTS

This report was prepared in consultation with the past and present members of the Subcommittee on Geomagnetism of the Associate Committee on Geodesy and Geophysics of the National Research Council.

REFERENCES

1. Garland, G. D., 1968. The earth sciences in Canada. Roy. Soc. of Can. Spec. Publ. No. 11, pp. 37-51.

2. Hood, P. J., 1969. Trends and developments in mineral exploration during 1968. Can. Mining J., Feb. 1969.

MAGNETOTELLURICS

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DEFINITION

For the purposes of this report, the designation Magnetotellurics will imply the use of the naturally occurring electromagnetic disturbances measured at the surface of the earth as a diagnostic probe for determining the subsurface resistivity structure. The measurement of the horizontal electric field components at a series of stations, together with similar measurements at a fixed base station, provide the data, under certain limiting conditions, for the Telluric Survey (TS) method. The simultaneous measurement of horizontal electric and magnetic field variations at a single station provides the data for the Magnetotelluric Sounding (MS) method, and a series of such stations will allow an additional interpretation by the Magnetotelluric Profiling (MTP) method.

Magnetotelluric methods can be used to explore through a whole range of depths from the near surface, which is of interest to the hardrock mining community, to the deep reaches of the earth's interior. Between these extremes lies the range of depths which is of fundamental interest to the oil industry. The depth that is of interest defines the frequency content and thus the design of the recording instruments used. Thus, in principle, only the frequency range varies for different practitioners, whether interested in economic exploration or more purely scientific concerns.

It should be noted that the closely linked subjects of micropulsations, which share the same sources, and magnetic deep sounding which shares much of the same theory as magnetotellurics, fall under the headings of aeronomy and geomagnetism respectively. The latter is the subject of a separate report in this volume.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT IN THIS FIELD

Berdichevsky (1) reports on the widespread and successful use of magnetotelluric methods in the U. S. S. R. He quotes 150 to 200 crew-months annually for the Telluric Sounding method, and for 1965 (the last year reported), 182 crew-months of Magnetotelluric Sounding and Magnetotelluric Profiling. He cites the relatively low cost and high efficiency of this method, and recognizes that a more sophisticated approach to data analysis must be taken. The situation in North America is strikingly different. Here the highly developed computer technology has encouraged the application of statistical methods to the analysis of data, and the techniques of analysis and interpretation are highly developed. Care must be taken in evaluating the reports from the U. S. S. R., since mineral exploration and scientific investigations are most frequently carried out in the same program and it is therefore difficult to evaluate that part of the cost and of the success which should be assigned to the discovery of minerals.

A magnetotelluric exploration system has recently been advertised as available to contractors. This achievement reflects the level of support by a consortium of oil companies as well as governmental granting agencies in the United States. The basis for it was laid at the University of Alberta. The current level of development at the University of Alberta, while equal to that of U. S. counterparts, is not concerned directly with the applied aspect which must be the concern of the private sector of industry.

The research carried out for purely scientific purposes will continue to expand man's knowledge of his universe and, in addition, will undoubtedly produce results which will prove of direct benefit to the oil and mining industry. The pace at which the research will continue will depend on the financial support given to universities and government laboratories.

HISTORY OF RESEARCH AND DEVELOPMENT AND THE CANADIAN CONTRIBUTION

While the Telluric Survey method started with the efforts of Schlumberger (2), the Magnetotelluric Sounding method originated with Tikhonov (3). The definitive work in this area was that of Cagniard (4) which has been followed by considerable theoretical and experimental advances.

The earlier contributions by d'Erceville and Kunetz (5), Cantwell (6) and others tended to deal with methods of interpretation and structure. In addition, the pioneer work of Fourier (7) and Schuster (8), expanded by Weiner (9) and, more recently, by other statisticians working on information theory was found to be directly applicable to the analysis of the stochastic processes of which the magnetotelluric effect is one example. Important contributions are described by Blackman and Tukey (10), and a further advance was made by Cooley and Tukey (11) in their development of the fast Fourier transform algorithm.

Early work in Canada in telluric surveying and magnetotelluric sounding was carried out by G. D. Garland and K. Vozoff at the University of Alberta, Edmonton, and work is continuing there under the direction of the author. In addition, co-operative programs in field work were carried out with the University of British Columbia and the University of California at Berkeley (12).

A major contribution from the University of Alberta has been in the development of instrumentation for magnetotellurics which are also useful in the study of micropulsations. Garland and Webster (13) report the first use in North America of telluric surveys for regional studies. The early works of Niblett and Sayn-Wittgenstein (14) and Vozoff et al (15) are among the earliest field work reported in magnetotelluric sounding and magnetotelluric profiling.

The Pacific Naval Laboratories at Esquimalt are concerned with the study of micropulsations, and have made important pioneering contributions in the field of magnetotellurics.

The Dominion Observatory, Division of Geomagnetism, has also made major contributions although they are more concerned with magnetic deep soundings.

Canadian interest in geomagnetism and aeronomy has undoubtedly contributed to the high level of activity in the specific area of magnetotellurics ; the contributions of Canadian scientists have kept pace with those of the United States and other countries.

It should be pointed out again that in the foregoing only the larger university and governmental groups involved in magnetotellurics have been mentioned. In addition, some petroleum companies have carried out experiments in telluric surveying in Ontario and Alberta.

PRESENT LEVEL OF ACTIVITY

At the University of Alberta, work continues on new interpretive techniques and the application of magnetotellurics to deep crustal studies and regional trends. At the University of Toronto, magnetotellurics is applied to the study of the thermal regimes of the mid-Atlantic ridge and also the application of high-frequency magnetotellurics to the shallow structures of interest to the mining industry.

The Dominion Observatory, both in Ottawa and Victoria, conducts magnetotelluric studies in conjunction with magnetic deep sounding programs. The Geological Survey of Canada also carried out a magnetotelluric program with emphasis on instrumentation and methodology. Programs are also under way at the University of Saskatchewan, the University of Victoria, McGill University, and the Bedford Institute of Oceanography. This does not exhaust the list of institutions at which work in magnetotellurics is carried out in Canada, but it does indicate the very high level of activity in the universities and governmental institutions. The level of activity can be expected to remain high if funds are available for this purpose.

NEED FOR INCREASED ACTIVITY

The magnetotelluric method is a relatively new technique for the investigation of subsurface structure and, despite its promise in terms of commercial application, needs considerable further development. The possibility of its use for large-scale regional surveys in remote areas where large field crews are not easily maintained should provide an incentive for further development to meet Canadian needs. Magnetotelluric studies are particularly neglected by industry in Canada, and further industrial research and application need to be encouraged.

TRAINING

Since the magnetotelluric method is relatively new, the instrumentation and interpretive techniques are not routine and consequently the method will require relatively highly trained personnel. Many of the contributions in this field have come from university research programs, and graduates from such institutions are in general well trained to continue this work.

If the method were to become well established for exploration purposes, it may be necessary for the companies to hire geophysicists trained in the method. Canadian graduates in geophysics are well trained for employment in universities and government agencies but over-trained for the Canadian oil industry, which is the major Canadian employer. Geophysics is, nevertheless, the area in which currently the employment situation for physicists is brightest as far as the availability of jobs is concerned. There is in Canada, however, a serious imbalance in the nature of employment opportunities in geophysics, especially for people with higher degrees.

CONCLUSIONS

1. Magnetotelluric studies should receive increased support because of their potential for the economic development of Canada.

2. The Government should increase financial support to its agencies and universities to carry out research in this field of earth science.

3. Co-operation between government agencies and the private companies should be promoted to carry out research in the application of this method to oil and mineral exploration in Canada.

4. Scientists should be encouraged to attend national and international meetings to promote research and stimulate discussion of this field of study.

REFERENCES

1. Berdichevsky, M. N. Magnetotelluric profiling and sounding. Lecture read at the Interregional Seminar of UNO held in Moscow, 1967.

2. Schlumberger, M. The application of telluric currents to surface prospecting. Trans. AGU, p. 271-277, 1939.

3. Tikhonov, A. N. Determination of the electrical characteristics of deep layers of the earth's crust. Dokl. Akad. Nauk., U. S. S. R. vol. 73, pp. 295-297, 1950.

4. Cagniard, L. Basic theory of the magnetotelluric method of geophysical prospecting. Geophys., vol. 18, pp. 605-635, 1953.

5. d'Erceville, I. and Kunetz, G. The effect of a fault on the earth's natural electromagnetic field. Geophys., vol. 27, pp. 651-66, 1962.

6. Cantwell, T. Detection and analysis of low-frequency magnetotelluric signals. Ph. D. thesis, Dept. of Geol. and Geophys., Massachusetts Institute of Technology, 1960.

7. Fourier, J. B. Memoire sur la propagation de la chaleur dans les corps solides. Nouveau Bull. des Sci., par la Soc. Philomatigne de Paris, vol. I. pp. 112-116. Barnard, Paris, 1807.

8. Schuster, A. Investigation of hidden periodicities. Terrest. Magnetism, vol. 3, pp. 13-41, 1898.

9. Weiner, N. Generalized harmonic analysis. Acta Mathematica, vol. 55, pp. 117-258, 1930.

10. Blackman, R. B. and Tukey, J. W. The measurement of power spectra. Dover Publications, New York, 1958.

11. Cooley, J. W. and Tukey, J. W. An algorithm for the machine calculation of complex Fourier series. Math. of Computation, vol. 19, pp. 297-307, 1965.

12. Srivastava, S. P., Douglass, J. L. and Ward, S. H. The application of magnetotelluric and telluric methods in central Alberta. Geophys., vol. 28, pp. 426-446, 1963.

13. Garland, G. D. and Webster, T. F. Studies of natural electric and magnetic fields. J. Res. NBS, vol. 64D (Radio Prop.), pp. 405-408, 1960.

14. Niblett, E. R. and Says-Wittgenstein, C. Variations of electrical conductivity with depth by the magnetotelluric method. Geophys. vol. 25, pp. 998-1008, 1960.

15. Vozoff, K., Hasegata, H. and Ellis, R. M. Results and limitations of magnetotelluric surveys in simple geologic situations. Geophys. vol. 28, pp. 778-792, 1963.

GRAVITY

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DEFINITION

Gravity is defined as the gravitational attraction of the earth on a mass of one gram at some point in space. It is an acceleration and obeys Newton's law of gravitation which applies to every particle in the universe.

As the earth is a rotating, non-spherical and inhomogeneous mass, the value of gravity varies over its surface from about 978 cm/sec^2 at the equator to about 983 cm/sec^2 at the poles. Measurements of these variations are important to the study of the crust and upper mantle, isostasy, geodesy and the exploration for mineral and petroleum resources.

SIGNIFICANCE OF RESEARCH AND PRACTICAL APPLICATIONS

Every object or unit of mass on earth, in the solar system or in the universe is subject to the laws of gravitation. Therefore, research into the nature of gravitation is of fundamental importance to man's social and economic well being. Although this report is concerned with gravity as it applies to studies in the earth sciences, it should be remembered that vast amounts of energy are derived from or spent in overcoming gravity and that an understanding of the fundamental cause of gravitation would be one of man's greatest achievements.

Gravity studies are useful in seeking and developing oil, gas and mineral resources. They can be carried out quickly and at relatively low cost and they are a valuable means of defining either regional or local areas with anomalous subsurface structures that warrant further detailed prospecting. Gravity data can also be combined with geological and other geophysical data for control to deduce important information on local or regional structures and structural processes governing the formation of an ore deposit.

Many of the developments and techniques of gravity instrumentation, surveying and interpretation have resulted from investigations by mineral and petroleum exploration companies. Such investigations combine information from other geophysical methods, geology and drilling to elucidate the shape, depth and other properties of the structure of interest. Various techniques are employed to isolate the gravity effects of local structures of interest from the gravity field or regional anomaly usually associated with larger and often deeper influences in the crust. The resultant or residual anomaly is a refinement which often more precisely defines the location of the source structure. From detailed systematic surveys of high accuracy, the second vertical derivative of the gravity field can be computed with the same net effect of outlining more precisely the anomalous area. The gravity method has been successful in locating many structures of economic importance in Canada including, the detection of reef structures in Alberta and Saskatchewan, and delineation of the Pyramid ore bodies at Pine Point, Northwest Territories. At sea, the discovery of the Orpheus gravity anomaly

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off Cape Breton, Nova Scotia by the Bedford Institute, led the oil industry to extend their lease holdings and increase their exploration activity in the area.

On a large scale gravity anomalies are used to study major crustal structures. Gravity along with seismic observations are used to determine the nature of the transition from continental to oceanic crust at continental margins. Other structures such as the mid-oceanic ridges, ocean trenches and island arcs and volcanic islands are studied by gravity as well as other disciplines of Earth Science. Important results of use to structural geologists and petrologists have come from gravity studies of the intrusive rocks. Sedimentary basins have been studied by the gravity method not only in search for possible oil traps but also in an effort to study the structural history of these basins. In areas of post-glacial uplift gravity measurements have provided a means of studying the response of the mantle to loading and subsequent removal of the load.

The interpretation of gravity data on a regional basis, that is over regions measured in thousands of square kilometres, provides information on the gross nature of the crust and upper mantle and a sound basis for many projects of economic importance. This follows from the fact that knowledge of the physical properties of the crust and upper mantle leads to knowledge of the processes taking place in the outer part of the earth. Consequently recent results of combined gravity and seismic interpretations have provided support for new theories of processes taking place below the continents and the oceans.

Gravity data are important to studies of the physics of the earth's interior as they contribute to knowledge of both the static and dynamic behaviour of the deep interior. Isostatic studies are in part concerned with the mechanical behaviour of the earth's outer hundred kilometres (the lithosphere) through studies of the relationship of topography (or more generally loads on the crust) and compensation at depth. The dynamic response of the lithosphere can be determined by studying regions in which there have been recent changes in the load on the crust. Measurement of earth tides and crustal tilt provide information on rigidity in the earth and it is the aim of researchers in this field to use regional variations in earth tides and crustal tilt to study the structure of the mantle. Perhaps the most important factor in current studies of the earth's interior are the long wavelength gravity anomalies defined by the perturbations in satellite orbits. These anomalies are almost certainly indicative of large scale lateral variations of mass within the mantle, but it is not known whether these anomalies are statically or dynamically supported in the mantle. Whichever is ture, understanding the cause of these anomalies will add greatly to knowledge of the properties of the mantle and the processes affecting it. These processes, of which convection is perhaps the most important, are basic to all tectonism, and therefore ultimately control the nature of the outer hundred kilometres of the earth.

Gravity data are the basis of physical geodesy which is concerned with the determination of the shape of earth. Knowledge of the gravity field over the earth determines the shape of the geoid and therefore provides the basic information needed for the construction of maps and charts, which are fundamental to practically all social and economic undertakings of man. As the requirements for more accurate maps grow in Canada more detailed knowledge of the geoid will be required and gravity mapping in greater detail will be necessary.

Gravity data are finding increasing industrial application. Among the more prominent are the requirements for precise values of gravity at instrumental development laboratories and meteorological stations and detailed knowledge of the gravity field in the vicinity of rocket facilities and military installations to control the orientation of rockets during the stage of powered flight.

As a contribution to interplanetary geophysical studies, lunar orbiting space vehicles have already provided sufficient tracking data to permit processing of a qualitative gravity anomaly map of the near surface of the moon. The results suggest that large mass concentrations occur under the lunar ringed maria and several explanations have been proposed which give some insight into the history and structure of the moon.

Gravimeters are used to measure gravity over the earth's surface. Since these instruments require calibration to determine their spring constants, it is essential that adequate control be available to ensure a uniform set of gravity measurements throughout Canada and the world. In Canada this control is provided by the Canadian National Gravity Network without which it would be difficult, perhaps impossible, to correlate the results of adjacent gravity surveys.

Research and development on instrumentation and techniques to provide adequate control measurements ensures improved gravity data, uniformity in the data and broadens their application. There is a large amount of research devoted to improving computerized techniques for reducing, analyzing and distributing gravity data. This research is important because it enables relative costs to be maintained or reduced and provides for more effective distribution.

HISTORICAL DEVELOPMENT

(a) General Development

The history of the gravity method has been greatly influenced by the need for great precision in measurement. Practical applications were not possible on a wide scale until the technological developments of this century provided a means to manufacture precise instruments and computational facilities to carry out the complex calculations needed for many applications. The history can therefore be summarized as one of early theoretical developments followed by a relatively short, but intense, period of practical developments.

The theory of gravitational studies begins with Newton and his Theory of Gravitation published in the latter part of the seventeenth century. As a result of Newton's early work a relatively primitive pendulum apparatus was developed to test Newton's hypothesis that the gross form of the earth is an oblate spheroid. By the end of the nineteenth century, mathematicians had virtually completed the development of general theory describing the properties of gravitational fields (potential theory) and it remained mainly for theoreticians of this century to formulate theory recognizing that the measurements are made on the earth's topographic surface and not some mathematical reference surface.

Pendulums remained the only means for making either relative or absolute measurements of gravity for about two centuries. The greatest improvements in the accuracy of pendulums have been realized during the past twenty years when it became possible to control the environment of the pendulum (pressure, temperature, humidity, etc.) to a high degree and to measure time to parts in a hundred million or better.

In this century the number of instruments available for measuring gravity, its components or its derivatives has increased greatly. Pendulums have now been nearly replaced by absolute apparatuses. The absolute apparatuses in use fall mainly into two classes: (a) those in which the object is dropped (b) the symmetrical or tossed ball experiments. The instruments in existence are designed for laboratory use, but it is expected that portable versions of these will be available within five years.

Perhaps the most important factor in the history of gravity studies has been the gravimeter which was developed in the 1930s by the oil industry in the U.S.A. These instruments are light in weight, easily readable in a few minutes and are sufficiently sensitive to find applications in prospecting as well as earth science research. Prior to the 1960s these instruments were used almost exclusively on land areas, but recent developments and modifications permit their application to studies of the continental shelves and ocean basins. The latter application involves the measurement of gravity from a moving platform (dynamic gravimetry). Although measurement of gravity from surface ships is commonplace, dynamic gravimetry is in its infancy and second generation instruments are just now coming into use. It is hoped that these instruments will eventually be suitable for accurate gravity measurements from an aircraft.

Artificial satellites became an important factor in gravity studies during the 1960s because they provided a means of quickly and economically obtaining the major features of the earth's gravitational field. This information has also provided a useful world-wide standard for gravity anomalies obtained from surveys over land and water covered areas. The urgency in establishing a global network of first order gravity stations has been reduced but not eliminated. Satellites have caused a major revolution in geodetic studies both in physical geodesy (geodetic studies using the gravitational field) and in geometric or other fields of geodesy. At the close of the 1960s increasing emphasis was given to studies in the field of satellite geophysics. Of particular interest has been the interpretation of long wave length gravity anomalies because of their possible significance to modern theories of global tectonism. Scientists today are attempting to determine whether these anomalies reflect an equilibrium condition or are indicative of dynamic processes now taking place within the mantle.

(b) History of Developments in Canada

The earliest known gravity measurements in Canada were made during the famous Arctic expeditions of the early nineteenth century. The first absolute experiment in Canada, and possibly in North America, was carried out at the University of Toronto in 1896. Pendulum measurements were first made by the Dominion Observatory in the 1940s and this institution has assumed responsibility for the operation of the Canadian pendulum apparatus. This apparatus has undergone several periods of reconstruction and of the original apparatus only the pendulums remain. In addition to the Canadian apparatus, American and British pendulum apparatuses were used to make gravity measurements in Canada during the 1940s and 1950s. In the late 1950s and early 1960s, the National Research Council carried out an absolute gravity experiment in Ottawa.

The torsion balance, which measures gravity gradients, appears to be the first gravity instrument to be applied to studies of geological structure. This instrument was used in the late 1930s and early 1940s to study faults in the Ottawa Valley. However, too much time was required to make a measurement and it was quickly replaced by the gravimeter which was applied by the University of Toronto and by the Dominion Observatory in studies of geological structures in Eastern Canada. By the mid 1950s the Dominion Observatory initiated a national program of regional and detailed gravity coverage throughout Canada, as an aid to studies of crustal and upper mantle structure and in the field of geodesy. This program provided for establishment of the Canadian National Control Network to serve as the standard for measuring gravity for regional gravity stations at intervals of 15 km throughout the land and water-covered regions of Canada, for a computerized system to reduce, store and retrieve gravity observations and for a data bank to serve as the medium for distributing gravity data nationally. It is still operating and has provided Canada with a standard among the highest in the world.

A major end product of the mapping program is the 'Gravity Map of Canada'. The recent edition, released in 1967, shows regional gravity coverage in Canada to be about 60 per cent complete.

Gravimeters were first applied to measurements of earth tides at the University of Toronto around 1950. Earth tide measurements were made by the Dominion Observatory during the International Geophysical Year in 1957-58 at Ottawa, Resolute, N.W.T. and Meanook, Alberta. These early measurements were essentially part of 'ad hoc' programs and it was not until 1963 that the Dominion Observatory commenced a long term study of earth tides and crustal tilt. This program was strongly supported by the Associate Committee on Geodesy and Geophysics which, in 1964, recommended an expanded program including financial support by the National Research Council for universities entering this field of research. Shortly thereafter, Dalhousie University purchased equipment for studies of crustal tilt and additional arrangements were made with the Dominion Observatory to cooperate in the measurement of earth tides in Eastern Canada.

Measurements of gravity at sea date back to 1955 when the Dominion Observatory undertook the development of a vibrating string gravimeter. Work on the development of this instrument continued until 1962 when tests on a working model of a quartz-fabricated vibrating string gravimeter were successfully completed. The instrument was not developed further because subsequent tests indicated that linear spring-type gravimeters could be more easily adapted for measurements from a moving vessel. Concurrently with this development work, the Dominion Observatory participated with American agencies in tests of gravimeters in submarines and, in 1960, initiated a program to map the continental shelves and inland waters of Canada using underwater gravimeters. In 1963 the newly formed Bedford Institute of Oceanography and the Dominion Observatory undertook joint tests of surface gravimeters off the east coast of Canada. The Dominion Observatory has continued its interest in gravity at sea by carrying out a broad program of underwater measurements off the east and west coasts and in the Great Lakes, a program of surface measurements off the west coast and large-scale surveys on the sea ice of the Arctic Ocean and inter-island channels. This last program is part of the Polar Continental Shelf Project initiated in 1958.

The Bedford Institute has implemented a major program to measure gravity at sea from ships. Measurements have been made off the east coast of Canada and over the Atlantic Ocean basin, with emphasis given to the mid-Atlantic ridge. Much of their research effort has been devoted to the development of a data acquisition system known as BIODAL. The advances made by the Bedford Institute have kept Canada in the forefront of marine gravity studies.

The petroleum and mineral exploration industry has been active in gravity studies but, because of the competitive nature of their activities, many of the results of the surveys and the methods used to interpret the data remain confidential. The development of the gravimeter and many of the early techniques of interpretation were pioneered by the petroleum industry in the United States. In recent years there has been a steady broadening of the projects undertaken by exploration companies in Canada. This is particularly noticeable with respect to the increased awareness of the value of regional gravity surveys in structural studies. Evidence of this trend comes from the increased number of requests to the Observatory for regional data and from the types of surveys carried out by the exploration companies. There are also indications that the exploration industry is becoming more research conscious and is more prepared to underwrite the costs associated with the research and development of techniques of potential use in mineral and petroleum exploration.

Eleven universities and at least two Provincial Government agencies are presently active in gravity research in Canada. In general, the universities, which include Alberta, British Columbia, Dalhousie, Manitoba, McGill, Memorial, New Brunswick, Queen's, Saskatchewan, Toronto and Western Ontario, have applied their efforts to the interpretation of gravity data in terms of crustal structure and to the development of new mathematical methods of interpretation employing the computer.

Much of the field work and map production carried out by universities has been restricted to the southerly areas of Canada where the costs of field work are lower. University staff have participated in northern projects through the use of government data. Frequently, post graduate students have been employed on government field parties and have used the observed data as the basis for their research problems and theses. Published maps of the Observatory have also formed the basis for university projects, but it is only within the last few years that sufficient regional data have existed to permit such undertakings. A wide range of more specialized gravity and geodetic studies has been undertaken at several of the universities.

In the last two decades perhaps the greatest influence on geophysics in Canada has come from the University of Toronto. Many graduates now hold senior positions in other universities, in industry and in government and they in turn have trained many of the geophysicists now working in Canada. Further evidence of this influence is provided by the standard text on the theory and applications of geophysical methods (Grant and West, 1965) which is now widely used throughout Canada.

Some examples of the larger projects undertaken by the universities and provincial agencies are:

(a) Cooperation between Dalhousie University and the Bedford Institute is well established in the field of marine geophysics and oceanography. Interpretation of combined gravity and seismic data has produced models of the crust of the Maritimes and eastern continental margin.

(b) As well as an active research program in geodesy using gravity data, the University of New Brunswick has completed a gravity survey of the Province of New Brunswick.

(c) The University of Manitoba in cooperation with the Manitoba Department of Mines and Natural Resources is currently engaged in multidisciplinary studies, which include gravity, of a large portion of the Canadian Shield. Gravity investigations by the Universtiy have contributed to the definition and understanding of the structure of the Manitoba Nickel Belt.

(d) Some of the initial development of the Canadian Pendulum Apparatus was done at the University of Western Ontario.

(e) The Nova Scotia Research Foundation has observed about 5,000 gravity stations annually in the search for barite and salt deposits. A computer system for data reduction, storage and retrieval has been developed to handle the results.

(f) The Saskatchewan Research Council has undertaken detailed gravity investigations of Precambrian structures in the province and has developed interpretation techniques for use in such detailed studies.

PRESENT LEVEL OF ACTIVITY

(a) General Programs

Much of the effort of both the Dominion Observatory and the Bedford Institute is given to regional mapping programs, although these agencies carry out special projects whenever possible. As the Observatory is also responsible for the maintenance of gravity standards in Canada, this agency is involved with the establishment and maintenance of the Canadian National Gravity Network. As an aid to maintaining standards and to meet the requirements of the exploration industry, research in the earth sciences and national defence, the Observatory maintains a storage and retrieval system for gravity data. The system includes data from sources other than the Observatory, but it is not as yet a complete repository for all gravity data within Canada. Storage and retrieval systems for gravity data are also operated at the Bedford Institute and the Nova Scotia Research Foundation and by various petroleum companies.

The Dominion Observatory owns and operates about twenty gravimeters. These include two La Coste and Romberg underwater meters, two La Coste and Romberg ice meters, four La Coste and Romberg land meters and about twelve quartz fabricated Worden or Canadian meters. The Bedford Institute operates two Askania sea gravimeters and one La Coste and Romberg land gravimeter. The latter is used for ship to shore connections to determine the drift of the Askania instruments. All of the major universities own a gravimeter as do provincial agencies in Nova Scotia and Saskatchewan. The number of gravimeters owned by the exploration industry is not known, but it is believed that an average of ten is operated each year.

At the Bedford Institute much effort is devoted to the development of advanced digital systems to permit automatic recording of all data observed during a cruise. The instruments sampled by the digital system include the gravimeter, depth sounder, several types of navigational aids and course and speed indicators. This information is recorded in a form suitable for on board reduction of data using an PDP-8 computer.

The Dominion Observatory also carries out a research program to adapt instrumentation to meet current requirements. The major aim of this institution's instrumental research is the development of an advanced central computer system to support highly mobile field parties. The diversified nature of their field program clearly lends itself to this type of operation.

(b) Manpower

The Department of Energy, Mines and Resources has approximately 25 professionals and 8 technicians engaged in gravity programs. About half of this staff is concerned with various phases of large scale data acquisition and processing including the development and assessment of new gravity surveying instrumentation and data acquisition systems. The remainder are involved with the development of new techniques for the interpretation of the gravity field and their application to the interpretation of crustal structure in terms of geological and other geophysical information. Other important activities include geodetic applications of gravity and the establishment and maintenance of gravity standards.

The number of professionals and support staff employed in full time gravity research programs in provincial research institutions and universities is probably less than 20. Their interests are concentrated mainly over small scale geological structures, often those of potential economic significance, and the development of interpretation techniques using the computer.

Gravity activity in the Canadian petroleum industry has increased in the last three years. The figures for crew months in gravity work are as follows: 1966 - 28.5 crew months, 1967 - 79.5 crew months and 1968 - 124 crew months. Most of the increase has been in the provinces of Alberta, Saskatchewan and Manitoba and in the Yukon and Northwest Territories reflecting the renewed interest in the search for pinnacle-type Devonian reefs in Alberta, surveys of the Winnipegosis Reef trend in Saskatchewan, and the impact of the recent discovery at Prudhoe Bay, Alaska on exploration in the Canadian north.

(c) Cost

The total budgetary allotment for gravity work in the Department of Energy, Mines and Resources during the past year was approximately $1,200,000 including salaries and aircraft charter but not shiptime. At least 30 per cent of this amount was expended in mounting large scale gravity survey parties. The expenditures of the oil industry on gravity surveys during 1968 was approximately $1,450,000 (R.R. Clawson, personal communication) including computing and interpretation costs, that of the mining industry is estimated at $250,000 based on figures for 1967. An additional $200,000 is estimated for the cost of gravity surveys done by provincial institutions and the universities.

(d) Output

The Department of Energy, Mines and Resources obtains about 7,000 new gravity observations annually over a land and frozen sea area of some 200,000 square miles. Continuous shipborne gravity measurements at sea provide data for approximately 20,000 miles of traverses per annum over the continental shelves and in the deep oceans. The mounting demand for regional gravity coverage over both land and water areas has caused considerable emphasis to be placed on development of the new data acquisition systems; a national system for the exchange of gravity data is now under consideration. The interpretation of gravity anomalies is playing an increasing role in combined geophysical studies of the Arctic Islands, the Canadian Shield, the eastern and western continental shelves and Hudson Bay.

NEED FOR INCREASED ACTIVITY

Increased effort is needed to provide more measurements. This can be done in two ways:

(a) increasing the number and size of field parties and improving equipment and techniques to provide for more rapid data acquisition,

(b) incorporating existing observations by private and public agencies into the national system maintained by the Dominion Observatory.

Of these two suggestions only the second needs to be discussed. There probably exist in Canada hundreds of thousands of gravity observations, mainly by exploration companies, which are on local reference systems and were made with gravimeters with scales constants in error by as much as 2-3 per cent. While it would be impossible to reclaim this large volume of data for a number of reasons, action can be taken to ensure that future work is done on the proper standard. This will require increased cooperation between companies and agencies engaged in gravity work and the Dominion Observatory to ensure that standards maintained by the latter are used properly. This will also involve the provinces because it will be necessary to obtain data from provincial files as they are made public.

Increased effort is needed to establish data banks to store existing data and to serve as the medium for more effective distribution of gravity data. Nationally this can be done through the Dominion Observatory's data library currently in operation.

An area in which a greatly increased effort is needed is the field of physical geodesy (the application of gravity data to studies of the shape of the earth). The Observatory employs a physical geodesist and plans its program with the requirements of this discipline in mind. The only other institution with a continuing program in physical geodesy is the University of New Brunswick. This is not a record of which Canada can be proud, especially as this country occupies such a comparatively large portion of the globe. Both existing agencies should increase their activities immediately and other universities should be encouraged to include physical geodesy in their curricula. No specific aspects of the discipline can be singled out as more important than others because this discipline is so poorly represented in Canada.

In recent years great strides have been made in understanding global tectonics. These studies have mainly concerned the oceans and consequently application of these new theories to understanding the development of continents is much needed. Since gravity data are important to studies of crustal structure and since Canada covers the entire spectrum of geological time, an increased amount of gravity interpretation is necessary to profit from recent theoretical advances. Universities as a group are not particularly active in gravity studies. Staff of university departments should spend more time with gravity data. This would have the added advantage of providing an adequate supply of graduates with training in the gravity method and thus cut down on Canada's reliance on foreign trained scientists.

With the exception of geodesy, where much more money is required, these suggested areas for increased activity are a matter of emphasis rather than large new programs. Some increase in expenditure and personnel will obviously be necessary, but this is minor in comparison to the value obtained in terms of a huge increase in data available and more effective application to Canadain problems.

TRAINING

Training for professionals working in the broad field of gravity investigations is provided by physics, mathematics and geology departments and specialists from each discipline are employed by agencies involved with gravity work in Canada. Most have training in potential theory, obtained from graduate or undergraduate training in one or more courses. Nearly all scientists active in the field have had graduate training to the Master's level and probably more than half have completed their Doctorate. Basic training is available at all universities in Canada, but opportunities for specialization at the graduate level are more restricted and consequently many of the scientists active in gravity studies have received their graduate training outside Canada.

Training for technologists engaged in gravity work now comes almost entirely from institutes of technology which have now been established in most provinces. Institutes in Alberta, British Columbia and Ontario (Haileybury) offer direct training in the gravity method, but most technical personnel have received their basic training in either electronics or surveying and received further training at their place of employment.

FUTURE TRENDS AND LEVELS OF ACTIVITY

As only about 60 per cent of Canada is covered with gravity stations at intervals of 15 km, compilation of this regional coverage must remain the most important objective. This will require at least ten years of work at the present level of activity and will be a difficult task because the areas that remain are the most difficult in which to operate.

There is a need for much more closely spaced gravity stations, as close as one kilometer, in various areas of Canada and this need will increase during the next ten years. This requirement cannot be met with existing manpower if current methods of gravity surveying are employed, and this will mean either increased manpower or improved procedures or, more likely, both. One possible solution is the development of a completely airborne system of measuring gravity. Such systems are still in their infancy but tests to date give reasons for optimism. The capital expenditure will be initially large for those systems but their operational costs will almost certainly be low and this coupled with flexibility should make airborne systems a powerful tool in the earth sciences.

Satellite gravimetry is at present only useful for studies of features with wavelengths of the order of thousands of kilometers. During the seventies improved techniques will permit definition of anomalous features of the earth's gravity field with wavelengths of about 300-500 km. It is likely that this work will be done in the United States, but the results will be available for application by all countries.

There is a need for more gravity data in regions of economic interest and provincial agencies should be encouraged to provide more of this data in accordance with the standards of the national system.

The measurements, reduction of measurements and presentation of the measurements will become more and more automated through increased use of electronic recording equipment and computers. It is also important that libraries of existing measurements be established and maintained in order that they serve the needs of future investigations. The cost of maintaining such libraries by computer is not large and if similar libraries can be established for topographic, geodetic, geologic and other geophysical data the contribution that can be made from gravity and other data can be greatly increased at comparatively small added expense.

Instruments such as earth tide meters, tiltmeters, gradiometers and other more specialized instruments have either been recently introduced or are being contemplated for work in Canada. The impact of these instruments is hard to assess at present, but their potential assistance to our understanding of processes that take place within the earth are great and more emphasis will gradually be placed on their use during the next decade.

Canada is among the more advanced countries in terms of applying computers to practical problems of gravity investigations. This role can be maintained only by continued emphasis on the development of computerized techniques.

CONCLUSIONS

(1) The Dominion Observatory should make every effort to complete the regional gravity survey of Canada within the next ten years. Oil search has given added impetus to the need for gravity coverage on Canada's continental shelves and inland waters and hence priority should also be given to completing the gravity coverage in Canadian waters. The Bedford Institute and the Dominion Observatory should cooperate more in planning the systematic gravity coverage of all Canadian waters.

(2) More detailed, follow-up gravity surveys of anomalous regions of interest are a natural consequence of the regional work. Much of this follow-up work is done by industry in the search for structures of potential economic importance, but the provincial agencies should be encouraged to play a more active role in detailing areas of local anomaly as is done for example, by the Saskatchewan Research Council and the Nova Scotia Research Foundation.

(3) Canadian earth scientists should continue to place the main emphasis in their research programs on Canadian problems. Areas of interest where problems have been identified should be studied by multidisciplinary surveys employing the different techniques of geophysics and geology.

(4) The Dominion Observatory should continue its program of pendulum measurements in Canada and should undertake measurements of absolute gravity at selected sites in Canada. These measurements are essential to the establishment and maintenance of the Primary Gravity Control Network of Canada which serves as a reference for all gravity measurements in Canada. The network is also essential to the establishment of local data banks designed to exchange gravity data (see recommendation 5). This network will also serve as a basis for future experiments designed to study medium and long term variations of gravity.

(5) Federal, provincial and industrial centres should maintain computer libraries of gravity and density measurements (along with other geophysical, geological and topographic data). These data banks should operate on a uniform system so that interchange of data is straightforward. A modest beginning has been made at standardizing gravity measurements throughout Canada to the national standards maintained at the Dominion Observatory. If uniform standards are maintained in all data banks the value of the data will be enormous to studies of earth science in Canada.

(6) In 1964 the Associate Committee of Geodesy and Geophysics of the National Research Council strongly recommended that the Dominion Observatory and the universities undertake a program to measure earth tides and crustal tilt throughout Canada. This program has been started but more and improved instrumentation is required with a more concentrated effort to operate stations in the different geological environments in Canada in order to study variations in the properties of the earth's interior.

(7) In recent years vertical movements and isostasy have resumed their important role in geophysical and geological studies. Such studies are important because they can be related to current geological phenomena and a thorough understanding of these processes will provide a better background for studying events that have taken place in the past. The collection of data pertinent to these studies is a long and tedious process at present, but the time required to acquire these data could be reduced by more financial support for improved instrumentation. It is specifically recommended that support should be given to applications for financial grants to study all aspects of this broad subject.

SELECTIVE BIBLIOGRAPHY

Garland, G.D. The Earth's Shape and Gravity, Pergammon Press, London, 1965.

Grant, F.S., and West, G.F. Interpretation Theory in Applied Geophysics, Intern. Ser. in Earth Sci., McGraw-Hill, 1965.

Hamilton, A.C. Gravity measurements in Canada, Jan. 1, 1957 to Dec. 31, 1959; Pub. Dominion Obs., vol. 24, No. 3, 1960.

Hamilton, A.C. Gravity measurements in Canada, Jan. 1, 1960 to Dec. 31, 1962; Pub. Dominion Obs., vol. 28, No. 3, 1963.

Innes, M.J.S. Gravity measurements in Canada, Jan. 1, 1951 to Dec. 31, 1953; Report for I.U.G.G. 10th Conference, Rome, Italy, 1954; Trav. de l'Assoc. Intern. de Geodesie, Rappt. Nationaux, tome 18, No. 1, Paris, 1954.

Innes, M.J.S. Gravity measurements in Canada, Jan. 1, 1954 to Dec. 31, 1956; Pub. Dominion Obs., vol. 19, No. 1, 1957.

Loncarevic, B.D. Techniques of gravity measurements at sea, Intern. Dictionary of Geophys., pp. 694-700, Pergammon Press, London, 1967.

Tanner, J.G. Gravity measurements in Canada, Jan. 1, 1963 to Dec. 31, 1966; Pub. Dominion Obs., vol. 36, No. 2, 1967.

GEODESY

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DEFINITION

Geodesy is the study of the size and shape of the earth and its associated potential field. This includes study of the changes in the size and shape with time, i.e. crustal movements, tidal motion and continental drift. These studies require major surveys to determine precisely the relative positions of points on the earth as well as the mapping and charting of the earth's surface. Study of the potential field is carried out using gravity and positional astronomy observations.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Geodetic activities result in a better definition of the size and shape of the earth which is essential to other geophysical disciplines as well as necessary for resource planners and developers in the design of projects. Canada, with its vast land and water area, has a special responsibility in these fields.

Research in geodesy is aimed at improving the determination of the relationship of points on the earth. This imposes the need for defining more precise models of the earth.

Development is concentrated on the design of more reliable and more accurate measuring instruments and other techniques for data collection. The use of satellites, for example, has provided geodesy with new observation techniques for a worldwide uniform framework of control points and a worldwide definition of the earth's geopotential field.

HISTORICAL DEVELOPMENT AND PRESENT LEVEL OF ACTIVITY

Most geodetic activities in Canada have taken place in the last 60 years, following the founding of the Geodetic Survey of Canada in 1909. The first important contribution to research and development was in optical instrument design. Before 1960 only limited geodetic research was done at Canadian universities. Since 1960 there has been a considerable increase in research at the Universities of British Columbia, Laval, New Brunswick and Toronto. The main areas covered in the university programs are in satellite geodesy, geophysics, photogrammetric applications in geodesy, crustal movement studies, study of datums, analysis of data, refractive index studies, and development of instruments.

Some detailed crustal movement studies, local geoidal studies, and mean sea level investigations based on tidal gauge data have been made by the Department of Energy, Mines and Resources, Ottawa. Development of instrumentation, data processing techniques and numerical analysis is also continuing.

The collection of geodetic data has increased sharply in the last 10 years. New framework control in northern latitudes has been established together with an extensive program of densification of and addition to existing control in southern areas. Results of relevelling have verified crustal movement in certain areas of Canada. Increased astronomical position determinations provide the Geodetic Survey with material for local geoidal profile and for Canada-wide geoid determinations. This activity provides a basis for co-operative continental and global studies of the earth's potential field.

NEED FOR INCREASED ACTIVITY, MAJOR OBJECTIVES AND FUTURE TRENDS

There is an increased need for control for the development of integrated surveys and mapping systems for the provinces and densely populated municipal areas.

Some of the provinces (i. e. the Atlantic Provinces with federal assistance) have embarked on the establishment of new land tenure systems, large-scale mapping programs and geo-coding for registration of property, population density, exploration, etc. This requires a dense system of accurately determined survey control and large-scale maps. National continental and global geodetic studies are the basis for an adequate framework to meet these demands. Canada covers half a continent and therefore has major responsibilities to international geodesy. Satellite and ground data collection provides an immediate benefit to resource development, as well as to the geosciences. Present and anticipated technological developments will lead to more accurate determinations of special relationships of points on and above the surface of the earth.

TRAINING

At present, two universities (Laval and New Brunswick) offer full courses in geodesy. The Universities of Toronto and British Columbia have options or special courses in geodesy. Master's and Ph. D. degrees with specialization in geodesy or photogrammetry can be obtained at the Universities of New Brunswick, Laval, and Toronto.

A number of technological institutes or colleges provide training for technicians and technologists in surveying and photogrammetry.

CONCLUSIONS

The following conclusions relate to the Canadian ability to meet, on the national and international level, the economic and scientific needs of the country.

1. Universities and federal agencies must continue to work closely with the United States Coast and Geodetic Survey in their program of global and continental satellite triangulation.

2. To provide an adequate system of control points for economic development and earth science research, the federal government should concentrate its efforts in geodetic surveying on the establishment of basic, national, horizontal and vertical control.

3. The national "astro-geodetic levelling" program should be accelerated to provide at least one east-west and one north-south geoid profile.

4. Precise levelling should be extended into the northern areas of Canada to establish a "minimum" reliable network of vertical control.

5. Closer liaison and co-operation among earth scientists and geodesists is necessary to obtain knowledge of the size, shape and behaviour of the solid earth in Canada.

GEOCHRONOLOGY AND STABLE ISOTOPE STUDIES

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DEFINITION

Geochronology in its most general sense is concerned with the assignment of numerical dates to geological events so that the evolution of the earth may be seen in proper perspective and thereby more easily understood. It seeks to answer such broad questions as: How old is the earth? When were the continents formed? Have the continents grown with time or is the continent largely reworked from a pre-existing crust? Have orogenies occurred with a relatively fixed frequency? Are the geological histories of different continents similar? What is the rate and variability of ocean floor spreading? When did life first appear on earth and at what rate has it evolved? Was ore formation confined to certain periods of time? What are the time relationships between magmatism, metamorphism, sedimentation and ore deposition?

On a smaller scale, geochronology is used to unravel local geological histories and aid stratigraphic correlations.

The principal methods used are based on the radioactive decay of K^{40} to Ar^{40}, Rb^{87} to Sr^{87}, U^{238} to Pb^{206}, U^{235} to Pb^{207}, Th^{232} to Pb^{208}, and the spontaneous fission of U^{238}.

Stable isotope studies carried out in Canadian laboratories involve principally the stable isotopes of sulphur, oxygen, hydrogen and carbon. In view of the economic significance of sulphide minerals, sulphur isotope studies are of particular importance. Stable isotopes give useful information regarding pressure-temperature conditions during the formation and subsequent history of a rock. They shed light on the sources of ore elements and their concentration, provide knowledge of the significance of biological activity in ore and petroleum formation, and aid in defining the meteoric or magmatic origin of sulphide deposits. Oxygen isotope studies have yielded new insights into the relative importance of juvenile and meteoric waters in ore-forming processes. Thus, water in the minerals of hydrothermal alteration zones associated with porphyry copper deposits has been shown to be dominantly of meteoric rather than magmatic origin.

PRACTICAL APPLICATIONS

Geochronology and stable isotope studies are of considerable but largely indirect importance. Geochronological studies have made a significant contribution to the delineation and mapping of tectonic provinces in Canada. The establishment of the relative ages of the major divisions of the Canadian Shield, for example, has been a major geochronological achievement. Information of this nature is of value to the planners of mineral exploration programs, since a number of important mineral belts occur at the boundaries between geological provinces.

It would clearly be most desirable to know the exact time of formation of ore bodies for correlation purposes. The common lead method is of particular interest in this context, since it is applicable to lead from galenas in orebodies. It provides information on the origin of such lead, the mechanism of ore formation, and the time of deposition. Eventually it should be possible with this technique to indicate the proportion of a given lead derived from the mantle and that portion derived from the crust. There is a tendency for leads satisfying certain geological criteria to have characteristic types of isotope ratios, and it may be possible in the future to use such observations for the purpose of economic prediction. Thus, regional variations in lead isotope ratios, or calculated thorium-uranium ratios for source rocks of multi-stage leads, may be useful in outlining centres of mineralization. In areas where both stratiform and fissure deposits occur, the two groups are commonly characterized by noticeably different lead isotope ratios. Since stratiform deposits are commonly much larger, it is obviously important to have such criteria for their recognition at an early stage in exploration. Studies of this nature and the determination of lead isotope ratios in connection with soil geochemical anomalies are currently under way for the East Kootenay district of British Columbia.

It cannot be overemphasized that geochronological and stable isotope data provide an essential framework into which nearly all geological and mineral exploration research must be fitted. Stable isotope studies provide information regarding temperature and pressure conditions during deposition which act as useful boundary conditions for theories of ore genesis. In the study of the Precambrian, from which much of our mineral wealth is derived, it is necessary to rely almost entirely on radiometric dating for long-range time correlation.

HISTORICAL DEVELOPMENT

The first geochronology measurements based on radioactivity were carried out around 1905 at McGill University by Rutherford and his associates. Development of the subject came about very slowly, however, perhaps for two reasons. First, it was necessary to await the invention and development of the mass spectrometer. Second, the U/He method of age determination was severely handicapped by the ease with which He escapes from minerals. Canadian workers were prominent in subsequent developments (1918-1939). Dempster was a co-inventor of the mass spectrometer; Ellsworth carried out classic U/Pb investigations; Keevil contributed greatly to the understanding of the limitations of the U/He method. The modern era of geochronology, however, really began in 1948 with the first detection of radiogenic argon in minerals. Since then the K/Ar, Rb/Sr, U/Pb and Th/Pb methods have been established and refined to a level undreamed of in 1950. Experimental precision has advanced so that ages are now generally analytically accurate to about ± 5 per cent, while advances in interpretation have been equally noteworthy. Current methods enable rocks ranging in age from 500,000 years to the age of the earth (4,600 million years) to be dated accurately. Within the last five years the K/Ar method has been developed sufficiently to allow minerals about 10,000 years old to be meaningfully dated. The overlap of the K/Ar method with the C^{14} technique is now a reality, although a great deal of additional improvement is needed. Canadian scientists have contributed significantly in a number of these areas. One might mention the pioneering work in the 1950's at the University of Toronto on lead isotope studies and K/Ar dating, developmental work on K/Ar dating at the University of Alberta, and the immense regional K/Ar mapping of the divisions of the Canadian Shield by the Geological Survey of Canada. In the rapid expansion of stable isotope studies in the 1950's, Thode and his co-workers at McMaster University made major contributions.

PRESENT LEVEL OF ACTIVITY

At the present time, isotopic research activity is increasing in laboratories across Canada. The situation is summarized in Table 1.

TABLE 1

Number of Isotope Facilities per Province

Province	No. of Labs.	Rb/Sr	K/Ar	Common Pb	Fossil Fission	U/Pb	Stable Isotopes
Ontario	6	4	5	2	2	1	3
Quebec	2	2	1	-	-	-	-
B. C.	1	1	1	1	-	-	-
Alberta	2	1	1	1	-	1	2
Manitoba	1	1	-	-	-	-	-
N. S.	1	1	-	-	-	-	-
Total	13	10	8	4	2	2	5

The facilities listed in Table 1 are located in 13 laboratories, of which 11 are located in university departments, one in a governmental agency and one in industry. Two C^{14} laboratories, in Ottawa and Saskatoon, are not included. It is immediately apparent that the K/Ar and Rb/Sr methods are much the most widely used. The K/Ar method is appealing because of its potential use with a wide variety of rocks and because of the availability of a relatively inexpensive but eminently suitable mass spectrometer, the A. E. I. MS 10. All the Canadian K/Ar laboratories use this instrument. The Rb/Sr method has become extremely popular since the development of the Rb/Sr whole-rock method. This is a very powerful tool, in many cases "seeing through" thermal episodes and long cooling histories, and enabling the original times of crystallization of intrusive bodies to be determined.

Table 1 illustrates strikingly Canada's considerable strength in geochronological studies.

TABLE 2

Number of Geochronological Laboratories in Several Countries

Australia	2	Italy	1
Belgium	1	Japan	5
Canada	11	Netherlands	1
Czechoslovakia	1	New Zealand	1
Britain	5	South Africa	1
Finland	1	Sweden	1
France	6	Switzerland	4
Germany	6	United States	43

The data for Table 2 were taken from a list published in the Geological Newsletter of the International Union of Geological Sciences (1968, No. 1). No similar list was available for stable isotope laboratories. While the compilers note that the list is not perfectly accurate, it is in fact a fair summary and demonstrates that Canada has a significant capability in the field of isotope geology. The only countries more deeply involved in isotope work than Canada are the United States, the Soviet Union, and perhaps Germany. However, the number of Canadian laboratories compares well with those in the United States.

TRAINING NEEDS

Isotope geology is an interdisciplinary field involving geology, geophysics, physics and chemistry. As a consequence, the current crop of research workers is largely a mixture of people of varying backgrounds. Usually a scientist receives his preliminary training in one or other of these fields. This variation in background training is reflected in the observation that isotope laboratories are found in Canada in eight geology departments, three physics departments, two geophysics, and one chemistry department. However, the newer laboratories tend to be located in geology departments, and as the techniques are now becoming standardized this seems to be a natural tendency. It is to be expected therefore that new specialists will come largely from geology with a strong background in physics and chemistry. They will probably have had an undergraduate training in geology and will have specialized in geochronological problems in their doctorate research.

Most technical assistants have had no previous experience with isotopic methods and require about two years of training to reach an acceptable level.

MAJOR OBJECTIVES AND FUTURE TRENDS

The prime objective of geochronology is to provide a time-scale against which the events of the earth's history may be measured. Such a detailed knowledge of the timing of events provides very rigorous boundary conditions for many significant geological and geophysical problems. The trend in future, therefore, must be toward the refinement and elaboration of the presently existing time-scale. Hence, future developments in geochronology, as in stable isotope studies, require advances on two major fronts - methodology and problem studies.

Methodology

The precision and range of application of the different analytical methods will be significantly improved. Several examples may be considered. To resolve questions concerning the geomagnetic field reversal time-scale and ocean-floor spreading, increased accuracy of the K/Ar dating of rocks less than 10 million years old is desirable. In common lead studies, more precise isotope ratios are required than are currently attainable with solid source mass spectrometers. It has been suggested that the Re/Os decay scheme may be useful for the direct dating of ores, and it would seem most interesting to test this possibility. The Ar^{40}/Ar^{39} method (developed in 1965), with its apparent potential for revealing the thermal history of rocks, will undoubtedly become widely used.

Problem Studies

(i) Isotope methods should be applied to many additional areas of the Precambrian Shield. While many K/Ar dates have been obtained, many more are required. The economically interesting carbonatite bodies have only recently been dated in any number. Study of the carbon and sulphur isotopes in Precambrian rocks is still in its infancy. The orogenic histories of the various provinces such as the Grenville Province are still poorly understood. Very few Rb/Sr whole rock, U Pb and Th/Pb age determinations have been made on Canadian Precambrian rocks. For instance, scarcely a dozen Rb/Sr whole rock isochron ages have been published for the Canadian Shield.

(ii) Calculation of the rate of ocean floor spreading will occupy workers with the K/Ar method for the next few years. Canadian geochronologists are already actively involved in dating rocks from the Mid-Atlantic Ridge.

(iii) A much greater effort is required in the dating of orebodies. Largely because of limitations in methodology, workers in the past have concentrated on dating such rocks as granites and lavas. The ore minerals themselves have been attacked consistently only by the common lead method which yields ages subject to a greater range of interpretation than Rb/Sr and K/Ar ages. In 1968 the first paper on the Rb/Sr analysis of sulphide ores (from Noranda, Quebec) was published. Very low rubidium and strontium concentrations were found but significant enrichments of Sr^{87} were observed, indicating that the direct dating of ores by the Rb/Sr method is an exciting possibility.

(iv) The various stable isotope methods should be applied in detail to rock types previously either not examined or merely cursorily surveyed. Carbonatites have already been referred to in this connection.

(v) The use of stable isotope ratios in geothermometry will undoubtedly receive much increased attention in the next few years. Thus, the differences in the O^{18}/O^{16} ratios for different mineral pairs give reasonable indications of the temperatures of final equilibration for a variety of rock types.

(vi) Few data are available on the oxygen isotope contents of such rocks as shales, greywackes and quartzites. Such information will help identify the sources of sediments.

CONCLUSIONS

From the foregoing, it is apparent that isotope geology is a field of great strength in Canadian Earth Sciences. While a considerable investment in terms of men and equipment has already been made, as may be seen from Table 1, in actual fact the investment has been spread rather thinly. With reasonable additions of financial support, all the Canadian facilities could become much more efficient. It is widely recognized that there are insufficient funds for the employment of technical assistants to assist in the routine operation of mas spectrometers and ancillary equipment. This is because all the isotope laboratories in Canada are located in the universities, with the exceptions of the one in the Geological Survey in Ottawa and one in industry. Most university professors are heavily burdened with teaching and administrative duties and consequently are relatively inefficient research workers. In the absence of a sufficient number of technical assistants, it is probably fair to say therefore that much of the research work is carried out by graduate students. While many useful projects are thus completed, it is also true to say that many are ignored as unsuitable for a Ph. D. thesis, or because the large amount of course work required leaves too little time for the student to conduct the necessary research. In such cases it is evident that considerable progress could be made by increasing the technical assistance available to a professor. However, the average amount of money per NRC award for isotopic studies has remained essentially constant at about $7,500 from 1963 to 1967. Thisis equivalent to the salary of a single technical assistant. If, as is typical, there are graduate students requiring summer support, it is not possible to hire an assistant chemist. The problem is compounded when one recognizes that additional significant expenses are also incurred in maintaining a chemical laboratory and a mass spectrometer laboratory, running field trips, and publication costs. Few researchers can adequately subsidize their NRC grants with awards from other bodies such as the Geological Survey of Canada and the provincial governments.

With regard to new equipment grants, several points may be made.

(a) K/Ar laboratories are relatively inexpensive and reasonably straightforward to establish and could therefore be reasonably located in institutions currently lacking them. Many geology laboratories, for instance, could use one fully. They are also almost an essential adjunct to a paleomagnetic laboratory.

(b) Rb/Sr, U/Pb and Th/Pb laboratories are more expensive to set up (largely because of the high cost of commercial solid source mass spectrometers) than are K/Ar laboratories. Results from them are also more slowly acquired. Nevertheless, they are more powerful tools for unravelling Precambrian problems of potential economic importance. It is concluded, therefore, that a number of new solid source mass spectrometers should be available in Canadian laboratories. In view of the expense, however, preference should be given to existing isotope laboratories. In this way, given problems could be studied using several different methods, and far greater rewards should be forthcoming than are usually found in investigations based on a single method.

(c) It is suggested that, while more instruments should be made available to existing laboratories for stable isotope studies, the establishment of a number of new laboratories should be encouraged. In view of the potential economic importance of these studies, it is in fact surprising that this field is not pursued more vigorously in Canada.

In conclusion, it would seem wise in the future first to emphasize the improvement of existing geochronology facilities mainly by increasing funds for the support of technical assistants and providing several more mass spectrometers. This would allow for a more effective use of existing men and equipment. In addition, there is a need for more new K/Ar laboratories.

Support for existing stable isotope laboratories should be increased and the installation of several new laboratories should be encouraged.

The establishment of new isotopic methods should also be supported generously. The fossil fission track method of dating, for example, seems to offer rich rewards for a very small financial investment. Finally, however, it is hoped that no formula for the support of isotope research will ever be adopted which completely denies the ingenious representations of talented individuals in unusual locations.

HEAT FLOW

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DEFINITION

In any attempt to understand the earth's history and its present physical state, a knowledge of its thermal conditions is of prime importance, since the earth is essentially a heat engine. Terrestrial heat flow is the amount of heat being lost from the solid earth by the process of conduction at the surface. The study of heat flow, and its spacial and temporal distribution, is a study of the thermal field of the earth and how it has reacted to sources at depth and the boundary conditions of temperature at the surface, which are imposed by the oceans, the atmosphere and solar radiation.

The study has no clearly defined boundaries, but contributes to the physics of the earth's interior: on the large scale it interacts with tectonophysics and vulcanology, and on the local scale with glaciology, permafrost studies, groundwater movement studies and mine ventilation. It includes both the measurement and interpretation of heat flow at the Earth's surface and the theoretical computation of the thermal conditions inside the Earth throughout all its history. The actual measurement of terrestrial heat flow constitutes only a small part of geothermal research, but most of the remaining wide field of study is neglected in Canada.

Heat is one of the principle forms of energy, and temperature is one of the principle factors governing the behaviour of materials and systems. It is hard to imagine that any natural science can be continued in a meaningful manner without due attention to heat and temperature. In the geological sciences heat and temperature are of prime importance in fields such as metamorphism, vulcanology, shock wave propagation, and theories of convective overturn in the mantle.

HISTORICAL DEVELOPMENT

The first heat flow measurements were made by the University of Cambridge and published in 1939, although measurements of underground temperature had been made for almost 200 years before that. After the Second World War, the study spread and increased slowly until the late fifties. A method for measuring the heat flow in the sea floor was developed at the Scripps Institute of Oceanography in 1949, and more measurements were made on land, notably in South Africa, United States, Australia, Great Britain and Canada. In the last 10 years there has been a rapid acceleration of the study in many of the industrialized nations of the world.

The first Canadian measurements were made by the University of Toronto and the University of Western Ontario, and were published by A.D. Misener and others in 1951. This early work was done in Ontario and Quebec, mostly in mines. The raw data from which some of the final conclusions were calculated were rather fewer in quantity than is now considered

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ideal. In 1957 A. E. Beck started work at the University of Western Ontario and has since played an important part in heat flow studies in Canada. Early topics of interest under Beck included the development of an in-hole method for the measurement of thermal conductivity of rock. This particular topic was followed for several years, and has also been studied at the University of Toronto. In 1962 the culmination of several important events occurred: first publications of heat flow data were made by the University of Alberta, McGill University, and the University of Western Ontario; of major significance also was the establishment of a small group at the Dominion Observatory for heat flow measurement and research which formed part of the expansion in geophysical science that was Canada's contribution to the International Upper Mantle Project.

It was intended that the Observatory group should have the ability to drill a small number of diamond-drill holes each year, primarily for heat flow studies. The original plan of the Upper Mantle Committee was that a network of about 25 widely spaced holes should be drilled throughout the entire country, but after 2 years it was realized by the Observatory group that a purely regional survey of an area the size of Canada on the scale on which it could be financially supported had little value. Better value for money and effort could be obtained by placing small patterns of holes to investigate specific features, and this has been Observatory policy since 1964. Features so far examined are the Mt. Edziza volcanic zone in northwestern British Columbia and the Kapuskasing gravity and magnetic anomaly in Ontario. The regional survey was continued as a secondary program by using as many abandoned commercially drilled exploration holes and operating mines as possible. Unfortunately, after the original two scientists were appointed in 1962, a Civil Service staff freeze occurred, which left the group without any support staff for the first 3 years of its existence. This created problems in routine measurement processes from which the group has never fully recovered.

A second group at the Dominion Observatory and the Polar Continental Shelf Project, under K. Whitham, used oceanographic heat flow techniques to investigate a specific problem in geomagnetism in the Canadian Arctic. All original members of that group have now dropped out of direct involvement in heat flow activities, but the project has been absorbed into the expanded original Observatory group, and is being extended to an investigation of making useful equilibrium measurements in shallow Arctic seas and lakes. The Bedford Institute of Oceanography has acquired equipment and provision for staff for the measurement of heat flow at sea, but has not been able to recruit staff to take advantage of the available positions and equipment. Appendix I summarized the history of Canadian heat flow measurement, and indicates the number of people currently involved, and the number of publications from each institute.

Between about 1950 and 1960 theoretical studies of the interior of the Earth were in progress at the Universities of Western Ontario and Toronto. At Western Ontario, R. J. Uffen performed calculations on the present day temperature and melting point distribution in the mantle and core and went on to propose the hypothesis of stress release as a mechanism in the formation of magma. Also at Western Ontario, A. E. Beck calculated the energy requirements for an expanding earth model. At Toronto, J. A. Jacobs obtained a theoretical temperature-time-depth relation for the Earth's thermal history.

Theoretical work of this nature was not continued in Canada, although ideas such as convective movement in the mantle, and low seismic velocity-high temperature zones were actively pursued elsewhere. Recently, D.E. Smylie of University of Western Ontario, has been studying the possibility of convection in the Mantle, and results of this study may be published shortly.

PRESENT LEVEL OF ACTIVITY

The level of current activity in data collection is shown in Appendix II, which lists all sites where measurements have been made or attempted by Canadian groups in Canada, and presents the totals of land measurements published, in the analysis process, in measurement process, and where holes are being drilled by all institutions. It should be noted that these totals do not include shallow sea and lake measurements by the Observatory groups, and some of the locations listed involve groups of holes (e.g., 82 holes at Noranda, 7 at Sudbury). Hence the totals reflected are only an approximate measure of current data collecting activities. Appendix III shows the number of measurements made by all countries. As seen in the appendices, Canadian effort on land and on the Arctic ice is at a reasonable level, but ship-borne heat flow measurement has been neglected. In the absence of short term benefits from geothermal research, Canadian industry has done virtually nothing in the field.

There is a clear difference between the modes of operation of the university groups and the Dominion Observatory group. The former undertake a small number of projects and study them intensively, achieving a high ratio of basic research to data collecting. For example, the Dominion Observatory borehole on the campus of the University of Western Ontario has been studied by the university group in far more detail than any other similar hole. This situation is dictated by the need to produce suitable material for degree theses. On the other hand, the observatory group, with its responsibility for drilling the series of special holes and for taking the best advantage of holes drilled by industry for other purposes, is forced to devote a large majority of its time to data collection at the expense of its research program. All research now in progress at the Observatory relates to methods and techniques of data collection and the interpretation of the results; there is no time for research in other geothermal fields. Equipment has been built which enables most routine measurements to be made by any competent technician, but the requirement for field parties of at least two, and the laboratory demands on the one technician available, require that field measurements must be made with at least one research scientist present.

It is not generally realized, even by other geophysicists, how few commercially drilled holes are suitable for heat flow measurement and how much time and effort must be spent to find these holes. Oil and gas exploration holes are particularly difficult to use, since productive holes have fluid movement problems and unproductive ones are abandoned, which totally prohibits entry. Furthermore core samples are virtually nonexistent from these holes.

NEED FOR INCREASED ACTIVITY

There is probably little need for an increase in land-based heat flow data collection relative to other geophysical disciplines at the scientific level, but there is a pressing need for adequate support staff, particularly in the Observatory group. An ideal ratio is probably one support staff member to one scientist. Heat flow data collection is specially vulnerable to this type of staff difficulty, owing to the very large number of routine measurements that go into the production of each completed heat flow value. There is an obvious and definite need for ship-borne oceanographic measurements, particularly off the west coast. A research program should be started to investigate the possibility of making measurements in shallow seas and on continental shelves to complement the observatory work in the Arctic channels and in lakes.

It is generally felt that more funds should be available for special drilling projects and, in particular, that some of these funds should be directed to the interested universities. One or two very deep holes, of 10,000 feet or more and fully cored could yield valuable results, particularly in the subject of disturbance to heat flow caused by fluctuations and irregularity in surface temperature. Evidence of climatic history of the Pleistocene period might be obtained in this way.

PRACTICAL APPLICATIONS

Most practical applications of Canadian heat flow research are several steps removed from current stages of activity. The main purpose, to find out more about the composition, structure and formation of the earth, may eventually lead to an understanding of the mechanism of mineral emplacement that would be invaluable to the mining industry. Attempts are being made to relate temperature and heat flow patterns with geological structure beyond the reach of present drilling techniques.

There are many side interests and measurement techniques that are immediately applicable, or might be if they were more widely known. A few examples are:

(i) Ground temperatures in permafrost zones are of importance to construction engineers and well drillers, and valuable data is slowly being accumulated.

(ii) Deep underground temperatures are of importance in mine environment control, and can be predicted.

(iii) Temperature greatly affects the nature and recovery possibilities of oil and gas deposits.

(iv) Temperature surveys can be used to obtain information on groundwater movement and underground water disposal. Accurate temperature measurement methods developed for measurement of terrestrial heat flow could be of value here.

A few countries are able to use anomalous amounts of geothermal energy for electricity generation, and heat flow measurement techniques are usef in further energy prospecting. Although there is no area of Canada where such development seems probable, the shortage of data and lack of attention prevents the possibility from being ruled out.

Looking ahead, one might expect possible applications in the design of large underground industrial or military establishments, or the possible exploitation of some of the enormous amount of low temperature energy that is available.

MAJOR OBJECTIVES AND FUTURE TRENDS

The most important objectives at present are:

(i) The establishment of a world-wide program of heat flow measurement. This will take many years and will involve a great deal of technique research before all the necessary data can be collected. Questions that will have to be answered include the following:

- How much reliance can be placed on a heat flow value from a single isolated borehole? Recent work at the University of Western Ontario suggests rather less than was earlier believed.
- Why is heat flow in the ocean floor approximately equal to that on land, when geochemical evidence suggests it should be less? Is this due to a fundamental misunderstanding of the earth's crust, or is it the result of bias in the measurement methods?
- How can heat flow be measured reliably in shallow seas and lakes, where present methods are dependent on bottom water temperature stability?
- How can the thermal conductivity of a large mass of coarse crystalline rock be determined from measurements of small samples in the laboratory? How can conductivity be determined when no cores are available and measurements must be made on drill cuttings?
- Canada's contribution to this effort, apart from in the field of oceanography, is adequate. However, large areas of Africa, South America, and Asia are essentially unknown.

(ii) A systematic study of the relationship between heat-producing elements and heat flow values.

Movement of heat by conduction cannot be interpreted fully without consideration of the origin of the heat. It seems probable that most of the surface heat flow comes from radioactive decay in the earth's crust. This study, in the context of heat flow, has been seriously neglected, but the need is now recognized. The University of Western Ontario has purchased equipment and has measurement programs underway. The observatory intends to obtain equipment within a short time.

(iii) A systematic study of the thermal and other physical properties of earth materials at high pressures and temperatures.

This type of study is just beginning in Canada, and will be of great value to geophysics as a whole. Major hypotheses, such as convection currents in the mantle and continental drift, imply assumptions about the behaviour of materials for which there is little evidence, either in favour or against. Many problems in the interpretation of geomagnetic data might be resolved by the availability of factual data.

Canada clearly has a responsibility to maintain an effort in geothermal research, and it is probably being done in the most effective way, by the maintenance of a permanent group in a government research establishment and by grants to universities where the interest exists. The role of industry is open to more question. Although industry is normally very helpful in providing boreholes for measurement there seems to be little return in benefits. Whether this is due to a genuine lack of need, a lack of application, or a lack of communications is not clear.

Whatever aspects of the field of geothermal research are chosen for future study, it is clear that the field has emerged in the last 20 years to become a major branch of geophysics. Insufficient heat flow data have been cited and will continue to be cited in arguments on such theories as continental drift, mantle convection, ocean floor spreading, and the origin of the earth and planets. An accelerating demand for data is anticipated as the new ideas and activities generated by the Upper Mantle Project and continuing research programs are expanded and developed.

CONCLUSIONS

(1) A Canadian laboratory, probably the Bedford Institute of Oceanography where provision for staff has already been made, should establish a program of heat flow measurement in the deep ocean floor. This is in demand by those who wish to investigate the unusual crust off the west coast of Canada, and would take extra advantage of expensive ship-time at sea.

(2) The routine data collecting facilities of the Dominion Observatory group should be improved by the addition of adequate technical support staff, thus freeing the scientists for a wide field of research. Otherwise, the present level of data collection will have to be reduced.

(3) The capability of drilling holes for scientific purposes should be improved, and the universities feel that they should be included. This could be done in several ways:

- Provision of funds for the current Dominion Observatory program to be extended into northern areas.
- Provision of funds for interested universities to begin similar programs.
- The drilling of one or more very deep holes of 10,000 feet or more for very detailed study.
- Revival of the idea of widely spaced regional coverage, although the cost of making this effective would be enormous.

In considering these proposals, it must be recognized that planning and supervision of drilling is a time-consuming occupation.

(4) More emphasis should be given to determining the distribution of radioactive heat sources in rocks.

This can be done with relatively minor outlay of capital for equipment. Because of the combination of scientific importance and relatively low cost, this development should be actively encouraged.

(5) Support should be given to the development of a laboratory or laboratories for the study of the physical properties of rocks under mantle conditions.

The setting up of such a program is a major undertaking, requiring good equipment and good staff. The University of Western Ontario has begun to set up a laboratory, but the subject has been so neglected throughout the whole world, that there is scope for more than one institution to enter the field. The importance of the study is such that it should be well supported financially.

APPENDIX I

Summary of Activity in Heat Flow Measurement

Laboratory	Supervising Scientist	Dates	Current Personnel	Publications*
Univ. Western Ontario	A. D. Misener	1949-51 approx.		11
Univ. Western Ontario	A. E. Beck	Cont. from 1957	1 sc., 2 gs.	
Univ. Alberta	G. D. Garland	1960-62 approx.		1
McGill Univ.	V. A. Saull	Cont. from 1960	1 sc., 1 gs.	3
Dom. Observatory	A. M. Jessop	Cont. from 1962	3 sc., 1 tech.	6
Dom. Observatory/ P. C. S. P.	K. Whitham	1964-66 merging with above		
Univ. Toronto	A. D. Misener	1946-49	1 sc.	5
Univ. Toronto	G. D. Garland	Cont. from 1965		
Dalhousie Univ.	R.D. Hyndman	Beginning 1968	1 sc., 1 gs.	
Univ. Calgary Bedford Inst. Oceanography	P. Gretener	Beginning 1968	1 sc., 1 tech.	

sc. - scientist, gs. - graduate student, tech. - technician

* Includes papers on techniques and instrumentation and data collection, but not theses.

APPENDIX II

List of Measurement Sites

Location	Description	Stage Reached	Laboratory
Nova Scotia			
Halifax	Dom. Obs. Borehole	Publ. 1968	Dom. Obs.
Oldham	Borehole	Analysis	Dom. Obs.
Antigonish	Borehole	Measurement	Dom. Obs.
Wallace	Borehole	Measurement	Dom. Obs.
Prince Edward Island			
Kelley Cross	Borehole	Measurement	Dom. Obs.
New Brunswick			
Bathurst 1	Borehole	Measurement	Univ. Toronto
Bathurst 2	Borehole	Measurement	Univ. Toronto
Bathurst 3	Borehole	Measurement	Univ. Toronto
Quebec			
Murdochville	Vertical hole in mine	Measurement	Dom. Obs.
Roberval	Dom. Obs. Borehole	Measurement	Dom. Obs.
Thetford	Horiz. holes in mine	Publ. 1951	U.W.O.
Ste Rosalie	Borehole	Publ. 1962	McGill Univ.
Lanoraie	Borehole	Publ. 1962	McGill Univ.
Valleyfield	Borehole	Publ. 1962	McGill Univ.
St. Jerome	Dom. Obs. Borehole	Analysis	McGill Univ.
Merrill Île.	Borehole	Measurement	Dom. Obs.
Calumet	Horiz. holes in mine	Publ. 1951	U.W.O.
Malartic	Horiz. holes in mine	Publ. 1951	U.W.O.
Noranda	82 Boreholes	Publ. 1968	U.W.O.
Noranda	Extended measurements	Measurement	U.W.O.
Ontario			
Russell	Borehole	Analysis	Dom. Obs.
Ottawa	Dom. Obs. Borehole	Analysis	Dom. Obs.
Franktown	Borehole	Publ. 1968	Dom. Obs.
Picton	Borehole	Analysis	Dom. Obs.
Brent	Borehole	Publ. 1962	U.W.O.
Brent	Borehole	Measurement	U.W.O.
Toronto	Borehole	Publ. 1951	U.W.O.
London	Dom. Obs. Borehole	Publ. 1967	U.W.O.
Western Ontario	20 Boreholes	Analysis	U.W.O.
Sudbury	Horiz. holes in mine	Publ. 1951	U.W.O.
Sudbury	7 Boreholes	Measurement	Dom. Obs.
Elliot Lake	8 Boreholes	In press	U.W.O.
Larder Lake	Horiz. holes in mine	Publ. 1951	U.W.O.
Kirkland Lake	Horiz. holes in mine	Publ. 1951	U.W.O.
Timmins	Horiz. holes in mine	Publ. 1951	U.W.O.

Appendix II (cont'd)

Location	Description	Stage Reached	Laboratory
Ontario (cont'd.)			
Cochrane	Dom. Obs. Borehole	Measurement	Dom. Obs.
Kapuskasing	Dom. Obs. Borehole	Measurement	Dom. Obs.
Hearst	Dom. Obs. Borehole	Measurement	Dom. Obs.
Terrace Bay	Dom. Obs. Borehole	Measurement	Dom. Obs.
Otoskwin River	Dom. Obs. Borehole	Drilling	Dom. Obs.
Minchin Lake	Dom. Obs. Borehole	Drilling	Dom. Obs.
English River	Dom. Obs. Borehole	Drilling	Dom. Obs.
Manitoba			
West Hawke Lake	Borehole	Lost	Dom. Obs.
Winnipeg	Dom. Obs. Borehole	Analysis	Dom. Obs.
Flin Flon	Horiz. holes in mine	Publ. 1962	U.W.O.
Saskatchewan			
Eldorado	Horiz. holes in mine	Analysis	Dom. Obs.
Alberta			
Redwater	Borehole	Publ. 1962	Univ. Alberta
Leduc	Borehole	Publ. 1962	Univ. Alberta
British Columbia			
Sullivan	2 Vertical surface holes Vertical hole in mine	Measurement	Dom. Obs.
Salmo	Borehole	Measurement	Dom. Obs.
Mica Creek	Borehole	Lost	Dom. Obs.
Penticton	Dom. Obs. Borehole	Analysis	Dom. Obs.
Bralorne	Horiz. holes in mine	Analysis	Dom. Obs.
Babine Lake	2 Boreholes	Measurement	Dom. Obs.
Tasu	21 Boreholes	Measurement	Dom. Obs.
Dease Lake	Dom. Obs. Borehole	Measurement	Dom. Obs.
Hotailuh	Dom. Obs. Borehole	Analysis	Dom. Obs.
Buckley Lake	Dom. Obs. Borehole	Analysis	Dom. Obs.
Yukon			
N. Cath	Borehole	Measurement	Dom. Obs.
Northwest Territories			
Reindeer	Borehole	Measurement	Dom. Obs.
Norman Wells	Borehole	Publ. 1962	Univ. Alberta
Muskox	Borehole	Publ. 1966	U.W.O.
Yellowknife	Borehole	Measurement	Dom. Obs.
Yellowknife	Vertical holes in mines	Measurement	Dom. Obs.
Providence	Borehole	Measurement	Dom. Obs.
Resolute South Camp	Borehole	Publ. 1955	U.W.O.
Resolute Bay	Borehole	Lost	Dom. Obs.
Neilsen Island	Borehole	Publ. 1968	Dom. Obs.

Appendix II (cont'd)

Location	Description	Stage Reached	Laboratory
Others			
Sable Island	Borehole	Measurement	Dom. Obs. / Dalhousie
Shallow Seas			
McClure Strait	3 Sites	Publ. 1965	Dom. Obs.
Crozier Channel	4 Sites	Publ. 1966	Dom. Obs.
Arctic Shelf	2 Sites	Publ. 1966	Dom. Obs.
McClure Strait	4 Sites	Analysis	Dom. Obs.
Fitzwilliam Strait	3 Sites	Analysis	Dom. Obs.
Lakes			
Lake Hazen	4 Sites	Analysis	Dom. Obs.
Lake Tuborg	3 Sites	Analysis	Dom. Obs.

Summary of Land Measurements

	Publ.	Anal.	Meas.	Drilling	Totals
Dalhousie	0	0	1/2	-	1/2
Dom. Obs.	3	10	21 1/2	3	37 1/2
McGill Univ.	3	1	0	-	4
Univ. Alberta	3	0	0	-	3
Univ. Toronto	0	0	3	-	3
U.W.O.	14	2	2	-	18
TOTALS	23	13	27	3	66

This summary must not be taken too literally since:

1. it does not give credit to the University of Toronto for its share in the results published in 1951;
2. several entries listed on single sites are really groups of holes within a small area;
3. it does not include Dominion Observatory or Dalhousie University work in shallow seas and lakes.

APPENDIX III

Published Heat Flow Data

Land and Lake-bottom Measurements

Africa:	Lake Nyasa	20	(Measured by scientists from U.S.A.)
	South Africa	14	
North America:	U.S.A.	131	
	*Canada	23	
Europe:	Iceland	13	
	France	2	
	Germany	12	
	*Czechoslovakia	52	
	Hungary	9	
	U.S.S.R.	58	
	Switzerland	3	
	Austria	2	
	Poland	1	
	Great Britain	10	
Asia:	India	14	
	Japan	37	
	U.S.S.R.	36	
	Iran	1	
Australasia:	Australia	48	

Oceanic Measurements

2179 (Mainly by expeditions from U.S.A., Great Britain, Japan, U.S.S.R.)

Summary

	All Countries	Canada	Percentage Canada
Land measurements	486	23	4.7
Ship-borne oceanographic	2140	0	0
Ice-borne oceanographic	39	10	25.6

- Area of Canada is about 6.7 per cent of total land area.

Data taken from:

1. Simmons and Horai J.G.R. 1968, 73, 6608-6629
2. Lee and Clark G.S.A. Memoir 97, 1966, 483-510

(except as marked "x" where up-to-date information is available)

SECTION III

GEOCHEMISTRY

EXPLORATION GEOCHEMISTRY

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INTRODUCTION

This paper, covering the field of exploration geochemistry, has been prepared after considerable discussion with many individuals in industry, universities, consulting firms, and government agencies. It is based largely on part of a survey previously done on chemistry in the Earth Sciences and related fields which forms a section of the Chemical Institute of Canada's "Survey of Chemical and Chemical Engineering Research and Development in Canada" on behalf of the Science Secretariat(1). This is a comprehensive report to which the interested reader should refer for details. Some features of the field of exploration geochemistry in Canada have changed since the Chemical Institute report was prepared. These changes are incorporated in the present report, together with some of the views expressed by individuals who commented on the background paper on exploration geochemistry circulated by the Solid-Earth Sciences Group during the early part of 1969.

DEFINITION

Exploration geochemistry or geochemical prospecting is the applied part of geochemistry that has as its aim the discovery of mineral deposits and accumulations of hydrocarbons.

Briefly, the various methods of geochemical prospecting which can be applied are based on major, minor or trace element analyses of weathered products, soils and glacial tills (pedogeochemical methods), on similar analyses of rocks (lithogeochemical methods), on similar analyses of natural waters, spring precipitates, and stream sediments (hydrogeochemical methods), on similar analyses of gases (atmogeochemical methods), and on similar analyses of biological materials, both fossil and living (biogeochemical methods).

The basis of geochemical prospecting by most of the above methods is the detection of minor or trace element halos or dispersion trains which may be either of a primary or secondary nature. In addition, certain igneous, sedimentary and metamorphic rocks may indicate the presence of mineral deposits by their specific trace or minor element content (e. g. nickel in basic rocks, copper in porphyry intrusions, etc.).

The primary halo or dispersion train is formed at the time the orebodies or accumulations of hydrocarbons were deposited; the secondary halo or train generally results from weathering and subsequent transport processes. These halos and trains in the rocks, soils, waters, stream sediments, rock gases, atmospheric gases, and biological materials reflect the presence of mineralization in many ways, both locally and regionally. The details of the halos and dispersion trains are much too complicated to be dealt with here, but a general idea of their nature can be obtained from a number of textbooks now available on geochemical exploration (2, 3).

The halos and dispersion trains provide the "anomalies" for which geochemical prospectors search, and the indicator-rocks point out general areas where orebodies may be located by further geological, geophysical and geochemical exploration methods.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT IN EXPLORATION GEOCHEMISTRY

The importance of geochemical exploration need hardly be emphasized since the methods and techniques are designed to locate and outline orebodies and accumulations of hydrocarbons that are vital to the economy of the nation. The methods employed are direct and have generally produced the best results when applied in conjunction with geological and geophysical exploration techniques.

In the past, prospecting has largely been confined to areas of outcrop in the mineralized belts of the world, and most discoveries of orebodies have resulted where their surface expressions were visible. This is also generally true of the great oil and gas fields, since these too have usually been indicated by oil seeps, gas jets, and other visual evidence. Today the visual phase of prospecting is rapidly passing, and most new orebodies and oil fields will be found under surficial deposits or deeply buried in the rocks.

Geochemical prospecting will play an ever-increasing role in the discovery of hidden ore deposits and accumulations of hydrocarbons. Geochemical methods are now well established, and it is generally recognized that they offer the only direct approach to the problem of locating deposits of minerals, oil, and natural gas. Regardless of how geophysical methods may develop, they will always remain indirect since they are based on secondary or induced properties of the elements or their minerals. They will thus generally lack the capacity to indicate precisely which elements are present in a deposit. Geological exploration methods, while of inestimable value, will also nearly always lack focus or capacity to pinpoint deposits. Discrimination and focus can only be provided by the application of chemical methods, particularly analyses. It is nearly axiomatic to say that chemical methods used in a variety of ways will continually assist in locating buried deposits of ores and hydrocarbons and will also point out those bodies, both rocks and waters, containing low concentrations of the elements that will become the orebodies of the future. Today, few would disagree with the statement made many years ago by A. E. Fersman that "the problem of prospecting for mineral resources is essentially a geochemical one".

The reader should not conclude from the above statements that geochemistry alone will solve all of the problems of prospecting for concentrations of the elements. On the contrary, it is essential in prospecting to use all of the methods available. It cannot be argued, however, as some have done, that geochemical methods are not applicable to certain types of deposits, terrains, etc. This bespeaks a lack of faith in the future of geochemical research. With minor exceptions, all rocks and deposits are the result of chemical processes, and it should be possible to determine the nature and history of these processes by the methods of modern chemical science. Armed with precise knowledge of this type, it will ultimately be possible, in conjunction with geological knowledge, to frame chemical methods for the discovery of any type of deposit in any given geological setting.

HISTORICAL DEVELOPMENT

The modern development of geochemical prospecting springs directly from the work in the 1930's of the famous Russian geochemists A. E. Fersman, V. I. Vernadsky, I. I. Ginzburg and A. P. Vinogradov; and the Scandinavians, V. M. Goldschmidt, S. Palmqvist, N. Brundin, Th. Vogt and K. Rankama (4, 5).

The concept of prospecting by geochemical methods was introduced into Canada by H. Lundberg in 1940, but it was not until 1945, when Drs. H. V. Warren and R. E. Delavault and their co-workers at the University of British Columbia began their research, that geochemical prospecting methods began to be taken seriously. Other early workers were J. E. Riddell at McGill University, and H. Hawkes, H. Bloom, J. E. Riddell and J. S. Webb, who conducted the first large-scale geochemical reconnaissance survey in northern New Brunswick in 1954.

Research in geochemical prospecting by the Geological Survey of Canada began in 1949 when a study of primary halos associated with gold deposits in the Yellowknife area was undertaken. This has been followed by work on waters and soils in the Yukon; reconnaissance surveys of waters and stream sediments in Nova Scotia and New Brunswick; biogeochemical surveys in a number of metalliferous belts in Canada; bedrock surveys in northern Ontario and in carbonate rocks in western Canada; and hydrocarbon analyses of soils over known oilfields in eastern and western Canada. In addition, a number of other projects have been carried out both in the field and laboratory, concerned with the development and improvement of geochemical methods and techniques.

Geochemical prospecting methods have been adopted by industry on an ever-increasing scale. From the initial effort of E. O. Chisholm in 1949, geochemical prospecting methods have grown to be one of the major tools in mineral exploration. Considerable research in geochemical methods is also now being pursued by exploration companies and consulting firms. Several of the provincial governments have also recently carried out regional geochemical studies as an aid to prospecting within their boundaries.

NEED FOR INCREASED ACTIVITY

The following comments are based on briefs and personal communications from a number of individuals in mining exploration activities, in consulting services, and universities, and on the comments made by numerous individuals on the initial background paper on exploration geochemistry.

The expenditures on geochemical prospecting by the mining industry is considerable: in 1967 it is estimated that the expenditure was $2.5 million; by 1972 this expenditure will increase to $7.5 million. The expenditures on geochemical prospecting by the petroleum industry up to and including 1967 were minimal compared with those spent on other methods of oil and gas exploration. Accurate estimates of the expenditures on geochemical prospecting for petroleum by companies in Canada are difficult to obtain but were probably not greater than half a million dollars up to and including 1967. There has been considerable improvement since then, and several companies contemplate much larger expenditures in the future according to confidential private communications.

The reason for the low level of activity in government institutions has been primarily due to the difficulty of recruitment and retention of qualified geochemists. In the past there has also been a failure on the part of government executives at all levels to appreciate the importance of geochemical prospecting research to the mining and petroleum industry of Canada.

The reasons for the low level of activity in geochemical prospecting research at Canadian universities is difficult to assess accurately but seems to stem from the fact that many geological faculties and faculty heads consider problems in mineral deposits and prospecting for mineral deposits not to be of scientific value - this despite the fact that the "bread and butter" of geological science is mineral and petroleum deposits. The comments by Professors H. V. Warren and R. E. Delavault, two of the pioneers in geochemical prospecting research in Canada, seem particularly pertinent in this respect:

> "When an attempt was made to introduce geochemistry into one Canadian university, with special emphasis on problems involved in mine finding, the attempt was vetoed on the ground that this type of work was not of high enough quality to be considered as a university subject, in spite of the examples provided by London University and California; surely centres of academic quality and competence."
>
> "Nor do the universities do much to raise the status of the mine-finding geochemists. Two of Canada's most important universities do have Institutes of Earth Science and under this umbrella one might reasonably expect to find some attention given to geochemistry as applied to mine finding. Such is not the case. Excellent and challenging work is being done in other geochemical fields, such as age dating, but a student enlisting in an Institute of Earth Science in

> Canada finds little, if anything, of substance offered in the fields of geobotany, biogeochemistry, and only a modest initiation to the various aspects of hydrogeochemistry, pedogeochemistry, and lithogeochemistry."

It seems hardly necessary to point out that these circumstances at our universities have led to the state where geochemists, trained in geochemical prospecting techniques and in the interpretation of geochemical data, are in short supply. It is encouraging to note that as this is being written, steps are being taken to improve this situation in at least two universities in Canada.

Research in the primary dispersion patterns of metals associated with mineral deposits continues at a low level in all institutions in Canada. This is a subject that requires immediate attention if deeply buried mineral deposits are to be discovered in the future. Research in the secondary dispersion patterns of metals in surficial materials, likewise, requires much more attention than it has received in the past. The comment in the brief by Dr. J. Hansuld, a well-known exploration geochemist in industry, seems particularly appropriate in this matter:

> "Research and development in the field of geochemical exploration is, with a few exceptions, just starting. Our understanding of the chemical processes taking place in surficial materials at or near the earth's surface is pathetic compared to what we know or think we know about the chemistry within the earth's crust. This situation is indeed ironic when one considers we can actually see and sample materials at the surface and yet know so little about them."

As this being written, extensive research is being planned in at least two Canadian universities on the precise details of secondary dispersion patterns and on the chemistry of surface waters, sediments, etc. The problems of the primary dispersion patterns of elements in and about mineral deposits and accumulations of hydrocarbons and the study of the chemistry of indicator rocks genetically related to these deposits is still, however, somewhat neglected.

A systematic long-term approach to research in geochemical prospecting for petroleum and other hydrocarbons should be pursued to promote this aspect of applied geochemistry. This should be done in universities or government institutions where the results will be published. In the past, oil companies have been remiss in publishing the results of geochemical surveys. This has led to a general behind-the-scenes assessment of the approach, some investigators lauding the successes of the methods and others denying that the methods are useful. No scientific method can make much progress without a detailed description and assessment of the techniques employed and a free discussion in the published literature.

Assessment of the extensive data of geochemical surveys now requires a statistical approach. There is, therefore, a requirement for students trained in geology and geochemistry to have an adequate knowledge of statistics and computer techniques.

Numerous exploration geologists and geochemists in industry and government have pointed out the necessity of establishing an institute for teaching and research in applied geochemistry at one of the universities in Canada. It is the considered opinion of all who were interviewed that such an institute should draw its funds from three sources - the mining industry, the petroleum industry, and government. The direction and teaching in this institute must be by adequately trained applied geochemists, and fundamental research should be mainly by thesis work leading to advanced degrees.

TRAINING NEEDS

A serious shortage of experienced geochemists capable of organizing, supervising and interpreting the results of geochemical surveys exists in Canada. To be effective and productive, geochemical surveys must be organized and carried out with care having due regard to the geological setting. This requires first of all that the supervisor have an accurate knowledge of modern geological exploration techniques and a knowledge of the methods and techniques of geochemical surveying. The geological and geochemical methods and techniques can be learned readily by any graduate geologist with a minimum of effort, and the necessary samples can generally be obtained quite effectively by students and unskilled labour. Similarly, analyses can now be done on a routine basis by commercial or company laboratories. The problem is at the interpretative phase of the geochemical work. In this respect an accurate knowledge of the geochemistry of the elements is required, and this can only be gained by an individual through courses in the chemistry and geochemistry of the elements and by experience. To be really effective, the individual interpreting geochemical surveys must think both geologically and chemically. There is no alternative.

Oil geologists have not, at least in Canada, seriously taken up the various methods available for chemical prospecting for deposits of hydrocarbons. Survey methods and extremely sensitive apparatus are now available for the analysis and location of hydrocarbons in every type of geological terrain and medium. Many geochemists believe that these methods could be applied to advantage in exploration programs for oil and gas. The results could be as rewarding as they have been in the mineral industry.

The training of exploration geochemists leaves much to be desired in Canada. Similarly, research in geochemical prospecting methods and in the interpretation of primary and secondary halos and secondary dispersion trains remains far below a desirable level at all institutions in Canada. This can be alleviated by more courses in geochemical exploration at the universities in Canada and by the foundation of an institute for teaching and the granting of graduate degrees in research in applied geochemistry at one of the universities in Canada.

CONCLUSIONS

Exploration geochemistry in Canada has grown enormously despite the general lack of interest by most universities and government institutions. The reason is, of course, economic incentive and the large number of mineral deposits and indications of mineral deposits that have been found by geochemical exploration methods in recent years. In 1967 and 1968 alone at least eight major discoveries of mineralization can be attributed solely to geochemical methods used in close conjunction with geological methods. The general interest in geochemical methods can be gauged by the attendance at two recent symposia on geochemical exploration in Ottawa and Denver, Colorado. Some 300 people attended the Ottawa symposium, and a greater number were present at the Denver symposium.

ACKNOWLEDGMENTS

I wish to thank the many individuals who contributed views, data and discussions on various features of Exploration Geochemistry during the period of preparation of the Chemical Institute of Canada survey and during the preparation of the present paper. I would especially like to thank the following for their briefs, personal communications, and criticism: Dr. D. R. Clews, Vice-President, Barringer Research Ltd; Professor J. H. Crocket, Department of Geology, McMaster University; Dr. J. A. C. Fortescue, Department of Fisheries and Forestry; Dr. H. V. Warren, University of British Columbia; Dr. R. E. Delavault, University of British Columbia; Dr. J.A. Hansuld, American Metal Climax, Inc., Toronto; Dr. C. F. Gleeson, SOQUEM, Quebec Mining Exploration Company, Ste. Foy; Dr. J. Alan Coope, Newmont Mining Corporation of Canada Limited; Dr. R. G. McCrossan, Institute of Sedimentary and Petroleum Geology, Calgary; Dr. E. M. Cameron, Geological Survey of Canada; Mr. A. Y. Smith, Geological Survey of Canada; Mr. E. H. Hornbrook, Geological Survey of Canada; and Dr. R. G. Garrett, Geological Survey of Canada.

Finally, I would also like to thank the many individuals who commented on the initial background paper on exploration geochemistry. The comments on this paper, often highly critical but to the point, have been of invaluable help in the preparation of this final report.

The individuals mentioned above should not be held responsible for any of the statements made in the present paper. They have simply offered opinions and advice which have been taken and integrated with the opinions and advice of many others. The final synthesis of opinions is due to the author alone.

REFERENCES

1. Boyle, R. W. et al. Chemistry in earth sciences and related fields. Unpub. paper prepared for Science Secretariat Survey of Research and Development in Chemistry in Canada, 1968. For summary, see Special Study No. 9, Chemistry and chemical engineering: a survey of research and development in Canada. Prepared by a Study Group of The Chemical Institute of Canada, A. E. R. Westman, Study Director, for the Science Council of Canada. Queen's Printer, Ottawa, pp. 62-64, 1969.

2. Ginzburg, I. I. Principles of geochemical prospecting (Translation from the Russian by V. P. Sokoloff), Pergamon Press, New York and London, 1960.

3. Hawkes, H. E., and Webb, J. S. Geochemistry in mineral exploration. Harper and Row, New York and Evanston, 1962.

4. Boyle, R. W., and Smith, A. Y. The evolution of techniques and concepts in geochemical prospecting, in The Earth Sciences in Canada, Roy. Soc. of Can. Spec. Pub. No. 11, pp. 117-128, 1968.

5. Boyle, R. W., and Garrett, R. G. Geochemical prospecting - a review of its status and future. Earth Sci. Rev. (in press).

BASIC GEOCHEMISTRY (ORGANIC AND INORGANIC)

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DEFINITION OF THE FIELD AND ITS BOUNDARIES

The earth can be logically divided into five spheres as follows - lithosphere, pedosphere, hydrosphere, atmosphere, and biosphere. The lithosphere comprises the solid portion of the earth which near the surface consists essentially of consolidated rocks; the pedosphere is composed of the weathered products and soils of the earth including glacial materials; the hydrosphere includes the oceans, fresh water surface bodies, and groundwaters; the atmosphere comprises the gases in the outer envelope of the earth and in the rocks; and the biosphere is the sphere of life and includes all living organisms on the earth as well as their fossil remains such as peat, coal, and petroleum.

Basic geochemistry is best defined as the acquisition and interpretation of data concerning the abundance, distribution, migration, and concentration of the elements and their isotopes in the five spheres of the earth. The subject is extremely diverse and impinges upon nearly every aspect of geology, mineralogy, and biology. Certain data of cosmochemistry, especially those derived from the chemistry of meteorites, are also useful in calculations of elemental abundances, in isotope work in geochemistry, and in other ways.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT

It need hardly be stressed that a knowledge of the chemistry of the earth and of the abundance of the elements and their isotopes in the earth have an infinite number of practical applications. These of course depend essentially on understanding the fundamental chemical processes taking place in the earth. Elucidation of these processes constitutes the basic research aspects of geochemistry, and on this acquired knowledge depends the development of ways and means of controlling and utilizing the natural chemical environment.

A knowledge of the chemistry of rocks assists in a better understanding of the nature of mineral deposits. Geochemical prospecting, one of the applied aspects of basic geochemistry, provides a relatively cheap and efficient method of discovering new mineral deposits and accumulations of petroleum and natural gas. Other and equally important aspects include utilization of the knowledge of the chemistry of soils for the betterment of agriculture and forestry; utilization of the knowledge of the chemistry of natural waters in water supply, fisheries, and the amelioration of the pollution problems that beset the nation as a result of industrialization; utilization of the knowledge of the chemistry of the atmosphere in assisting meteorology and alleviating air pollution; and utilization of the knowledge of the distribution of certain elements in soil and water in combating certain endemic diseases in plants, animals, and man caused by deficiencies or excesses of these elements.

HISTORY OF RESEARCH AND DEVELOPMENT

The term geochemistry was introduced in 1838 by C.F. Schönbein, the Swiss chemist who discovered ozone. Not until the twentieth century, however, did the science reach maturity. Most of the fundamental aspects of geochemistry have been worked out in Europe and the United States, principally by V.I. Vernadsky (1863-1945), A.E. Fersman (1883-1945), V.M. Goldschmidt (1888-1947), and F.W. Clarke (1847-1931). In Canada the study of geochemical processes and the acquisition of geochemical data began with T. Sterry Hunt (1826-1892), a longtime member of the Geological Survey of Canada. Since Hunt's time various facets of the chemistry of the earth have been pursued by many Canadian agencies and academic institutions concerned with geology, mining, agriculture, forestry, fisheries, meteorology, water supply, the oceans, and the health of the nation.

No consensus could be obtained on the most significant advances in the field of basic geochemistry in Canada, probably because of the great diversity of the subject and the bias of individuals for certain fields. It is fair to say that Canadians have contributed significantly to advances in soil and water chemistry, to general rock geochemistry, and to the chemistry of isotopes and meteorites.

PRESENT LEVEL OF ACTIVITY AND SUGGESTIONS FOR INCREASED ACTIVITY

Research in basic geochemistry is pursued in at least three ways - (1) by chemical and isotopic analyses of meteorites, rocks, mineral deposits, soils, sediments, waters, the air, and biological materials; (2) by studies of dynamic chemical processes in the five spheres of the earth, at the interfaces of these spheres, or where one sphere impinges on one or more of the other spheres; and (3) by chemical and isotopic experiments devised to simulate the natural situations. Analyses of materials from the five spheres, after statistical treatment, yield abundance figures for the respective spheres, and these figures when integrated, with due regard to the volume of each sphere, yield overall abundance figures for the earth. A knowledge of the chemical reactions in and on the earth yields information on the migration, concentration and dispersion of the elements in the various spheres of the earth. All of these aspects are of vital importance in the practical use of geochemistry, especially in agriculture, in forestry, in the fishing industry, in pollution control, and in geochemical prospecting for mineral deposits. The fundamental data on abundances and on the chemistry of the elements in the earth are the foundation on which all practical work in geochemistry is based.

The data[1] of fundamental or basic geochemistry come from several sources, as follows: (1) geological, mineralogical, and petrological

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[1] I do not wish to convey the impression that basic geochemistry is purely a data gathering exercise. On the contrary most geochemical work, including analyses, is done to test certain theories or hypotheses. It should be stressed, however, that the permanent residue of geochemical research is the accumulated data. Theories and hypotheses are temporal. A few are found to be in the nature of laws, but most are ultimately relegated to the rubbish heaps of science.

investigations, (2) surveys and investigations by soil scientists, (3) surveys and investigations by oceanographers, hydrologists, and water control agencies, (4) meteorological and air chemistry studies, (5) various biochemical and biogeochemical investigations, and (6) specialized geochemical investigations including meteoritic studies.

Because of the diversity of the origin of the data it is impossible to estimate accurately the number of personnel engaged in geochemical research and providing fundamental geochemical data. An arbitrary figure of perhaps 100 investigators seems reasonable. It is quite impossible in the time available to this writer to determine the money expended on the acquisition of the data since the geochemical aspect of the various investigations ranges all the way from minor to major proportions.

Since 1945 research in basic geochemistry at Canadian universities and government institutions has increased yearly. However, on a per capita basis, compared with the U.S.A., U.S.S.R., Britain, and France, it is the consensus of many who were interviewed that the level of activity is still relatively low. There are some serious gaps in fundamental research and acquisition of data from certain spheres of the earth in Canada mainly because of too much specialization in certain fields, particularly in those concerned with igneous rocks and igneous processes.

The state of research and acquisition of data in basic geochemistry is discussed briefly below. The views expressed summarize the consensus of experts in the various fields as well as geochemists, geologists, soil scientists, etc. in industry, universities, and government institutions.

1. Research and acquisition of chemical and isotopic data on meteorites is proceeding at a satisfactory level and is maintaining pace with falls of these extra-terrestrial objects.

2. Research and acquisition of geochemical data on igneous rocks, igneous processes, metamorphic rocks, and metamorphic processes is adequate and expanding yearly at a desirable rate. This is probably because of the traditional stress at Canadian universities and government institutions on igneous rocks and igneous processes and metamorphic rocks and metamorphic processes.

3. Research and acquisition of geochemical data on sedimentary rocks and sedimentary processes is low and not expanding rapidly enough, having regard to the importance of these rocks and processes in petroleum and metallic ore geology.

4. Research and acquisition of geochemical data on all varieties of surficial materials (soils, till, glacial clay, stream and lake sediments) is adequate for agricultural needs and probably also adequate for the needs of the foresters. It is inadequate for pollution research, and certainly inadequate as far as geology is concerned, especially geochemical prospecting. Few geochemists have been addressing themselves to surficial materials research in Canada mainly because most universities have neglected to expand training and research in this fundamental field commensurate with present day needs. Government geological institutions have, likewise, failed to expand sufficiently in this field. Research in surficial chemical processes at universities and government institutions is woefully inadequate, a state that urgently requires correction, considering that the surface geology of Canada is largely concerned with Pleistocene deposits and soils developed on them.

As this is being written some steps at a few universities and government institutions are being taken that will partly correct this situation.

5. Research and acquisition of geochemical data on natural waters (ocean, lake, river, stream, and groundwaters) falls into two categories - that concerned with major constituents and that concerned with trace constituents. Research and acquisition of data on major constituents by various government institutions and agencies has been extensive and will probably expand in the next 5 years to a level commensurate with the requirements of the country. Research and acquisition of data on the trace constituents of all natural waters is completely inadequate at this point in time, having regard to the fact that this data is particularly valuable in pollution control, in fisheries research, and in geochemical prospecting.

There is also a dearth of research activity concerned with the solution, migration, and precipitation of the elements in natural waters at both the universities and various governmental institutions. Furthermore, there is no attempt to train students intensively in the complex chemistry of natural waters at any of the universities in Canada.

Chemical research on cold springs, hot springs and their related underground waters has been neglected in Canada, despite the fact that these phenomena are important in understanding certain subterranean aqueous processes that may have a bearing on the deposition of certain ores. In addition many springs may contain elements which could be extracted economically. As a measure of the neglect it should be stated that the last comprehensive chemical report on the springs of Canada appeared in 1926. As this is being written planning for intensive chemical and isotopic research on cold and hot springs is in progress at two Canadian universities.

6. The acquisition of fundamental data on the atmosphere continues at a relatively low level, insufficient for the purposes of the vital problem of pollution control.

7. Research on biogeochemical processes and acquisition of biogeochemical data is not adequate in Canada considering the importance of the field to pollution, geochemical prospecting, the petroleum and natural gas industries, and the health of the nation. With the exception of some notable work done at one university and two federal government institutions few geochemists have addressed themselves to the problems of biogeochemical processes involving plants and animals. Likewise, with the exception of one federal and one provincial government institution, where some good work has been done, there is a dearth of research on the geochemistry of the natural hydrocarbons. This despite the fact that Canada is a major producer of petroleum and natural gas. There is also little if any geochemical research on coal.

8. Research in stable isotopes continues at a relatively high level in Canada. Some commentators have expressed the opinion that research on the isotopes of elements other than sulphur and lead requires considerable attention.

COMMENTS ON TRAINING AND RESEARCH

Many faculties of geology now have courses in basic geochemistry, and it is apparent that others intend to introduce a course in the subject. Today, a geologist who has not had a course in the chemistry of the earth is an incomplete geologist, just as he would be if he had omitted a course in structural geology or elementary paleontology.

The quality of the courses in basic geochemistry at Canadian universities varies widely. Some are good; others leave much to be desired. Many geologists have commented that in some institutions there is far too much emphasis on phase diagrams and igneous processes to the exclusion of processes that occur in the natural surficial environment. Other comments include the one that some professors seem to be oblivious to the fact that theoretical chemistry has changed considerably in the last 25 years. Thus, a glance at a modern textbook on chemistry soon reveals that the space allotted to the phase rule and phase diagrams is generally only a few pages. It seems time that rocks and their processes of formation were described in other than pictorial phase diagrams.

Several geochemists have commented on the content of geochemistry courses. Their general opinion is that the courses should include: the fundamentals of the distribution of the elements in the spheres of the earth and the laws governing these distributions; elements of the thermodynamics of open and closed systems as applied to natural systems; elements of crystal chemistry; elements of solution chemistry and gas phase chemistry as applied to natural systems; phase equilibria in solid, liquid, and gaseous systems as applied to natural rock systems (igneous, metamorphic, sedimentary); and biogeochemistry including organic geochemistry of fossil hydrocarbons, etc.

The direction of research in geochemistry, viz field-oriented as contrasted with laboratory-oriented research, stimulates considerable controversy among geologists and geochemists. The question is an old one and dates back to the Hutton-Kirwan controversy of the eighteenth century. It is apparently not a matter of the validity of the two types of research but one of balance according to most commentators. Many geologists and geochemists see, and criticize, a trend for more and more investigators to ensconce themselves in laboratories and deal with synthetic systems or thermodynamic arguments, with few field checks to see if their data are compatible with the natural systems that they are supposed to explain.

On the other hand geochemistry has many problems involving high temperatures and pressures, complex solution phenomena, diffusion, and reactions in the solid state, all of which are peculiar to the science and are rarely if ever of interest to the theoretical chemist. Many of these problems require detailed and concerted research in the laboratory.

It is difficult to adjudicate between these two schools of thought since both the field and laboratory approach are vitally important in advancing our knowledge of the chemistry of the earth. The consensus weighs heavily on the field approach since most commentators note that all of the problems lie therein. The interpretation of the chemical data obtained in the field may in some cases give an unequivocal explanation of the processes involved. In other cases that may not be so - syntheses may be required to elucidate the mechanisms, or thermodynamic treatments may be necessary to restrict the speculations. The aim in geochemical work should be to clearly differentiate the chemical systems in the field by analyses and to supplement this work where necessary by synthetic laboratory experiments or thermodynamic treatments. Surely most geologists and geochemists are aware that nature has performed the great chemical experiment. It is doubtful if this experiment can be elucidated by a flight from the field to the laboratory.

RECOMMENDATIONS

The following recommendations are suggested:

1. That the present growth in research activity and data collection be continued in all fields of basic geochemistry. Greater emphasis should be placed on surficial materials and processes in order to bring research in these fields up to a level commensurate with that prevailing in the field of igneous and metamorphic rocks. More emphasis should also be placed on biogeochemistry and organic geochemistry.
2. That every geologist graduating from a university have as one of his basic tools a knowledge of the basic geochemistry of the earth. In this respect less emphasis on phase equilibria and more on the kinetics of open disequilibrium systems is suggested.

ACKNOWLEDGEMENTS

This paper was prepared after considerable discussion with numerous individuals in industry, universities, consulting firms, and government agencies. It is based largely on part of a previous survey on chemistry in the earth sciences and related fields which formed a section of the Chemical Institute of Canada's "Survey of Chemical and Chemical Engineering Research and Development in Canada" prepared for the Science Secretariat. This comprehensive report is available from the Science Council of Canada and the interested reader should refer to it for details. Some features of the field of basic geochemistry in Canada have changed since the Chemical Institute report was prepared and these changes were incorporated in the present report together with some of the views expressed by individuals who commented on the background paper on basic geochemistry circulated by the Solid-Earth Sciences Group during the early part of 1969. I wish to thank the many individuals who have contributed views, data, and discussions on various features of basic geochemistry during the period of preparation of the Chemical Institute of Canada Survey and during the preparation of the present paper as well as the many individuals who commented on the initial background paper on basic geochemistry. The comments on this paper, often highly critical but to the point, have been of invaluable help in the preparation of this final report. Their opinions and advice have been taken and integrated with the opinions and advice of many others. The final synthesis of opinions is due to the author alone.

PHYSICAL GEOCHEMISTRY

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DEFINITION

If geochemistry is defined in broad terms as the application of chemistry to geological problems, then physical geochemistry is that portion which deals with the application of the knowledge and techniques of physical chemistry to geological problems. A large part of it is concerned with the application of experimental and theoretical methods to determine the stability relations in geologically interesting systems, and includes "mineral synthesis and stability relations", "mineralogical phase chemistry" and even "experimental petrology". Physical geochemistry also includes studies of reaction kinetics, diffusion in solids and melts, surface phenomena, crystal growth and various other disequilibrium processes, and systems containing ore minerals, magmas and aqueous solutions as well as silicate minerals. This report deals with physical geochemistry as related to the solid earth, and excludes the chemistry of the atmosphere and the oceans.

SIGNIFICANCE OF RESEARCH AND RELATED ACTIVITIES

Research in physical geochemistry has had and will continue to have great significance to the earth sciences. Most studies have as their ultimate objective the better understanding of some fragment of the earth's history, often in a specific geographic area. Aspects of the chemical and thermal history of many rocks are recorded in the mineral compositions and their relationships, just as aspects of the structural or biological history are recorded in the folds or fossils.

By investigating these relationships with both experimental (laboratory) and theoretical methods and comparing the results with selected measurements on naturally occurring materials, great progress has been made, particularly in the fields of igneous and metamorphic petrology, but also in the study of ore deposits and of some surficial processes. It is safe to predict that the methods of physical geochemistry will continue to be one of the main sources of information in these areas.

PRACTICAL APPLICATIONS

Research in physical geochemistry has a very wide range of practical applications. Proof of this is the fact that a sizable proportion of graduates in this specialty in the United States take up jobs in the research departments of ceramics, glass, cement, metallurgical, semi-conductor and communications industries. Unfortunately, little of this research is done by the Canadian branches of these large firms. The mining industry does little of this type of research, although at least one U. S. company has started a major experimental program.

The reason for this lack of effort by mining and exploration companies seems to be that the problems involved in finding orebodies are typically geological; that is, extremely complicated, and that any given research project seems to offer little chance of contributing directly to the finding of an orebody. There are definitely exceptions to this statement. For example, one physical geochemist has quantified the diffusion of metal from vein solutions into limestone country rocks and developed a technique for determining the direction and distance to mineralization based on information from drill core analyses. Other examples could be cited but these cases appear to be exceptions to the general conclusion that research in physical geochemistry contributes to the solution of geological problems on a level which is just a bit beyond that which allows direct application to ore-finding. Mining men sometimes say of geological research that "it's pretty good at explaining how the ore got there, but only after it has been found", and they prefer to invest in the largely empirical methods of exploration geochemistry and geophysics.

Regardless of whether this is a valid assessment of the situation, the meagre support of physical geochemical research relating to orebodies and their environments is an extremely shortsighted policy. If the history of science teaches any lesson, it is that the use of complex natural phenomena for man's benefit is only possible after reasonably complete understanding is achieved and, at this level, research in physical geochemistry is probably the main contributor to an understanding of the origin of ore deposits. With the variety and number of deposits in Canada, and the importance of the mineral industry to our economy, the shortage of research of this type is inexcusable.

There is no doubt whatsoever that research in physical geochemistry will help materially in discovering orebodies, given time. Even if this were not true, however, the case for solid support of research in physical geochemistry would be only slightly diminished. In other words, although direct practical applications of pure research may appear at any time it is more important in the more general sense that pure science is always essential to applied science. That is, it forms part of the basic knowledge without which no applications can be made. Many people still regard research in physical geochemistry as somewhat esoteric, a bit removed from the realities of geological problems. They forget that much of the material which is almost taken for granted in mineralogy and petrology was first determined by the experimental approach. For example, understanding igneous rocks is impossible without knowing that albite and anorthite form a solid-solution series, but their relationship was quite uncertain before Bowen elucidated it experimentally.

HISTORICAL DEVELOPMENT

In the broad context of the history of geology, physical geochemistry is a relatively recent arrival. Although significant beginnings were made in isolated cases by outstanding individuals in the 19th century, the real contributions that this discipline could make were first clearly seen in the work of scientists at the Geophysical Laboratory in Washington, which was established in 1905. Ingenious techniques were developed which allowed investigation of silicate crystal-liquid relationships at high temperatures, and the paper by Bowen in 1913 on the plagioclase feldspar system is still probably the single most fundamental piece of work in the study of igneous rock crystallization. In the 1930's, similar studies under high water pressures were also begun at the same institution, and since then there has been a steady growth of the science in universities and government agencies in several countries.

In Canada, little was done before 1944 when F. G. Smith began his career at the University of Toronto. In 1948 the Mines Branch in Ottawa began its contributions under the direction of A. T. Prince (who was Bowen's first graduate student). Only in the last few years, however, has activity in this field spread across the country, and by now almost every major university in Canada has at least one staff member in this field. There are, however, no privately endowed institutes working in this field in Canada, and very little is done or even supported financially by industry.

The growth of physical geochemistry is one aspect of a general trend toward a more quantitative and, where possible experimental approach in all phases of geology. This trend is a normal development in the evolution of a mature physical science from an early observational, descriptive, speculative phase to a more scientific or quantitative, hypothesis-testing phase in which the use of mathematics in the formulation of theories and the performance of critical experiments is typical. This transition has begun at different times in different branches of geology (in crystallography it began very early), but in general it has occurred much later than in physics or chemistry because geological problems are inherently more complicated. When physicists and chemists began experimenting with simple systems under controlled conditions, geologists were still speculating on the difference between granite and basalt, and on problems which are not completely solved to this day. The well-organized inferior "image" of geology as a science can very likely be traced to this delayed development of its more quantitative aspects, and therefore can only improve with time.

PRESENT LEVEL OF ACTIVITY

Physical geochemistry is more active now than ever before, having enjoyed a continuous and in fact accelerating growth up to the present time. The United States is still pre-eminent in the field, the main contributors being the Geophysical Laboratory, the U. S. Geological Survey experimental laboratories, and several university departments. Significant contributions have come from several other countries, and it seems very probable that the science will continue to grow, especially in these other countries, as more universities, government agencies and industries increase their activities in this field.

NEED FOR INCREASED ACTIVITY

The growth of physical geochemistry, both in research and in teaching, should be encouraged, as discussed in other sections. More difficult is the question of relative needs within the science.

In Canada at the present time there are slightly less than two dozen scientists whose principal interests could be said to lie in this field (there are many others, of course, whose interests somewhat overlap this field). Generally speaking, the principal interests lie either with silicate and carbonate minerals (i. e. the experimental petrologists) or with the sulfide and other ore minerals, andthe former group outnumbers the latter by roughtly three to one. On this basis we can say that Canada's main contribution in this discipline is in the fields of igneous and metamophic petrology, and that, in view of the imbalance and of the value of the mineral industry in Canada, some expansion of the experimental studies related to orebodies should be encouraged. Whether or not this occurs, and whether or not application of experimental studies in petrology continues to expand as it should, depends in large measure on the attitudes of the people responsible for the teaching of economic geology and petrology in our universities. Many of them are not yet convinced of the value of the experimental-theoretical approach.

Physical geochemists whose main interest lies in mineral solubilities, magma-water relationships, wall-rock alteration, metasomatism and related topics involving the chemistry of hydrothermal solutions are in quite noticeably short supply. Much of this work can be carried out (at temperatures up to 100°C or so) very inexpensively, and the results are of far-reaching significance. The importance of aqueous solutions in the earth's crust has long been recognized, and many of their effects have been deduced from geological evidence. Facilities are now available for studying them quantitatively, and more effort should be expended in this direction.

Aqueous solution chemistry overlaps with another field that is very largely neglected in Canada, the geochemistry of surficial processes including weathering, Eh-pH and other chemical relations in near-surface waters of various types, dispersion of metals in near-surface environments and so on. These studies have obvious relevance to the near-surface formation of ore deposits (a topic of fast-growing interest), geochemical prospecting and environmental pollution.

The study of stable isotopes, particularly oxygen isotopes in silicate materials, is another topic of proven importance to igneous and metamorphic petrology which is largely neglected in Canada and, in fact, not widely pursued anywhere.

TRAINING

Probably the single most important aspect of the role of physical geochemistry in the earth sciences is the matter of its place in university curricula. It is essential that more understanding of this subject be imparted to undergraduates and graduate students alike, along with a greater emphasis on mathematics, chemistry and physics. What is involved is much more than "how to read a phase diagram"; it is nothing less than a whole point of view about geology. It is not the only point of view or even the most important one, but certainly a unique one. Students must be trained to see rocks as chemical systems just as they must be trained to see them as structural units or as possible orebodies. In many cases it is the most powerful single method of determining some of the conditions of origin of rocks and ores, and thus of getting at the whole purpose of geology - unravelling the history of the earth, or parts of it.

In emphasizing these aspects, other more traditional teaching concepts will have to be modified. One which must not be modified is that every student should have some field experience. Field and theoretical studies are not antithetical but mutually beneficial. On the one hand, it has been shown repeatedly that what a man <u>sees</u> in the field depends very largely on what he <u>knows</u>, or what he looks for, and thus a theoretically competent person is aware of significant mineralogical or structural relationships when he sees them. Similarly, the experimental petrologist will contribute significant new knowledge only to the extent that he is aware of significant petrological problems which are amenable to this type of approach. This naturally depends to some extent on his field experience. The best physical geochemists have a good field background and are impressed with how greatly the significance of laboratory work is governed by acute field observations. With its strong tradition of long field seasons for student geologists, Canada has a unique opportunity to train scientists who are competent in both field and laboratory.

The introduction of more quantitative aspects into geology courses has broader implications. The advance of the science as a whole will be related to the quality of students attracted to it, focussing attention on the early college years and the high schools. To attract the best students available, geology needs a new image, one of challenge and the promise of interesting and even exciting problems to be solved as well as some prospect that answers will be found. This is related to the need for more emphasis on mathematics and chemistry in the early years, because the best minds are not satisfied with a qualitative answer when a quantitative one might be obtained. Traditionally, of course, geologists have had courses in mathematics, physics and chemistry, but too often these subjects have never been mentioned significantly in their geology courses, and this is a great challenge today. One way of alleviating the overloading of courses which might develop by injecting this newer material while keeping the older will be to integrate the two. In other words, instead of a course in physical chemistry from the chemistry department followed by one in geochemistry, why not one course in physical geochemistry taught in the earth science department?

Similar combinations could be considered for strength of materials and structural geology, statistics and geomorphology and palaeontology, and so on. This trend is already visible in some institutions. Another advantage of this approach is that students retain their interest when they see some relevance to their main field of interest.

This obviously places great demands on the qualifications of professors, but perhaps rightly so. Also implied is the concept that every geology department should have at least one staff member who is competent in some aspect of physical geochemistry, and that a department without one is as badly staffed as one without a mineralogist or structural geologist. This certainly does not mean that every department will have to acquire the expensive equipment and machine shop facilities needed for high-pressure research. As mentioned before, many aspects of the discipline can be pursued with nothing more than a few hundred dollars and some good ideas. Fortunately, it is still true that the value of the research done cannot be simply related to the cost of the equipment.

MAJOR OBJECTIVES AND FUTURE TRENDS

The major objectives of physical geochemistry in Canada have already been suggested. They are (or should be): to penetrate deeper into the teaching of geology at Canadian universities in the conviction that the insights it has to offer are valuable; to cover a wider spectrum of research than it does now with a much stronger emphasis on studies of ore deposits and their environments; and to investigate problems closely controlled by field observations.

Another major objective proposed by many is the establishment of some type of independent research institute staffed by many types of earth scientists, free to pursue full-time, adequately supported studies of ore deposits and perhaps other geological problems. The example of the Geophysical Laboratory in Washington is usually mentioned in this regard. The idea has a great deal to recommend it. Since there seems little hope of private or industrial financing of such a venture, government support is indicated, and the possibility of developing such a body of scientists within the existing framework of the Geological Survey or the Mines Branch (where several scientists with these interests are already located) should be carefully considered. The outstanding research carried out in the U. S. Geological Survey could serve as just as good a model as the Geophysical Laboratory in this regard. Financing a research group does not, of course, ensure that significant research will be done, and since mediocre research is little better than useless, one of the main considerations in discussing the establishment of such a group should be the availability of more-than-competent scientists.

As for trends in the science, certain current ones are obvious. These include the rapidly expanding role of the electron microprobe and other analytical tools, the amazing growth of computer usage (now taught to undergraduates and used by them in course work), and the increasing use of more sophisticated mathematical techniques (set and group theory, vector algebra, tensor calculus, etc.) for the handling of data. These three factors together constitute an important aspect of physical geochemistry.

Another factor which is not so much a trend as an integral part of physical geochemistry which has grown with it is the use of chemical thermodynamics. It remains one of the principal tools of the science and must continue to be emphasized.

Looking farther into the future, it seems likely that eventually phase equilibria will be explained on a level more fundamental than that provided by classical thermodynamics; that is, by consideration of the interactions on an atomic and electronic level. Crystal field and related studies are proceeding in this direction now.

CONCLUSIONS

In the training of geologists

1. Every earth science department should have at least one or two physical geochemists so that students are made aware of the insights provided by this discipline. Hopefully, of course, some larger centres will have a "critical mass" of four or five.

2. More and better mathematics (including probability and statistics), physics, chemistry and computer science should be introduced in the early undergraduate years. If possible, this should be done in earth science departments by earth scientists. This should be accompanied by an increased use of these topics in other geology courses.

3. Training in physical geochemistry should be linked as closely as possible with field studies.

In research fields

1. There is considerable strength in Canada in the physical geochemistry of igneous and metamorphic processes. This strength should be allowed to grow.

2. Similar studies on ore deposits and their environments and on experimental systems related to them are badly lacking and must be encouraged, for economic as well as scientific reasons.

3. A largely neglected area is the physical geochemistry of surficial processes. This area has widespread importance, from geochemical prospecting to pollution studies, and research in it is relatively inexpensive.

4. Other areas that have broad significance and need added emphasis are the chemistry of aqueous solutions and of magma-water relationships, and the study of stable isotopes, particularly oxygen isotopes of silicate minerals.

In general

1. Careful consideration should be given to the proposal to set up an independent research-oriented group to concentrate on the physical geochemistry of earth science problems, or perhaps on a more restricted field within earth science, such as ore deposits. The Department of Energy, Mines and Resources should examine its functions in order to see whether such a group could be set up within it, using the Geological Survey or the Mines Branch as a nucleus.

2. The Science Council should recognize not only that a trend towards more quantitative work (experimental, analytical and theoretical) exists today in geology and earth science in general, but that there is considerable opposition to it. A clear recognition by the Science Council that this quantitative trend is natural, desirable, and even inevitable in the light of the history of science, and that the scientists urging this trend do not wish to ignore Canada's proud tradition of field-oriented geology but to build on it, might (possibly) do much to advance the standards of earth science in Canada.

BIOGEOCHEMISTRY IN CANADA

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INTRODUCTION

This report deals primarily with Canadian aspects of biogeochemistry, and especially with the role of trace elements in the biological and earth sciences. Geochemistry, as applied to mineral and petroleum exploration, and fundamental aspects of geochemistry, are dealt with in other reports and, therefore, are discussed, only incidentally, in this presentation.

Biogeochemistry is the science that attempts to establish chemical relationships in, and link the biological and earth sciences. Eventually biogeochemistry may make possible the correlation of normal concentrations of various elements with normal health in all units and species of living matter, and abnormal concentrations with abnormal health or illnesses of various types. However, it is well to remember that, until quite recently, it has been the interest in abnormal concentrations of elements in the earth's crust, namely in ore bodies, that has generated support for much of the early research in biogeochemistry.

Biogeochemistry also provides a useful tool for measuring radioactive fallout. Some years ago the Geology Department of the University of British Columbia provided samples of vegetal material from the west coast of Vancouver Island which allowed scientists at Ottawa to monitor "fallout" from nuclear explosions.

More recently, Sir Ernest Marsden (1) has presented evidence to show that Lead 210 and Polonium 210 concentrations in foodstuffs and tobacco may be harmful to human health. In the whole of Canada we could not find a laboratory able and willing to co-operate with us by testing some critical samples. Eventually, Professor Chow, of the University of California, generously made a few determinations for us, and reported that the Lead 210 content of our selected samples of soil varied by as much as a factor of 20, and, in addition, Professor Chow was able to report the pressure of thallium in a soil where its presence had been suspected but never confirmed.

Biogeochemistry invades many fields including agriculture, geology, medicine, and hydrology. Biogeochemistry has ties on the one hand with the earth, and on the other with the life sciences, and is concerned alike with the fundamental and with the applied aspects of science.

Biogeochemistry is relatively young, so young that in some quarters it is denied recognition as a science in its own right: in many universities it receives little or no support from the geology, chemistry, or medicine departments, all of which have much to contribute to, and much to learn from, this integrating discipline.

A few of the problems properly falling within the present day scope of biogeochemistry are: trace element deficiencies of food and drink, natural and unnatural occurrence of toxic substances in soil; chemistry of rocks, soils and plants as a support for life; genesis of fossil fuels; fertility of streams, lakes, and oceans, and their threatened degradation by pollution. All of these problems encompass broad areas of scientific knowledge, and none can be dealt with competently by specialists belonging to a single discipline. Advancements that are being achieved result largely from a team of researchers having the ability to co-operate and communicate over a relatively broad range of human knowledge.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT IN BIOGEOCHEMISTRY

Biogeochemical problems have only become a subject of serious investigations during the past twenty five years. Research and development are therefore in their relative infancy and constitute the principal activity of biogeochemistry at the present time. With such a comparatively young science, it is not surprising to find that in Canada there are, as yet, relatively few major economic dividends accruing from it. However, Land (2) has shown that the pattern of mine discovery indicates that geochemistry is slowly beginning to take its place beside geology and geophysics as a weapon in the mine-finders armory. Although, perhaps not generally realized, the opening up of both the Bethlehem (3), and Endako Mines (4) in British Columbia, were foreshadowed in biogeochemical reports. Today, we know that the ash of some of the fireweed (Epilobium angustifolium) growing over what is now the open pit of the Endako Mine, ran one and three quarters per cent molybdenum, a fact that might well have influenced the early history of that property had biogeochemistry been taken more seriously in the nineteen fifties.

It should always be realized that each geographical area tends to have problems peculiar to its own specific environment. Thus, various geobotanical techniques so well demonstrated in the reports of Cannon (5) and some of her colleagues in the United States Geological Survey, for parts of the U.S.A.; Cole (6) and her associates for Africa and Australia; and Malyuga (7) and numerous other workers for the U.S.S.R.; are of great interest. However they are of little practical value in Canada, which is recently glaciated and has not yet developed new species of vegetation. Conversely, ore finding methods involving Douglas Fir (8) cannot be used widely outside Western North America, because the tree is indigenous and widespread only in that particular area. Failure to appreciate the fact that some problems are peculiar to a specific geographical environment has led some Canadian administrators to suggest that biogeochemical research should be left to workers in the United States having far greater financial resources than Canadians. The implication was that if the United States researchers proved the worth of biogeochemistry we could "climb on the bandwagon". However, Kurland (9) probably would never have solved the problem of Minamata disease - a disease caused by human ingestion of too much mercury - had he not been able to visit Minamata Bay in Japan, and see for himself the unique combination of circumstances that gave rise to the disease at Minamata, a comparatively poor community consuming a relatively high percentage of shell fish which, owing to the vagary of an ocean current were exposed to a mercury-bearing effluent from a synthetic fibre plant. The shell fish involved were not affected, but the unfortunate people who consumed the shell fish were.

The potential returns from research and development in biogeochemistry are great. The problems involved relate to almost all facets of human ecology, including a few of the factors contributing to the health of plants, animals, and man, and, undoubtedly, some causes of their lack of health or sickness. In a world where pollution is becoming an increasing problem, biogeochemical research and development has much to offer mankind.

Biogeochemistry deals with the search for mineral deposits and fossil fuels, and can aid in the more effective development of each of our primary reproductive industries, agriculture, forestry and fishing. However, until the present time the reluctance of many administrators to accept biogeochemistry and the circumscribed nature of the individual problems that have been investigated have together limited the amount of practical work done to the output of a few laboratories in Canada.

Today, one of the more important problems faced by biogeochemistry is that of training young scientists in research and development laboratories so that they may, in turn, act as heads of routine laboratories. The number of people with an adequate background knowledge of chemistry, physics, geology, pedology, botany, and epidemiology, to name a few of the disciplines, is bound to be extremely modest. Obviously, background training that will permit a team approach to various problems, is badly needed.

PRACTICAL APPLICATIONS

It follows from what has already been said that biogeochemistry has immediate practical applications in (i) resource development and (ii) health and welfare.

In support of resource development, it is essential that the normal and anomalous mineral content be established for as many soils, trees, and lesser plants as possible. More must be learned about the circulation of chemical elements in nature and how they affect the growth of living organisms. Eventually it may be possible to deal with various aspects of biogeochemistry by means of rigorous mathematical methods using computors and applying methods of systems analysis. However, in the opinion of the writers, more fundamental knowledge and data must be assembled before such sophisticated treatment will be fully justified. After establishing biogeochemical provinces it will be possible to make increased use of biogeochemistry as (i) a prospecting tool, (ii) a guide in planning forestry development and (iii) a means of assessing the mineral quality of agricultural soils.

Although certain trace elements may have a direct effect on human health, remarkably little is known about the trace element contents of cereals and common vegetables and similarly next to nothing is known as to the form in which these trace elements are present. Obviously this information is essential if even an estimate is to be made of how much ingested material is assimilated. Such trace element studies as have been made of food products have been made with comparatively little attention to the geological background. Once the normal mineral content of food and vegetables are known it will be much easier to recognize and assess various types of pollution and trace element imbalances in specific localities. Pollution involves not only pesticides and herbicides but also many inorganic materials.

If and where geochemical provinces are known to show measurable abnormalities it would surely be rewarding to initiate morbidity studies among human and animal populations.

A classic illustration of how biogeochemistry has been useful has been provided by the element lead. Lead from automobile exhaust, orginating from tetraethyl lead, for years was suspected of contaminating our environment. Much medical work was done by way of testing what concentrations of lead in the atmosphere could be tolerated by man. Eventually geologists became interested and showed that the particulate matter from automobile exhausts eventually settled on the ground and became incorporated in vegetal matter. In short man was menaced, as far as lead was concerned, as much from ingestion from food as he was by air.

It is occasionally said that some supporters of biogeochemistry are overly enthusiastic in claiming there are proven links between trace element imbalances and epidemiology. Any such "Doubting Thomases" should read "The Proceedings of the University of Missouri's 2nd Annual Conference on Trace Substances in Environmental Health (10). In this excellent publication many specialists produce data that show how trace elements affect human and animal health. Copper, zinc, lead, chromium, manganese, and calcium are among the many elements discussed.

HISTORY OF RESEARCH AND DEVELOPMENT WITH PARTICULAR EMPHASIS ON CANADA

Interested readers may refer to Malyuga (11) for some samples of how biogeochemistry was first put to use both as a guide to water in desert areas, and as an indicator of buried mineral deposits. Dealing with comparatively recent times, say the last forty years, it is probably safe to say that the recent surge of interest in biogeochemistry commenced in the nineteen thirties when N.H. Brundin in Sweden, and V.I. Vernadskii (12) in the U.S.S.R. set the stage for the science of biogeochemistry, as we know it today, by demonstrating the possibility of using the chemical content of vegetation as a guide to buried mineralization. Vernadskii was also one of the first to write about the chemical composition of living matter in relation to the chemistry of the earth's crust and interest in this subject was also shown by A.P. Vinogradov and D.P. Malyuga (13) and by several other scientists of the U.S.S.R. During the past twenty years Soviet scientists have produced many papers related to biogeochemical prospecting.

During the nineteen forties, T. Vogt in Norway (14), H. Hawkes and some of his associates in the U.S.A. (15), V. Marmo (16), M. Salmi (17) and J. Lounamaa (18) in Finland, and H.V. Warren and R. Delavault and their associates at the University of British Columbia (19-23), all apparently working independently, had also demonstrated that biogeochemistry had practical possibilities for providing aid in the search for buried ore bodies. J. Webb and various students at the Royal School (London, England) also carried on biogeochemical investigations but, like many other investigators in the U.S.A. and the U.S.S.R., they came to the conclusion that other geochemical techniques, such as soil and sediment sampling, offered better possibilities for mine finding.

However, methods that work in areas where soils are mature and primarily residual, as well as geologically and pedalogically old, are not necessarily the best to use in countries such as Canada and Norway where the majority of soils are transported and pedalogically young. Thus, through the fifties and sixties extensive work was carried on at the University of British Columbia on biogeochemistry and closely related studies (24-53).

Fortunately, every branch of geochemistry has developed rapidly over the last twenty years and in April, 1966, geochemical prospecting may be said to have come of age in Canada when a symposium on Geochemical Prospecting was held in Ottawa, sponsored by the Geological Survey of Canada, and the National Advisory Committee on Research in the Geological Sciences (54).

In the meantime in 1957, at the suggestion of Professor W.C. Gibson, and after consultation with Dr. Wilder Penfield, the authors commenced tentative investigations on possible relationships between trace elements and the epidemiology of some diseases. These tentative investigations culminated in the presentation of a series of papers to numerous medical and earth science journals (55-69).

PRESENT LEVEL OF ACTIVITY

Our biogeochemical laboratories at the University of British Columbia are tackling the trace element content of vegetation not only as guides to concealed mineralization, but also as indicators of various types of pollution, and as keys to some specific epidemiological abnormalities. The Geological Survey of Canada, The Canadian Departments of Agriculture, of Forestry and Fisheries, and of National Health and Welfare, as well as a few Provincial Departments, have all been involved in investigations dealing with specific problems that have arisen from time to time.

From personal conversations with A. Kvalheim (Norway), N.H. Brundin (Sweden), and M. Cole (Great Britain), it appears that there is renewed interest in biogeochemistry in the above countries. Personal communications with three Soviet geologists have suggested to us that there is still considerable interest in this field of research in the U.S.S.R. At Aberystwyth (University of Wales), at the Royal School of Mines (London), at the Geological Survey and the Ministry of Health in Great Britain, and several agricultural research stations in the British Isles, we have noted a marked increase of interest in trace elements because of an increasing awareness that they are in some way involved in the health of plants, animals, and humans.

One reason for agriculturists showing an increasing interest in biogeochemistry arises from the growing gravity of the various problems posed by pollution. Politicians are now becoming aware of pollution. They realize that the waste of cities may no longer be discharged into streams and rivers and they reason, with a measure of logic, that because much of our urban wastes come originally from the earth's crust, in the form of vegetal and mineral products, why not return these urban wastes to the earth's crust whence they originated? The politicians suggest, therefore, that after removing major solids all waste should be shredded, then sterilized and transformed into granules resembling vermiculite in texture, and spread on land which would thereby have its nutrients restored to their original concentrations. Unfortunately, what is forgotten or overlooked is that modern civilization depends on concentrations of many minerals that, in many instances, are in no way related to the normal concentrations in the earth's crust. Moreover, some of these minerals which, although they are harmless when used appropriately, and, indeed, are in many places essential for life in the concentrations in which they normally occur in the earth's crust, are nevertheless highly toxic when present in unusual concentrations in soils. Examples of such elements are lead, arsenic, cadmium, and mercury, but many more could be cited. Already an agriculturist is finding it necessary to draw attention to this new threat of pollution (70).

NEED FOR INCREASED ACTIVITY

It appears to us that intelligent and understanding co-operation is needed between different specialists and between various laboratories presently engaged in high class work, but in many cases largely ignoring what is going on in different but indirectly related fields of investigation. Many nutritionists are doing admirable work on trace elements in food and their effect on animals, while seemingly they are indifferent to the fact that geology can also materially alter the trace element content of cereals and vegetables. Some agricultural laboratories, although doing excellent work with respect to animals have never considered that they might also deal helpfully with human problems. During the summer of 1968 we discussed trace element problems with many geologists, agriculturists, and medical men, and we were highly gratified with the interest shown. Virtually all those with whom we discussed biogeochemical problems felt that there was a great future for trace element-epidemiological studies, some going so far as to suggest that the results accruing from such studies might parallel the advances made when bacteriology and vitamins became an integral part of medicine. Some laboratories are already engaged in co-operative programs and others are hoping to commence work on them soon. London (England), Aberystwyth, Missouri, and Belfast are centres for such programs.

That brand of biogeochemistry which deals with the influence of biological factors on the earth's crust in past periods, and the resultant end products - coal, petroleum, and natural gas - has developed fully only so far as it deals with the origin and nature of these fossil fuels, and the search for their deposits. It seems desirable that what is now known as "Organic Geochemistry" should be widely enlarged in scope possibly by providing a program of "Paleo-ecology and Paleo-biogeochemistry" for soft rock geology students. There will be no concensus as to how room should be made for undergraduates to take this specialized matter. Perhaps it might be possible to put less stress and time on some details of paleontology as it is taught at present. For specialists in biogeochemistry, consideration might be given to de-emphasizing vertebrate evolution, and reduce invertebrate fossils to what is essential for understanding the principles of evolution and stratigraphy.

Helen Cannon has reminded us that a North American study committee on "Environmental Geochemistry as Related to Health and Disease" is being planned. This committee will probably be sponsored jointly by the Geological Society of America and the U.S. Department of Health, Education and Welfare. The purpose of this committee will be to determine the "state of the art"; to plan what needs to be done, and the order of priority for this work; and to establish a means for informing the growing number of workers who are interested in the many facets of this subject. It would be a tragedy if Canada does not participate in this important program.

Helen Cannon has also drawn our attention to the fact that The International Association of Geochemistry and Cosmochemistry, working closely with UNESCO, has a committee on Applied Geochemistry, chaired by Dr. L.V. Tausson of Russia, which will have a study group on prospecting by both soils and plants, and a Committee on Applied Biogeochemistry co-chaired by Dr. John Webb of the Royal School of Mines, London, England, and Helen Cannon herself. This latter committee will have a study group on Medical Applications of Biogeochemistry. It is expected that there will be exchanges of information between the International and the North American Committees.

It would seem to be of the utmost importance for Canada to work with these groups from their commencement. This, in turn, indicates that Canada should establish, without delay, three or four university centres of geochemistry. If Canada falls behind in these new developments, it will be much more costly and difficulty to "join the club" later on!

TRAINING

The present system of tiered prerequisites in our Canadian universities makes it virtually impossible for a student to take all the courses in physiology, botany, geology, chemistry, physics, mathematics, and agriculture that theoretically would be demanded for a program leading to a degree in biogeochemistry.

At the University of British Columbia some of the most successful graduates are those who have taken a Bachelor's degree in one discipline and followed that up with a Master's degree in some related field. Possibly some such plan might be considered for those who plan to become specialists in geochemistry. At all events this might bridge an interim period until geochemistry acquires full stature, comparable with that now held by geophysics. The authors, however, are firm in their conviction that geochemistry should remain closely allied to geology: geochemistry would include biogeochemistry.

Whatever training is given it is most important that all geochemists appreciate the importance of methodology. However this is surely a _sine qua non_ for all scientists.

The best system for training is probably to rely on co-ordinated teamwork, at least until the University system is reformed and made less rigid. There are still some persons in our universities who do not recognize biogeochemistry as an academic subject: fortunately their numbers are diminishing.

CONCLUSIONS

1. Biogeochemical maps should be prepared on the basis of the trace element composition of selected organic material chosen from areas that would establish a broad picture of weathering and plant absorption under different climatic, physiographic and geologic setting. If this work were

done in conjunction with parallel studies with the rocks and soils, the stage would be set for future biogeochemistry to practical use, either in assessing the mineral possibilities, or the degree of pollution, or possible medical or agricultural implications in particular areas.

2. Parts of the biogeochemical cycle on which there are comparatively few data require elucidation. For example, relatively little is known about the form in which many metals are present in vegetables and cereals. As phythates, metals and be more readily digested than as oxalates. The importance of acquiring more knowledge concerning the biogeochemical cycle is pointed up by the fact that a particular element may be of a high concentration in a soil, and yet not necessarily have any effect on man, because there is much discrimination in the soil food chain. In a general way, the trace element content of plants is related to the soils and rocks with which they are involved, but surprisingly exceptions do occur, and, as yet, the reasons for these exceptions are not always understood.

3. A few specialized laboratories should be established where material collected by scientists in other disciplines could be analyzed, if and when this was desirable, and where analytical techniques that are peculiar to trace element investigations could be developed and tested. Experience indicates that not all laboratories turning out trace element analyses on organic material are equally reliable. It would be most helpful if standard samples could be established for trace element analyses similar to those already available to geologists.

   Future trends are hard to predict. They will probably arise from whatever is found when studying some of the urgent problems concerned with human health. However, it is possible that an entirely unexpected and urgent demand for some element may call for the use of every tool in the mine-finder's kit, including biogeochemistry.

4. Geochemistry, and this includes biogeochemistry, should be given a status in its own right, such as has been accorded soil science, biochemistry, and geophysics. In this way, geochemistry will not fall between the two stools of geology and chemistry, and it will not need to make apologies all the time for intruding on other people's territories. In British Columbia, assessment work in mineral claims in the form of geochemical data, may only be reported by a Professional Engineer. A geochemist, however well qualified, and whatever his credentials, may not file geochemical assessment work. This inferred downgrading of geochemistry has been the source of much frustration and exasperation for many years.

   Concomitantly, adequate funds must be made available to establish at least one University department with appropriate facilities in each major geographic area of Canada. British Columbia cannot be expected to be as familiar with the problems of the Maritimes as can the Maritimes. The Geological Survey of Canada has already given a lead in biogeochemical matters, and should not only continue their own investigations, but might well set a lead by initiating a co-ordinating committee of some kind in Ottawa, where all who are involved in trace element studies could exchange views, and, where practical, eliminate unnecessary duplication. The Geological Survey might also take the lead in linking up with the appropriate international bodies referred to in an earlier part of this report.

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A word of explanation about the bibliography may be in order. The references are meant to be representative rather than all inclusive, and if the Canadian references are somewhat repetitive with respect to some authors, it is because biogeochemical investigations in Canada were few and far between until a few years ago.

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BIBLIOGRAPHY

1. Marsden, E. Incidence and possible significance of inhaled and injested polonium. Nature, July, pp. 203-230, 1964.

2. Lang, A.H. Discovery methods of post-1955 new producers. Can. Mining J., vol. 88, No. 1, pp. 47-50, 1967.

3. Warren, Harry, V., Delavault, R.E., and Cross, Christine, H. Geochemical anomalies related to some British Columbia copper mineralization. Methods and case histories in mining geophysics. 6th Commonwealth Mining and Metallurgical Congress, pp. 277-282, 1959.

4. Warren, Harry, V., Delavault, Robert E., and Routley, D.G. Preliminary studies of biogeochemistry of molybdenum. Trans. Roy. Soc. Can., vol. 47, Third Series, Section 4, pp. 71-75, 1953.

5. Cannon, Helen, L. Botanical prospecting for ore deposits. Science, vol. 132, No. 3427, pp. 591-598, 1960.

6. Cole, M.M., Provan, M.J., and Tooms, J.S. Geobotany, biogeochemistry and geochemistry in mineral exploration in Bulman-Waimuna Springs area, Northern Territory, Australia. Trans. Inst. Mining Met., Section B, vol. 77, Bull. No. 741, pp. B81-B104, 1968.

7. Vinogradov, A.P. *The geochemistry of rare and dispersed chemical elements in soils*, 2nd Edition, Revised and Enlarged, Translated from Russian, Consultants Bureau, Inc., New York, 1959.

8. Warren, Harry V., Delavault, R.E., and Barakso, J. The arsenic content of Douglas fir as a guide to some gold, silver and base metal deposits. *Bull. Can. Inst. Mining Met.*, vol. 61, No. 675, pp. 860-866, 1968.

9. Kurland, Leonard, T., Faro, Stanley, N., and Siedler, Howard. Minamata disease. *World Neurology*, 1, No. 5, pp. 370-395, 1960.

10. "Trace substances in environmental health". Edited by Delbert D. Hamphill, University of Missouri, Columbia, Missouri.

11. Malyuga, Dmitrii Petrovich. *Biogeochemical methods of prospecting*; Authorized translation from the Russian. Consultants Bureau, New York, 1964.

12. Vernadskii, V.I. Problems in biogeochemistry. I – The importance of biogeochemistry for an understanding of the biosphere. 2nd Ed. Leningrad, *Izd-vo Akad. Nauk SSSR*, 1934.

13. Vinogradov, A.P., and Malyuga, D.P. "The biogeochemical method of exploration of ore". 20th Int. Geol. Congress, Mexico, 1958.

14. Vogt, Thorolf, and Braadlie, O. Plantevekst og jordbunn ved Rørosmalmane (Vegetation and soil at the ore deposits at Røros). *D.K. Nordske Videnskabers Selskal*, Forkandlinger, vol. 15, No. 7, pp. 25-28, 1942.

15. Hawkes, H.E. Geological Survey's Geochemical Prospecting Unit. Paper presented November 13th at the meeting of Geological Society of Washington, p. 4, 1946.

16. Marmo, Vladi. Uber die anwendnung van Ledum palustre in der biogeochemischen Prospektierung, *Arch. Soc. "Vanamo" 9*, suppl., pp. 170-174, 1955.

17. Salmi, Martti. Prospecting for bog-covered ore by means of pead investigations. *Bull. Comm. Geol.* Finlande 169, pp. 1-34, 1955.

18. Lounamaa, J. Trace elements in plants growing wild in different rocks in Finland. *Annales Botan. Soc.* 'Vanamo', Tom. 29, No. 4, 1956.

19. Warren, Harry, V., Delavault, Robert E., and Irish, Ruth, I. Biogeochemical researches on copper in British Columbia. *Trans. Royal Soc. of Canada*, Third Series, vol. 43, Section 4, pp. 119-137, 1949.

20. Warren, Harry, V. and Delavault, Robert, E. Gold and silver content of some trees and horsetails in British Columbia. Bull. Geol. Soc. Am., vol. 61, pp. 123-128, 1950.

21. History of biogeochemical investigations in British Columbia. Can. Inst. Mining Met. Trans., vol. 53, pp. 236-242, 1950.

22. Water analysis a new key to hidden ore. The Northern Miner, annual number, pp. 105 and 110, 1950.

23. Biogeochemistry and hydrogeochemistry. B.C. Prof. Engineer, pp. 19-22, 1951.

24. Warren, Harry, V., Delavault, Robert, E., and Irish, Ruth, I. Improved dithizone field test for heavy metals in water. Bull. Geol. Soc. Am., vol. 62, pp. 609-618, 1951.

25. Further biogeochemical data from the San Manuel copper deposit, Pinal County, Arizona. Bull. Geol. Soc. Am., vol. 62, pp. 919-929, 1951.

26. Preliminary studies on the biogeochemistry of iron and manganese. Ec. Geol., vol. 47, No. 2, pp. 131-145, 1952.

27. Biogeochemical investigations of the Pacific northwest. Bull. Geol. Soc. Am., vol. 63, pp. 435-484, 1952.

28. Trace elements in geochemistry and biogeochemistry. Sci. Monthly, vol. 75, No. 1, pp. 26-30, 1952.

29. Acetonic dithizone in geochemistry. Ec. Geol., vol. 48, No. 4, pp. 306-311, 1953.

30. Water testing for minerals – A new tool for prospectors. The Western Miner and Oil Review, vol. 26, No. 7, pp. 38-43, 1953.

31. Geochemical prospecting finds widespread application in British Columbia. Mining Eng., vol. 5, pp. 980-981, 1953.

32. Warren, Harry, V. and Delavault, Robert, E. Variations in the nickel content of some Canadian trees. Trans. Roy. Soc. Can., Third Series, Section 4, vol. 48, pp. 71-74, 1954.

33. Geochemistry in mine finding. The Western Miner and Oil Review, vol. 28, No. 3, pp. 35-39, 1955.

34. Warren, Harry, V., Delavault, Robert, E., and Fortescue, J.A.C. Sampling in biogeochemistry. Bull. Geol. Soc. Am., vol. 66, pp. 229-238, 1955.

35. Warren, Harry, V. and Delavault, Robert, E. Soil and what it means to us. Trans. 8th B.C. Nat. Resources Conf., pp. 91-94, 1955.

36. Warren, Harry, V. and Delavault, Robert, E. Some biogeochemical investigations in eastern Canada. Can. Mining J., Part 1, vol. 76, No. 7, pp. 49-54, July. Part 2, vol. 76, No. 8, pp. 58-63, August, 1955.

37. Biogeochemical prospecting in northern latitudes. Trans. Roy. Soc. Can., Third Series, Section 4, vol. 49, pp. 111-115, 1955.

38. Prospecting for cobalt. Trans. Roy. Soc. Can., Third Series, Section 4, vol. 51, pp. 33-37, 1957.

39. Rubeanic acid field test for copper in soils and sediments. Mining Eng., vol. 10, No. 11, pp. 1186-1188.

40. Geochemistry and prospecting. Portion of "A symposium on saturation prospecting". Bull. Can. Inst. Mining Met., vol. 52, No. 561, pp. 55-60, 1959.

41. Readily extractable copper in eruptive rocks as a guide for prospecting. Ec. Geol., vol. 54, No. 7, pp. 1291-1297, 1959.

42. Aqua Regia extractable copper and zinc in plutonic rocks in relation to ore deposits. Extract from Trans. Inst. Mining Met., vol. 69, Part 9, 1959-60.

43. Trace element variations in related rocks. International Geological Congress XXI Session, Part 11, Norden, Copenhagen, pp. 57-64, 1960.

44. Observations on the biogeochemistry of lead in Canada. Trans. Roy. Soc. Can., Third Series, vol. LIV, pp. 11-20, 1960.

45. The lead, copper, zinc, and molybdenum content of some limestones and related rocks in southern Ontario. Ec. Geol., vol. 56, No. 7, pp. 1265-1272, 1961.

46. Aqua Regia extractable lead and molybdenum in eruptive rocks. Trans. Roy. Soc. Can., Third Series, vol. LV, pp. 67-73, 1961.

47. Pathfinding elements in geochemical prospecting. International Geological Congress – XX Session, Mexico, 1956, Symposium de Exploracion Geoquimica, vol. 2, pp. 255-260. 1959.

48. Warren, Harry, V. Background data for biogeochemical prospecting in British Columbia. Trans. Roy. Soc. Can., Third Series, vol. LVI, Section 111, pp. 21-30, 1962.

49. Warren, Harry, V., Delavault, R.E., and Barakso, John. The role of arsenic as a pathfinder in biogeochemical prospecting. Ec. Geol., vol. 59, pp. 1381-1389, 1964.

50. Warren, Harry, V., and Delavault, R.E. Further studies of the biogeochemistry of molybdenum. Western Miner, vol. 38, No. 10, pp. 64-72, 1965.

51. Warren, Harry, V., Delavault, Robert, E., and Cross, Christine, H. Geochemistry in mineral exploration. Western Miner, vol. 39, Part 1, No. 2, pp. 22-26. Part 2, No. 6, pp. 36-42, 1966.

52. Warren, Harry, V., Delavault, Robert, E., and Barakso, John. Some observations on the geochemistry of mercury. Ec. Geol., vol. 61, No. 6, pp. 1010-1028, 1966.

53. Warren, Harry, V., and Delavault, Robert, E. Geochemical prospects have now come of age. Annual review number of Northern Miner, pp. 49 and 57, 1967.

54. Canada Geological Survey. Proceedings, symposium on geochemical prospecting, Ottawa. Geol. Surv. Can.; Paper 66-54, 1967.

55. Warren, Harry, V. Geology and multiple sclerosis. Nature, No. 184, p. 561, 1959.

56. Health and geology. (Paper presented at a meeting of The Canadian Mineralogical Society.) Western Miner and Oil Review, vol. 33, No. 8, pp. 35-42, 1960.

57. Some aspects of the relationship between health and geology. Can. J. Public Health, vol. 52, No. 4, pp. 157-164, 1961.

58. The role of geology in diet. Can. Dietetic Assoc. J., vol. 23, No. 1, 1961.

59. Warren, Harry, V., and Delavault, R.E. Lead in some food crops and trees. Sci. of Food Agr., No. 2, pp. 96-98, 1962.

60. Warren, Harry, V. Does geology hold a key to better health? (Paper presented to The American Institute of Mining and Metallurgy.) Mining Eng., vol. 14, pp. 41-45, 1962.

61. Trace elements and epidemiology. Journal College of General Practitioners, No. 6, pp. 517-531, 1963.

62. Geology, trace elements and epidemiology. Geograph. J., vol. 130, Part 4, pp. 525-528, 1964.

63. Medical geology and geography. (Paper presented to The American Association for the Advancement of Science.) Science, vol. 148, No. 3669, pp. 534-536, 1965.

64. Warren, Harry, V., and Delavault, R.E. Medical geology. Geotimes, vol. 10, No. 2, pp. 14-15, 1965.

65. Warren, Harry, V. Some aspects of lead pollution in perspective. *J. College of General Practitioners*, No. 11, pp. 135-142, 1966.

66. Warren, Harry, V., Delavault, Robert, E., and Cross, Christine, H. Some geological factors in medical geography. (Presented to The Commission on Medical Geography of the International Geographical Union.) (In Spanish) *Sociedad Mexicana de Geografia y Estadistica*, Tomo VI, pp. 47-53. Reunion Especial de la Comision de Geografia Medica, 1966.

67. Mineral contamination in soil and vegetation and its possible relation to public health. *Background Paper A 3-3, Canadian Council of Resource Ministers "Pollution and our Environment"*. A National Conference, Montreal, 1966.

68. Possible correlations between geology and some disease patterns. *Annals of the New York Academy of Sciences*, vol. 136, Art. 22, pp. 657-710, 1967.

69. Warren, Harry, V., and Delavault, Robert, E. Lead in vegetables. (Letter to the Editor), *The Lancet*, p. 1252, June 8, 1968.

70. Purves, D. Trace-element contamination of soils in urban areas. *9th Intern. Congress of Soil Science Transactions*, vol. 11, Paper 36, pp. 351-355, 1968.

SECTION IV

GENERAL

HISTORY OF EARTH SCIENCE

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Scientists have always regarded the history of their disciplines as a matter of significance. Many writings which have led science into new pathways have been prefaced by a historical analysis. The opening chapters of Charles Lyell's Principles of Geology afford an excellent example. In addition, the place of science in history and the interaction between science and philosophy are topics which have long been of interest to scholars. This interest has culminated in the establishment of a number of departments of history of science in universities in all parts of the world. International scientific unions have also given historical studies a formal place in their structures. The International Geological Congress established a commission for the history of the geological sciences in 1964, and the International Union of Geodesy and Geophysics has a similar committee for the history of geomagnetism. These developments reflect the steady growth in interest in the history of science.

CAN THE HISTORY OF SCIENCE HELP IN THE PLANNING OF SCIENCE?

Numerous studies have been made on how the various factors governing the growth of the sciences determine the course of their development. In these studies, the pattern of a particular science through time can be seen to form and change in a complex interweaving of threads from general history, from other sciences, and from its own history. From a knowledge of these inter-relationships it is theoretically possible to forecast how that science may develop in the future. Much has been learned about how science develops, and why it sometimes experiences accelerated growth and change while at other times it remains relatively unchanged for long periods. The history of a science may then give ideas on how the science will develop under various proposed conditions in the future.

NATURE OF THE SOLID-EARTH SCIENCES

Their relationship to science in general: As might be expected, the course followed by one science or group of sciences may be very different from that followed by another. In this respect, the solid-earth sciences constitute a distinctive group, differing from other sciences while possessing certain characteristics common to the other sciences. These characteristics, related to a longer time-scale and a larger spatial environment than is encountered in normal laboratory or technological experience, have given the solid-earth sciences a remarkable and interesting place in the history of science. Their unique subject matter, the earth, has been an attraction to noted scientists from many other fields of science, drawn to the earth as an object worthy of study. The earth has a very critical place in the hierarchy of scale that exists in nature. This position is such that some of the most fundamental scientific ideas have come, in whole or in part, from the study of the earth.

The earth and fundamental scientific ideas: The earth has repeatedly figured in the most fundamental of scientific quests - that of establishing the basic laws of matter and energy. In magnetism the earth figured in the work of William Gilbert and Karl Friedrich Gauss; in gravitation the earth figured in the work of Isaac Newton and Albert Einstein. The reason is that natural laws are based ultimately on the results of experiment. By far the greatest amount of scientific experiment has, throughout the history of science, been done in laboratories and within at most the life-span of individual observers. But natural laws ultimately describe processes operating on a scale in time and space appropriate to the universe as a whole. Thus small-scale experiments cannot in general lead to more than an approximate understanding of fundamental principles.

When we go beyond terrestrial experience and consider bodies such as the earth or the planets, or the larger cosmic bodies, we meet new phenomena, characteristic of aggregations of matter on a vast scale, showing more clearly the fundamental natural laws (1). Perhaps the most striking example is the discovery of the theory of relativity, which owes its existence in part to the Michelson-Morley experiment using the earth as an observational platform.

Geology has made major contributions to the basic understanding in science: the concepts of geologic time and the evolution of life are ideas of the first rank (2, pp. 233-234), and many of the results of natural experiments, observable in the geological record, are major contributions to science (3, pp. 71-73). These contributions are another result of the earth's position in the hierarchy of scale.

In some cases, for example the development of Maxwell's equations, laboratory experiments have led to basic laws which are of sufficient generality to be applicable also to phenomena on the earth and cosmic scales. We still find in these cases that a study of the larger bodies gives insights into nature which are not easy to gain from the simpler, basic laws, even though the larger-scale laws are ultimately derivable from the latter. Hydromagnetic phenomena afford a good example. The concepts of frozen-in or slowly leaking fields and of hydromagnetic waves explain some rather complex phenomena in a direct way. These concepts and phenomena are predictable from the basic laws of electromagnetism. Yet these consequences were not in fact derived until hydromagnetic phenomena were observed and classified during studies of bodies on the cosmic scale - the sun and the earth. It is more fruitful when considering these cosmic phenomena to work with the laws at the appropriate level than to return every time to the basic laws behind them. These cosmic hydromagnetic phenomena later suggested technical applications on the laboratory and industrial scale.

The consequences of this special position of the solid-earth sciences will be seen throughout the history of their development. An awareness of it will aid in our understanding of the various factors that we will see in operation as we review this history.

HOW THE SOLID-EARTH SCIENCES HAVE DEVELOPED

The sciences leading to the modern earth sciences have been developing since ancient times. The main characteristics of the present-day form of the solid-earth sciences were acquired, however, during four decisive periods. These were: (1) 1492-1700, with developments markedly accelerated during the last 50 years; (2) 1760-1830, the period of the Industrial Revolution; (3) 1830-1880, the period of European expansion following the Industrial Revolution; (4) 1880 to the present.

The period of 1492-1700: The great commercial expansion of Europe during these centuries set off an era of sea voyages, discovery and overseas trade. These events set into motion a most remarkable development of science which has been termed the Scientific Revolution (4, pp. 99-150; 5, pp. 251-343). This was the age of Mercator's maps, Copernicus' solar system, Kepler's planetary orbits, Galileo's telescopic observations and dynamics, Boyle's gas laws, crowned by Newton's theory of gravitation. Throughout the period, the problems of navigation inspired scientific investigations (4, pp. 193-293; 5, p. 277, p. 313). The desire for maritime supremacy was great among European nations. This brought problems in map-making, terrestrial magnetism, and geodesy to the fore (6). Leading scientists made contributions in these fields. Christiaan Hüygens, Robert Hooke, and Isaac Newton contributed to the solution of the problem of the figure of the earth. In 1701, Edmond Halley published a map of the variation of declination in the North and South Atlantic Oceans, following 2 years of voyages on a vessel commissioned by the British government exclusively for the purpose of measuring magnetic declination. At the time of writing of Isaac Newton's Principia Mathematica, many scientists suspected that the earth was an oblatum in shape. Newton, using this assumption, and derived in the Principia (1687) the first-order term in the expression for the variation of gravitational acceleration with latitude. By that time a number of pendulum gravity observations has been made in various parts of the world. By 1700, at least two branches of geophysics - geodesy and terrestrial magnetism - were established and acquired essentially present-day characteristics. The decisive period in the formation of concepts of these sciences was passed, but they continued to flourish. Their scientific results continued to be in demand for improving and extending maritime charts and techniques of navigation.

In the following century, the hypothesis that the earth's shape is an oblate spheroid was tested by geodetic and pendulum gravity surveys. Many nations sent out expeditions and surveying parties for this purpose, the most notable being the French expeditions to Peru and Lapland, which returned in 1737. The theoretical proof that an ellipsoid is the equilibrium figure of a rotating fluid was first given in 1741 by Colin Maclaurin. In the course of a long series of papers and monographs devoted to the figure of the earth, Adrien Legendre and Pierre Laplace developed mathematical methods to deal with the problems encountered in this field. One group of these new methods, published separately by these authors in 1785 (7, vol. 2, p. 23) had most important applications, in the form of techniques of spherical harmonics, to mathematics, physics and other branches of science.

Laplace's Théorie du mouvement et de la figure elliptique des planetes, published in 1784 and later refined and summarized in his Méchanique Céleste, represented the limit to which the theory of the figure of the earth could be taken without the rheological theories applied to the same problem by William Thomson (later Lord Kelvin), G. H. Darwin, and others a century later.

Developments in general history during this period were setting the stage for the development of the sciences. Those branches of earth science - which were related to navigation and mapping and plotting trade routes across the globe-developed rapidly. These problems were felt to give the highest scientific challenge and to be of an order worthy of the best scientific effort, and attracted the great scientists of the time to them. There was a long preparatory period in which ideas and observations were collected, but in which overall development was slow. This was followed by a period of rapid development, in which the characteristics of the sciences were established. These characteristics remain for some time after through a period of application of the new branches of science, in which significant results were obtained. It is important to note that a new science does not necessarily continue on into a period following its appearance. There must be a real need for the new science - perhaps a technical application - if it is to continue developing. Electricity is an example of this. William Gilbert laid the foundations of both electricity and magnetism before 1600. Magnetism, which could be put to good purpose at the time developed rapidly, while electricity lay dormant for a century (5, p. 431).

Science in general was advanced during this period because of the importance and abundance of earth-directed problems. Much of the work of the great mathematicians of the time was inspired by these problems. However, the earth sciences were dependent on the state of development of other sciences. The rapid development of the science of the figure of the earth during the last part of the period was made possible by the development of mechanics and of mathematical technique which put it on an adequate theoretical foundation.

The period 1760-1830: The Industrial Revolution - a period of profound transformation in manufacturing and in economic life - began in Great Britain, where it was essentially completed by 1830. Later in the nineteenth century it spread to other parts of Europe and to other continents. It had profound effects on cultural and scientific life which spread throughout and beyond Europe.

During this period, a great and fruitful upsurge of activity in the geological sciences took place. The period from 1790 to 1820 has been called the heroic age of geology by Von Zittel (8, pp. 46-145). It may also be noted that the basic techniques of stratigraphy were established at this time, notably by William Smith, Georges Cuvier, Abraham Werner, Lamarck, and Alexandre Brongniart. Those of economic geology were developed to a considerable degree at the Freiberg School of Mines, where Werner was director from 1775 until 1815.

The period of consolidation of modern geology is marked by two great works of geological literature - James Hutton's Theory of the Earth published in 1785 and Charles Lyell's Principles of Geology published in 1830. Since this development of modern geology can be ascribed to the Industrial Revolution (9) the dates commonly given for this period are used in the present paper as marking off a significant period in the development of the solid-earth sciences.

Many of the sciences included in modern geology had been long in existence. Agricola published his De re metallica in 1556 and has been referred to as "the father of modern mineralogy" (10, p. 185). The fact that the development of modern geology did not take place at an earlier time can be explained by the dominant economic interest in earlier periods centered around overseas trade, channeling scientific interest towards map-making and navigation. When the new industrial developments began to gather momentum, interest shifted to natural resources, including minerals, for use in industrial processing, and to large-scale engineering works such as the building of canals. The effect of the growing industrialism can be seen in the case of James Hutton, "the father of modern geology" (11, 12, 13). Hutton lived during the Industrial Revolution, and was himself part of it as the manager of a chemical industry and of a modern scientific farm. He lived in Edinburgh, perhaps the most remarkable and stimulating city of that time, which had developed a brilliant intellectual life (11). This development was the result of a northward shift of leading centers of science and the arts in Britain, following the Industrial Revolution (13).

James Hutton viewed the earth as a heat engine. His chemical and thermal ideas were very much a part of the general scientific knowledge growing up around him as part of the Industrial Revolution. He was trained in medicine and was a most versatile man. His publications were on scientific and technical matters of all kinds as well as on philosophy and agriculture. He was recognized as a philosopher and scientist of talent. The fact that he came to work on geology, when he could have gone in almost any direction, may be viewed as a result of the new industrial age with its emphasis on natural and mineral resources. In the previous century, geology and theories of the earth had fallen rather low in the opinion of the learned world. The new age elevated interest in the earth to a place of standing, or at least held out this possibility. Hutton was a man of independent means, and did not receive financial or other support as an encouragement to work on geology. This illustrates an important principle: that the general social and intellectual climate is a force that can direct the course of development of science, even without the inducement of direct financial support. The case of Alexander von Humboldt, whose work on geography, geophysics and geology was inspired by the ideas of the period although in a more indirect way, is similar. As did Hutton, Humboldt financed his own work from a legacy which he had inherited (14).

The consolidation of industrial bases on home territory inspired a new interest in land exploration and in mapping which in turn assured a continuing interest in geodesy and terrestrial magnetism. The work of Carl Friedrich Gauss reflects the attraction of these subjects. He carried out geodetic surveys in the field from 1821-28. This interest led him to make major contributions to pure mathematics in the theory of curved surfaces (15, p. 636). The general interest in terrestrial magnetism, including that of Alexander von Humboldt who was Gauss' life-long friend, influenced Gauss to take up work in this subject. Gauss invented geomagnetic instruments, founded an observatory, inspired the establishment of other observatories, and organized international observations through the Göttigen Magnetic Union in the years following 1833 (14, pp. 170-171; 15, pp. 152-162). This interest led Gauss to publish the first comprehensive mathematical analysis of the earth's magnetic field, in 1838, and to develop an interest in other aspects of magnetism. Problems inspired by the earth, coupled with the supporting activities of naturalists like Humboldt, therefore resulted in drawing a great scientist to work on the earth while simultaneously making contributions to basic science.

The developments during this period illustrate further ways in which earth science has developed. The rapid consolidation of a number of pre-existing disciplines to form a new science - geology - illustrated. We see again the close relationship of developments to general history and as was the case with Hutton and von Humboldt, the influence of the general spirit and ideas of the age. The history of Hutton's theory illustrates the dependence of earth science on other sciences, since a successful theory of the earth had to await a proper development of the sciences of heat and chemistry. These sciences were themselves stimulated by the same movement which generated Hutton's interest in geology. In turn, the general interest in the earth acted as a stimulation to the basic sciences, as we saw in the case of Gauss. After its period of rapid consolidation, geology was to continue to develop, under the stimulus of continued application to economic and other problems. Later in the nineteenth century geology was to develop into a science of moment not only in economic applications but in the sphere of ideas, when the concepts of geological time and biological evolution at first became the centre of scientific and philosophical controversy, and later moved on to become recognized as major contributions to science and philosophy.

The period 1830-1880: A new stage in economic life became apparent after 1830, especially in Britain, when industrialism had become essentially established. In this period, technical innovation was of lesser importance than it had been during the Industrial Revolution, and the expansion of existing types of industrial facility became the primary concern, including the growing industrial centres required raw materials for their factories and markets for their products. In the technical sphere, interest shifted to transport and communications; this was the age of steamships, railways, and telegraphs. It was a period of strong belief in progress through the application of science. Even so, governments were often slow in appreciating the possibilities of science. As a result, scientific societies to promote scientific research and its application were founded. The British Association for the Advancement of Science (16) initiated and supported some of the best British scientific work of the mid-nineteenth century. Geodesy and terrestrial magnetism came into prominence again, reflecting growing interest in transport and communications.

The British Association in its early period made terrestrial magnetism one of its primary concerns, with special emphasis on its place in maritime affairs (17, p. 38). Geodesy and terrestrial magnetism, the two oldest branches of geophysics, changed their character considerably during the period. Knowledge about the anelastic behaviour of materials had accumulated and was applied in theories of the figure of the earth. The Industrial Revolution had stimulated the growth of the science of electricity. Particularly important for terrestrial magnetism was the discovery by Hans Christian Oersted of the magnetic effects of electric currents in 1820 and the discovery by Michael Faraday in 1831 of induced currents. Theories of electromagnetism make it possible to understand the nature of time variations in the geomagnetic field, and the relationship of the magnetic field to earth currents. Invention of the telegraph gave an immediate practical application for studies of earth currents. Research and publication on this topic grew after 1849.

This was the age of worldwide networks of geomagnetic observatories and of ocean voyages for the purpose of making scientific observations, including geomagnetic measurements. Research developed rapidly in most of the fields that make up present-day solid-earth geophysics. Prominent scientists of other specialties continued to be attracted to the earth as a subject for research - evidence that the earth was seen also in this period as the source of first class scientific problems. For example, 30 per cent of the 661 scientific contributions of William Thomson (later Lord Kelvin) were in earth science. In addition, the number of scientists giving their full time to earth science grew. Geology of course continued to grow as a profession. What was new in the period was the springing up of the geophysical sciences, and their convergence into a unified field. The name geophysics was in use at least as early as 1853. Interest in time variations of the magnetic elements had persisted for two centuries. With the new electromagnetic theory an explanation became possible. The dynamo theory of their origin was put forward in 1882. In the twentieth century, interest in this same topic led to contributions to basic physics in the studies of sunspots leading to the postulation of hydromagnetic waves and a growth of interest in the science of hydromagnetics.

In this period we see the earth continuing to be a source of basic scientific ideas, and a source of interest as an area of research for many of the great scientists of the day. We see also advances in basic sciences contributing to changes and developments in the older geophysical sciences, and to the development of new ones. A new factor was that scientists themselves became prominent in initiating projects in earth science and obtaining support for them. Some of these were of an international character such as those organized by the Göttigen Magnetic Union. These trends toward organization and promotion of international projects by scientists led to the First Polar Year in 1882 (18). This enterprise was to mark the beginning of a new period in solid-earth science, extending to our own day.

The period after 1880: The First Polar Year is a landmark in the history of the earth sciences because it was the first of a series of ventures in which scientists from many nations collaborated in planned and syncronized observations directed towards the scientific understanding of relatively unexplored portions of the globe. This type of effort led (through its successors, the Second Polar Year and the International Geophysical Year) to exploration of regions beyond the earth's surface - the upper atmosphere and near space. This was the first step in the scientific explorations of the space age.

Two world wars, the inception of what has been called the new industrialism, and atomic and space developments are characteristic of this period. Bound up with these developments is the new industrialism (19, pp. 517-520), a factor of the greatest significance for the solid-earth sciences. Following the Industrial Revolution, industry gradually changed its character from the traditional reliance on coal and steam to an increasing application of new energy sources and new materials. These energy sources and materials became much sought after in the face of the growing demands of industry in the present century. As a result, geological, geochemical, and geophysical, prospecting grew rapidly and new methods of mapping and exploration began to develop. In the course of this development, these sciences grew and changed radically.

SOME CRITICAL PERIODS IN THE GROWTH OF CANADIAN SOLID-EARTH SCIENCE

Notable in the explorations following the Industrial Revolution in Europe were the sea expeditions to the Canadian arctic, sent out by the governments of many nations. Arctic voyages had, of course, been made in previous centuries, and some scientific measurements had been made. Henry Hudson's voyage to Hudson Bay in 1609 had, through measurements of the magnetic inclination, given an early proof of the correctness of William Gilbert's theory of geomagnetism (4, p. 201). Then the number of voyages of exploration increased considerably about 1850, and strong interest in geodesy and terrestrial magnetism led to the inclusion of scientific officers in many of these expeditions. In fact, many of the voyages themselves were initiated following urging by scientific organizations such as the British Association and the Royal Society. Geomagnetic observations in northern Canada were considered to be of special importance, because of proximity to the north magnetic pole as well as the excellent opportunity of observing variations of the magnetic elements in such latitudes (20, p. 79). This led to a large number of scientific voyages to Canadian arctic waters, and to establishment of a geomagnetic observatory at Toronto in 1839. One result was that a major discovery was made by Edward Sabine - his proof of the extra-terrestrial origin of magnetic storms in 1848 - using results from Toronto.

Resources mapping and the Geological Survey of Canada: Although colonies like Canada did not themselves become industrialized during the Industrial Revolution, they were affected by it, through colonial policy and influence (21, p. 349). Among other things, many people had a strong desire to discover and develop local resources as a basis for increased industrialism in Canada. The Geological Survey of Canada was founded in 1842 after almost 10 years of agitation within the country (22, p. 123). The subsequent development of the Geological Survey and its role in the solid-earth sciences has been described by Alcock (23). In keeping with the circumstances of its origin, the Geological Survey was from the beginning directed towards economic applications. Sir William Logan, the founder and first director of the Geological Survey, referred to his work as "economic researches carried out in a scientific way" (22, p. 293). The Survey achieved sufficient success in this work to receive notice and high esteem abroad. The London Quaterly Review in 1854, 12 years after the establishment of the Geological Survey, remarked that "in Canada especially there has been proceeding for some years one of the most extensive and important Geological Surveys now going on in the world" (22, p. 296). The influence of technology based on the Industrial Revolution is evident in the fact that Logan had been previously engaged mainly in coal geology, and some of his earliest researches in Canada were on coal measures in the Atlantic provinces.

Confederation and the solid-earth sciences: One of the conditions under which British Columbia entered Confederation was that "an undertaking had been given to British Columbia in 1871 that a railroad would be begun within 2 years of the admission of that province to the Dominion and completed within 10" (19, p. 413). The Geological Survey of Canada was directed to help investigate the proposed railway routes through the Cordillera to British Columbia and to investigate "the mineral resources along these possible lines" (23). This commitment led to six parties in the field by 1870, eight parties by 1880, and fourteen parties by 1890. In addition, much astronomical work was done in determining latitudes and longitudes, leading indirectly to approval soon after 1885 for the establishment of a government-sponsored astronomical observatory in Ottawa. In 1905, the Dominion Observatory was established (24, p. 88) and its geophysical divisions have had a considerable effect on Canadian solid-earth science.

Prospecting-based earth science: Canada did not become industrialized in the nineteenth century on the pattern of western Europe or the United States as had been hoped by some of the early proponents of the Geological Survey of Canada. It has been suggested that in fact such industrialism was "not, for Canada, an open alternative" (19, p. 516). Many mineral deposits had of course been discovered in Canada, as shown in the much praised Canadian display in London at the Exhibition of 1851 (22, p. 269). But the real movement toward exploiting the vast mineral wealth that has been discovered in Canada did not begin until about 1900, when industry began to grow in Canada and in other countries on a new pattern, which has been called "the new industrialism" (19, pp. 517-520). New energy sources such as hydroelectricity, new materials and industrial processes began to change the character of industry away from and beyond the traditional coal, iron and steam of the Industrial Revolution. Canada proved to be rich in the energy and mineral resources important in the new industries. The difficulties of Canadian terrain made it necessary to employ air transportation and geophysical surveying in the search for minerals. These conditions led to a remarkable development in prospecting-based earth science in Canada. Canadian advances in this field are today recognized abroad. Canadian airborne surveys and equipment are highly admired in all parts of the world. The new industrialism has acted, in Canadian conditions - natural and economic - from the beginning of the present century, though two world wars and the intervening periods to give a strongly prospecting-based character to Canadian earth science.

CONCLUSIONS ON THE HISTORY OF SOLID-EARTH SCIENCES AND ITS PLACE IN UNDERSTANDING THEIR FUTURE

I have examined some of the many and varied trends in the solid-earth sciences as they develop through time and have indicated some features that are common to all or many of the trends, suggesting that there are some common principles about which the study of the history of the solid-earth can be developed. Some incidents in the development of the solid-earth sciences in Canada have been chosen, to relate these principles to the Canadian scene. I will now summarize some of the principles of development that have emerged from this historical study, relative to the question posed at the beginning - can history of science help in the planning of science?

By and large, the developments in solid-earth science have been a part of broader movements in general history. This is seen circumstantially through the mere fact that the critical periods of development of the solid-earth sciences have coincided with corresponding periods in general history. The general atmosphere and intellectual climate of an age is a very powerful directing force for scientific development. The very great influence of the general spirit of the Industrial Revolution shaped the scientific activities of James Hutton and Alexander von Humboldt even without any great inducement in the form of financial support or formal direction. This same conclusion emerged from Bernal's (5, p. 910) study of the history of science as a whole -

"the satisfaction of the material needs of a science is a necessary but not a sufficient condition for its advance; with it must go a sense of excitement and novelty great enough to draw the most capable people into the adventure of science". If one is to influence the development of a branch of science he must not only control the flow of support, but also understand the whole complex of general needs and intellectual climate of the time to determine if and how favourably the science might react to attempts to direct its development. The support given by the British Association to terrestrial physics is an example of a successful policy. The proposals of the scientists in the association on what should be done correctly reflected the scientific needs of the time. Through their influence on the British government, they obtained support for disciplines which grew into a healthy science of geophysics. Part of the benefit came to Canada in the form of geophysical projects and establishments. The indirect effects of the Industrial Revolution, through the ideas of the period following it, were seen in Canada by the circumstances surrounding the foundation of the Geological Survey. An example of a beneficial result of government policy is seen in the scientific exploration of parts of western Canada where scientific departments were deployed after Confederation in the fulfilment of its commitment to British Columbia.

The effect of the new industrialism in determining the character of a good part of Canadian earth science was shown in the preceding survey of Canadian solid-earth science. It is important to be aware of these external influences on the character of science. The same principles which have operated elsewhere to determine the development of the solid-earth sciences also have operated in Canada; thus the more general conclusions also apply to Canada.

One thing that consistently emerges is the fact that the solid-earth sciences have at various intervals become sciences of great standing. They attracted the best scientists of the time and inspired new developments in the basic sciences and in the world of ideas. This process is going on today, as the example of hydromagnetism shows. Thus the solid-earth sciences are a vital part of a healthy science in any nation.

As several of the previous examples have shown, three stages can be seen in the growth of a science. The pre-existing branches of the new science-to-be develop slowly and over a long period of time. Then, in response to some stimulus - in all the cases studied, the technologies of various historical periods - there is a rapid consolidation into the new science. There is no guarantee that the new science will continue to flourish. If it finds an immediate application to the technology or another vital concern of the age it continues to grow, while maintaining for some time the form it acquired during the formative stage. If it does not find an application, it might stagnate or lie dormant for some time, as the science of electricity once did. There are signs that the earth sciences, along with the infant planetary sciences are moving together and converging in many ways. If so, an important synthesis of the earth sciences might be approaching. This would be a more important upsurge into a new science than the ones we have viewed in our historical survey, because it would involve a synthesis of all of earth science and not just one branch. Since some of the major problems facing all nations lie partly in the earth-sciences area, any newly-formed comprehensive earth science would immediately find the application to stimulate its continued development. If such developments are in the offing, any planning of science would need to consider the possibility that a newly-formed science in the earth-planetary area may in the future come to be one of considerable moment.

The large number of possibilities which emerge from this historical study justify the conclusion that History of Science can help in the planning of science.

REFERENCES

1. Wilson, J.T., 1966. A theory of planetary behaviour; Indian Geophys. Union, Hyderabad.

2. Hagner, A.F., 1963. Philosophical aspects of the geological sciences; in The Fabric of Geology, C.C. Albritton, editor, Addison-Wesley, Reading, Massachusetts, pp. 233-241.

3. McKelvey, V.E., 1963. Geology as the study of complex natural experiments; in The Fabric of Geology, G.G. Albritton, editor, Addison-Wesley, Reading, Massachusetts, pp. 69-74.

4. Mason, S.F., 1953. A history of sciences; Routledge and Kegan Paul, London, 520 pp.

5. Bernal, J.D., 1965. Science in history, 2nd ed.; Watts, London, 1039 pp.

6. Taylor, E.G.R., 1937. The geographical ideas of Robert Hooke: Geog. J., 89, pp. 525-538.

7. Todhunter, I., 1873. A history of the mathematical theories of attraction and the figure of the earth; Macmillan, London. Reprint, 1962, Dover Publications, New York, vol. 1, pp. 1-476, vol. 2, pp. 1-508.

8. Von Zittel, K.A., 1901. History of geology and palaeontology; Walter Scott Press, London, 562 pp.

9. Tomkeieff, S.I., 1950. James Hutton and the philosophy of geology; Proc. Roy. Soc., Edinburgh, 63B, pp. 387-400.

10. Adams, F.D., 1938. The birth and development of the geological sciences; Williams and Wilkins, Baltimore, 506 pp. Paperback reprint, 1954, Dover, New York, 506 pp.

11. Macgregor, M., 1950. Life and times of James Hutton; Proc. Roy. Soc., Edinburgh, 63B, pp. 351-356.

12. Bailey, E.B., 1950. James Hutton, founder of modern geology; Proc. Roy. Soc., Edinburgh, 63B, pp. 357-369.

13. Crowther, J.G., 1962. Scientists of the industrial revolution; Cresset, London, 365 pp.

14. Kellner, L., 1963. Alexander von Humboldt; Oxford, London, 246 pp.

15. Dunnington, G.W., 1955. Carl Friedrich Gauss: titan of science; Hafner, New York, 479 pp.

16. Howarth, O.J.R., 1931. The British Association for the Advancement of Science: a retrospect 1831-1931; Brit. Assoc., London, 330 pp.

17. British Association, 1839. Report on memorandum to Her Majesty's government; Rept. Brit. Assoc. Advan. Sci., pp. 33-37.

18. Heathcote, N.H. de V. and Armitage, A., 1959. The first international polar year; Ann. Intern. Geophys. Yr., 1: 6-99 (in English), pp. 105-204 (in French).

19. Easterbrook, W.T. and Aitken, H.G.J., 1956. Canadian economic history; MacMillan, Toronto, 606 pp.

20. Sabine, E., 1837. On the magnetic intensity of the earth; Report of the seventh meeting, Brit. Assoc. Advan. Sci., 6: 1-85.

21. Thomson, D., 1960. The United Kingdom and its worldwide interests; in The new Cambridge modern history, J.P.T. Bury, editor, vol. X, the zenith of European power 1830-1870, University Press, Cambridge, pp. 331-356.

22. Harrington, B.J., 1883. Life of Sir William Logan; Sampson Low, London, 422 pp.

23. Alcock, F.J., 1948. A century in the history of the Geological Survey of Canada; Natl. Museum of Can., Spec. Contrib. 47-1.

24. Harper, W.E., 1939. The history of astronomy in Canada; in A History of Science in Canada, H.M. Tory, editor, Ryerson Press, Toronto, pp. 87-99.

COMPUTER APPLICATIONS IN THE EARTH SCIENCES

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DEFINITION

During the past ten years computers have assumed an important and growing role in the Earth Sciences. The new technology they represent has been applied in three areas:

Data storage and retrieval
Data analysis and synthesis
Information transfer.

For purposes of this report, "data" refers to basic scientific observations and measurements. "Information" is a broader term taken to include data and other communicable knowledge such as conclusions, theories and summaries. Although scientists have always been involved in these activities, the advent of computer technology supplied new tools that have made a revolutionary impact on their scope and significance.

SIGNIFICANCE OF RESEARCH AND DEVELOPMENT

The ability of computers to provide selective, near-instant access to an enormous store of data and information has significance in two important respects: Improving the efficiency of mineral resource development, and strengthening the foundation of basic data upon which the Earth Sciences rest. Greater efficiency will be achieved by placing existing public data in the right place at the right time, by avoiding duplication of data collection, by allowing explorationists to spend most of their time in inventive and decision-making thought and analysis, and by reducing the unit cost of acquiring and preserving data. Our scientific data base will be greatly augmented and improved through the combined effects of creating truly large, usable files of data and the widespread adoption of standards for data (Burk, 1968).

Computers have made it possible, even routine, for Earth Scientists to analyze their data with sophisticated statistical and other techniques that could not be considered without computers. The results of such analysis supply more information and insight into problems than mere inspection of raw data can provide. As new mineral resources become harder to find, the value of these techniques increases. The computer processing and analysis of seismic data in the petroleum industry, for example, has greatly increased the resolving power of this tool in locating oil and gas prospects (Lindseth, 1967). The genesis of petroleum-bearing carbonate rocks is

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now better understood as the result of using computers to analyze, classify and synthesize data (e. g. Harbaugh and Merriam, 1968).

Computers hold much promise as tools for solving the widely recognized problem of information transfer. Our existing system threatens to bury us in paper, and it is becoming increasingly difficult to find the information we need when we want it. Research and development in information science is beginning to provide computer-oriented systems that help scientists ascertain if the information they seek is available, where it may be obtained and, ultimately, to supply the information itself. The economic significance of this work from a national perspective has been recently described for the Science Council of Canada (1969).

PRACTICAL APPLICATIONS

1. Rapid retrieval of pre-selected data needed for a specific purpose (e. g. formation elevations used to prepare a structure map).

2. Rapid scanning of large blocs of data preliminary to planning projects (e. g. searching for the number and location of analyses for nickel in a geochemical data file).

3. Publication by government agencies and others of data as it becomes available and as custom requests, with less delay and at costs considerably lower than required for equivalent traditional hard-copy publication (e. g. chemical analyses of rocks).

4. Efficient exchange of data between companies, government agencies, individual scientists and others (e. g. formation tops supplied to industry by provincial agencies).

5. Manipulation of large blocs of data with a high degree of flexibility and scope (.e. g. listing all Canadian mineral deposits by type, age, reserves, etc.).

6. Immediate availability of data for graphic display by plotters, line-printers and cathode-ray tube displays, in the form of tables, graphs, histograms and maps (e. g. isopach maps).

7. Numerical, statistical and other analyses of data, including a growing list of methods that cannot be applied without computers (e. g. factor analysis).

8. Immediate access to all public information and data on any topic (e. g. all reports for a given area reporting uranium assays).

9. Retrospective searches of scientific literature for both research and economic purposes (e. g. retrieval of descriptions of base-metal deposits in Scandinavia).

HISTORICAL DEVELOPMENT

Significant activity in data storage and retrieval began little more than ten years ago with the building of well-data systems by oil companies in western Canada. One large company created a file that by 1963 contained data on each of the approximately 37,000 wells drilled to that time (Stauft, 1966). The initial motives for establishing such files stemmed from the great volume of data at hand, made available for the most part in relatively standardized form by provincial regulatory agencies.

The first attempts at using computers for storage and retrieval of data were not without serious difficulties. Following an initial phase of romantic enchantment, many organizations became frustrated and disappointed. So-called "minor" problems were not resolved and expenses mounted rapidly with little useful return. A key problem, then as now, concerned the nature of most available data. Hard-copy records contained a surprisingly large number of errors; original sources in many instances used an irreconcilable variety of intellectual standards, terminology and definitions; fundamental items such as geographic location were commonly lacking, and data were found mixed with interpretations and other high-level information. In addition, problems were encountered with the computer systems used. Many were oriented toward the computer specialist, not the scientist-user; definition of purpose and good planning were commonly lacking. Out of these experiences there emerged a more mature understanding of both the requirements and potential benefits of computers as storage devices, but it became evident that if these benefits were to be realized, better management of our data resources would be required.

The size and variety of computerized Earth Science data files grew steadily until by 1968 there were over 135 in Canada, including files on such diverse disciplines as geophysics, geochemistry, stratigraphy, oceanography, petrology, paleontology, economic geology, and photogeology (Brisbin and Ediger, 1967). Some files contained in excess of one million data items. During the same period there was a rapid increase in the number of computers installed in Canada. From 502 in 1964, the number rose to 1,613 in 1968, and 2,100 are projected for 1970.

The National Advisory Committee on Research in the Geological Sciences recognized the implications of computers for future development of the Earth Sciences and in 1965 commissioned an ad hoc committee of Canadian scientists to develop a concept for a computer-oriented national system for storage and retrieval of geological data. Its final report (Brisbin and Ediger, 1967) received widespread Canadian and international distribution, and Canada was placed in a position of leadership among nations interested in better management of their data resources. For example, the American Association of Petroleum Geologists adapted the stratigraphic coding method recommended in the Canadian report (Cohee, 1967). The chairman of the ad hoc committee later assumed chairmanship of an international (IUGS) committee in this field and another committee member was invited to serve on a United States (AGI) project to develop a national information program for the Earth Sciences in that country. Canada was asked to contribute a review paper on computerized geological data files for the 1971 Eighth World Petroleum Congress.

The national system concept developed by NACRGS provides broad principles within which individual data files can be assembled by any organization. When developed, the system would consist of a network of owner-controlled files which belong to the network voluntarily by virtue of adopting certain minimum standards for their data. No central "data bank" is envisaged, but an independent co-ordinating body would be required. During 1968 the Geological Survey of Canada established the Secretariat for Geoscience Data to provide co-ordination on an interim basis until such time as a permanent body is organized.

The petroleum industry recognized the need for data standards and during the past few years working committees of the Canadian Petroleum Association have been active in developing standards for digital log and well analysis data.

Most data analysis and synthesis programs used in Canada have been imported from the United States, but increasingly original work is being produced here. The use of computers to calculate such standard statistics as mean, variance, correlation coefficients and others was followed by their use in more sophisticated techniques such as polynomial trend, harmonic trend, cluster, and factor analysis, to mention only a few (Harbaugh and Merriam, 1968). These analyses cannot be made without aid from computers, and thus a number of significant new analytical tools were introduced. In the petroleum industry, heavy investments were made in developing seismic data processing programs, to the point where analysis of these data is now wholly dependent on computer technology.

The end products of most Earth Science studies are commonly graphic in nature, including histograms, maps and cross-sections. Over the past ten years a variety of automated output devices has been built to provide ever more accurate, useful and appealing graphic products. Automatic contouring machines have proved to be of particular value to Earth Scientists. Other useful output is produced by line-printers and cathode-ray tube displays. Microfilm containing graphic information can also be processed by computer systems.

Information transfer applications for Earth Scientists have been seriously studied in Canada only during the past few years. One large oil company developed a computer-oriented indexing system in the mid-sixties which was later used as the basis for a system to produce the proposed Canadian Index to Geoscience Data. This index, a part of the national system concept, would eventually indicate the existence and location of all public data on the geology of Canada. In contrast to activity here, much effort has been expended in the United States in developing computerized bibliographic tools, indexes, catalogues, and library functions. For the Earth Sciences, this work has been co-ordinated by the American Geological Institute's Committee on Geoscience Information since late 1967 (Smith et al, 1967).

PRESENT LEVEL OF ACTIVITY

The bulk of computer activity in the Earth Sciences is associated with the development of petroleum resources, and 90 per cent of this is carried on in Calgary where seven commercial data centres and more than 12 oil companies have invested about $24 million in computer "hardware" and about $6 million in "software" developments. Individual investments range from $200,000 to $3 million. Most of these facilities are used to process seismic data, but as large files of other types of data become available, the emphasis will shift accordingly (Heise, 1969).

The most important public and commercially available data files used by the petroleum industry include the International PetroData Inc. PETRODATA file (data on about 55,000 wells, 31 reels of magnetic tape); the Canadian Stratigraphic Service Ltd. CANSTRAT file (lithologic data on about 2,500 wells, 7 reels of tape); the Saskatchewan Department of Mineral Resources well file (data on about 15,000 wells; 2 reels of tape); the Alberta Oil and Gas Conservation Board well file (data on about 30,000 wells; 6 reels of tape); the Ontario Department of Energy and Resources Management well file (data on about 10,000 wells; 1 reel of tape); and the CDP Computer Data Processors Ltd. SONIGRAM file (digital sonic logs for about 2,000 wells; 2 reels of tape). Several oil companies maintain in-house files similar to these, in addition to others such as water analyses, core analyses and digital log files (e.g. Stauft, 1968). Another service company, Riley's DataShare International Ltd, is engaged in a project to digitize and make available in this form the one billion feet of wireline log curves from western Canada.

In contrast to the petroleum industry, there is very little activity associated with the mining industry. A few companies are active but only one has publicly described an operating computerized storage and retrieval system (Drummond, 1969). This lack of activity can be at least partially attributed to the absence of large blocs of standardized data analogous to those provided by provincial legislation for the oil industry.

Federal and provincial agencies are becoming increasingly active. In addition to the provincial well-data systems mentioned previously, other examples include the Alberta Research Council HYDRODAT file (groundwater data), Bedford Institute geophysical data files, the Geological Survey of Canada GEODAT file (about 250,000 laboratory analyses; 8 reels of tape), and the Inland Waters Branch GOWN file (groundwater data). Bedford Institute now "publishes" its geophysical data in the form of reels of magnetic tape, a practice that will become more common in the future.

Although a general awareness of computers is increasing in universities, their use in teaching and research in the Earth Sciences has not materialized as quickly as had been anticipated. This has been rectified to a degree through special Geological Survey of Canada grants for research in the development of computer-processable files of geological data. At present, these grants are supporting eight projects, including three on mineral deposits data, two on geochemical data, one on oil and gas pool data, one on geological field data, and one on water analysis data.

A result of this research has been development of a promising new user-oriented, free-format filing system for the generation of computerized data files (Sutterlin and de Plancke, 1969). This university work is being co-ordinated by the Secretariat for Geoscience Data with the objective of building a prototype for the proposed national system (Burk, 1969a).

Data analysis and synthesis is being vigorously pursued by petroleum exploration companies and service centres, and by about six university Earth Science departments. Federal agencies are doing some work, provincial agencies almost none. In the petroleum industry, most activity is associated with seismic data processing, and the analysis of various contoured maps such as structure, isopach and porosity maps. Polynomial analysis, harmonic analysis and spatial filtering techniques are used. Factor analysis is used in petrological studies using data from cores, samples, outcrop and well logs. With the prospect of obtaining one billion feet of digitized well logs in the future, research is now very active in the analysis of log curves (Heise, 1967), the results of which will have an impact on many other areas (e. g. electrocardiograms).

The computer system that will produce the Canadian Index to Geoscience Data is being prepared as a co-operative project of Imperial Oil Limited, the Geological Survey of Canada, and the Universities of Saskatchewan and Calgary. This system, known as SIS-II, was developed and operated in its original form by Imperial Oil Limited and subsequently offered to these other organizations. The University of Saskatchewan has spent over 950 hours of programming time in preparing the basic three modules of SIS-II, and the system will become operational in 1969 (Burk, 1969a).

NEED FOR INCREASED ACTIVITY

The management and utilization of data and information in the Earth Sciences are in a state of transition due to the introduction of computers and related new data-handling methods. Experience gained to date with these new technologies points to a number of basic needs that must be filled if the potential benefits of these technologies are to be realized.

Standards for Earth Science data

As a prerequisite to the building of a generally usable data file, basic intellectual standards for the data placed in it must be established. Geologists must overcome their common tendency to record only their interpretations of field and laboratory observations and, instead, record the observed facts. There must be consistency in the parameters recorded and in the terms and units of measurements used to record them. National standards for most types of data, including those of the most fundamental nature, are nonexistent, and therefore meaningful files of these data simply cannot be assembled at present.

User-oriented data systems

Operating data systems should be designed to meet more closely the real needs of the scientist-user. Many existing systems reflect the design criteria of programmers, systems analysts and efficiency experts, most of whom regard Earth Science data in the same black-and-white terms as they do figures in a financial statement. Such approaches can no longer be justified with today's large, fast, flexible computer systems.

Data analysis and synthesis

Most Earth Scientists are so accustomed to living with minuscule volumes of data (their own) that many are unaware of the vast array of powerful computer-oriented techniques for processing, analyzing and synthesizing data, all designed to extract more information than the mere listing of data in raw form can provide. The acquisition of data should not be regarded as the end of an investigation, but rather the beginning. There is a general educational need to acquaint more scientists with these techniques and their application.

Access tools

Before scientists can use existing data they must know where to get it. With the multiplicity of data sources in Canada and ever-growing volumes of data being generated (Burk, 1969b), there is an increasing need for the development of comprehensive, flexible access tools such as the proposed *Canadian Index to Geoscience Data*. To meet the intellectual needs of science and the pragmatic needs of a dynamic, far-ranging mineral industry, such tools must be at least national in scope.

Of the four needs described above, the development of standards for data is the most important for the long term. It cannot be expected, however, that existing groups in the Earth Sciences will co-operate spontaneously to develop such standards, especially if the purposes are not clearly defined and scientific freedom and data ownership rights are believed to be impaired. Such co-operation will take place only through the aegis of a permanent, user-controlled, co-ordinating body filling a role somewhat comparable to that of the Canadian Standards Association (CSA) in the manufacturing industry.

COMMENTS ON TRAINING

In order to progress in the directions espoused in this report, students must develop new attitudes toward the value and use of basic observations and measurements in the Earth Sciences. There should be concern for the particular standards used and thought given to future uses of data collected today. Practical experience in the creation and use of computer files by students, and in programming, coding, and other technological skills will help students develop these attitudes. At the same time, these activities should be secondary to concern for the basic purpose of these exercises and the development of creative applications.

OBJECTIVES AND FUTURE TRENDS

The objective of computer storage of Earth Science data is to make data available on a selective basis to more scientists, in larger volumes, more quickly, in more readily usable forms, and at lower unit cost than we are presently accustomed to. These data may be used in familiar ways or in newly created ways made possible by the added dimensions of data volume, processing speed, and analytical power provided by computer technology. In turn, the objectives of developing these new capabilities are more efficient development of Canada's mineral resources and increased capacity for scientific research and development.

In the near future, the Earth Sciences can expect a deluge of new data contributed by numerous technological innovations. To handle these data, more files, computers, magnetic tapes, discs, and other devices will be employed, and, depending on policy decisions of the new Department of Communications, a variety of new media for transmitting digital data will be available, including cable, microwave, satellite and laser beam. As a result of these new technologies, Earth Scientists will be able to pursue their investigations with significantly greater objectivity and scope.

CONCLUSIONS

1. Industry, government and universities should reappraise current policies and practices for managing their Earth Science data, especially with regard to adequacy for conservation of these data as costly and potentially reusable resources.
2. Immediate collective action should be taken to ensure development and application of standardized methods for the future collection and storage of Earth Science data.
3. A national index to the existence and location of Earth Science data should be developed, as an essential first step in the proper management of our data resources.
4. A permanent body, such as the proposed[1] Canadian Geoscience Data Institute, should be established to implement the national system for storage and retrieval of geological data, and to help ensure an orderly development of computer applications in the Earth Sciences in Canada.

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[1] Hon. J. J. Greene, Minister of Energy, Mines and Resources, at Mines Ministers' Conference, Quebec, September 16, 1968.

REFERENCES

Brisbin, W. C. and Ediger, N. M. (Eds), 1967. A national system for storage and retrieval of geological data in Canada. Nat. Advisory Comm. Res. Geol. Sci., 175 p. (available from Geol. Surv. Can.).

Burk, C. F., Jr., 1968. Data in the earth sciences, in The Earth Sciences in Canada. Roy. Soc. Can. Spec. Pub. 11, pp. 75-81.

_____ 1969a. Towards a national system for geoscience data. Oilweek, vol. 19, No. 50, pp. 38-40, 48.

_____ 1969b. Supply and demand of geoscience data. Western Miner, vol. 42, No. 2, pp. 30-36.

Cohee, G. V., 1967. Standard stratigraphic code adopted by A. A. P. G. Am. Assoc. Petrol. Geol. Bull., vol. 51, No. 10, pp. 2146-2150.

Drummond, A. D., 1969. Development of a geological data retrieval system. Western Miner, vol. 42, No. 2, pp. 47-50.

Harbaugh, J. W., and Merriam, D. F., 1968. Computer applications in stratigraphic analysis. John Wiley & Sons Inc., 282 p.

Heise, H., 1967. Log data daze now digitized. Oilweek, 10 July 1967, pp. 10-12, 24-27.

______, 1969. Computer power concentrated in Calgary. Oilweek, vol. 19, No. 50, pp. 27-30.

Lindseth, R. O., 1967. The nature of digital seismic processing. Can. Soc. Exploration Geophys., vol. 3, No. 1, pp. 31-111.

Sci. Council of Can., 1969. Scientific and technical information in Canada, Spec. Study 8, 62 p.

Smith, F. D., Creager, W. A. and Sayer, J. S., 1967. Developing a co-ordinated program for geological scientists in the United States. Am. Geol. Inst., 51 p.

Stauft, D. L., 1966. Computer well data systems: a company case history. Can. Petrol. Technol. J., vol. 5, No. 4, pp. 165-170.

_______, 1968. Computer applications in an oil exploration company. Can. Petrol. Geol. Bull., vol. 16, No. 1, pp. 64-86.

Sutterlin, P. G., and de Plancke, J., 1969. Development of a flexible computer-processable file for storage and retrieval of mineral deposits data. Proc. Univ. Brit. Col. Symp. on Decision-Making in Mineral Exploration II, Feb. 6-7, 1969, pp. 11-42.

"HARD ROCK" CORE STORAGE LABORATORIES

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REASONS FOR STORAGE OF "HARD ROCK" CORE

Diamond drill cores are the most definitive and valuable data collected in any exploration program and represent by far the greatest proportion of expenditures made in the search for new ore bodies. In spite of this, most of these cores are thrown out without much thought being given to their possible future value. For the following reasons, it is suggested that the destruction of diamond drill core should cease immediately.

1. The re-examination of old mineral properties often produces new mines and the drilling of needless holes can be avoided if previously obtained cores are available for inspection.

2. In many areas, cores are the only "outcrop" available as sedimentary cover or low relief reduces the number of surface exposures that yield useful information in providing a three-dimensional picture.

3. Geologists are now recognizing the existence of certain trends in Precambrian rocks and are coming to the conclusion that ore bodies may not be isolated occurrences, totally unrelated to each other. Examples: the Wollaston-Sandfly trend in Saskatchewan and the Thompson - Moak Lake trend in Manitoba.

4. In the search for ore bodies it is becoming more significant to compare the volcanic successions in widely separated areas.

5. Diamond drill cores provide the only source of data for carrying out three-dimensional geochemical studies.

6. Detailed study of cores obtained from known geophysical anomalies may be of great assistance in interpreting similar types of anomalies encountered elsewhere.

7. A log is not a suitable record of a core, as it represents only the opinion of the geologist logging the core. Concepts change with time, and features that would be considered of little importance when the core was first logged may become of great significance at a later date.

CURRENT PRACTICE IN INDUSTRY

Many companies remove portions of core that appear to be mineralized and provide temporary storage for the remaining part of the core at the site. On conclusion of the exploration program, the core is either destroyed in order to recover the boxes or it is left at the site where, within a few years, all record of the core is lost through weathering and destruction by animals.

It is known that several companies do not adhere to the above practice but instead carefully preserve all cores taken. These companies indicate that they find storage of diamond drill core to be economically desirable.

CURRENT PRACTICE BY PROVINCIAL GOVERNMENTS

As far as is known, only Nova Scotia and Saskatchewan make any attempt to store diamond drill core on a systematic basis. The Nova Scotia Department of Mines maintains facilities at Stellarton for storage and examination of more than 200,000 feet of diamond core. The Saskatchewan Department of Mineral Resources operates a Precambrian geological laboratory at La Ronge. Space is provided at the laboratory for storage of 200,000 feet of AX diamond drill core, and complete core study facilities are available.

In Ontario and Quebec, resident geologists make collections of rock and drill core specimens that are representative of the main rock types in their respective districts, and these collections are made available for public inspection. Diamond drill cores are not, however, sampled on a systematic basis so that no large collections are retained and provision of storage facilities is not a problem.

In January 1969, the Ontario Department of Mines instituted a policy whereby additional assessment credit is granted for diamond drilling with the submission of one 3-inch core specimen representative of each 25-foot section of core. Each properly labelled specimen is worth one day's assessment credit when submitted with the drill log. Department officials indicate that very few core samples were submitted during the first four months that the policy was in effect.

GENERAL POLICIES WITH RESPECT TO "HARD ROCK" CORE STORAGE LABORATORIES

In order that core storage libraries may be of greatest assistance to the industry and also be economically feasible, it is suggested that the following general policies be followed:

1. With respect to responsibility for the laboratories

(a) The laboratories should be constructed and operated by the provincial Departments of Mines and all costs in connection with establishing the laboratories should be borne by the provincial governments.

(b) The laboratories should come under the supervision of the resident geologists employed by the provincial government.

2. With respect to the collection of cores

(a) Only about 10 per cent of the total core taken should be stored. The intervals chosen for storage should be systematically selected by the resident geologist. Suggestions for the sampling of core are offered under the heading "Recommended Operating Procedures".

(b) The resident geologist should assume responsibility for selecting the cores to be sampled keeping in mind the need for good areal distribution of samples as well as the need for having representative samples of each rock type in his area.

(c) Any operator who wishes to have his cores sampled and these samples retained at the laboratory should be permitted this privilege without any cost to himself.

3. With respect to the scope of the facilities

In addition to providing complete core storage and examination facilities, the laboratory should in addition provide:

(a) Complete core study facilities such as diamond saws, thin sectioning equipment, basic chemicals, microscope tables with electrical outlets, etc. ;

(b) A library of all available reference material on the area including assessment work reports, government reports and maps, basic textbooks, etc. ;

(c) Representative samples collected from outcrops in the area;

(d) Unless exceptional circumstances dictate otherwise, claim recording and other services to the mining industry should be provided in the same building as houses the laboratory.

4. With respect to the location of the facilities

(a) One central core storage for the entire shield area of most provinces would not be practical due to transportation problems;

(b) Several smaller core storage centres should be established in each province having regard to road and rail connections in each area and, if at all possible, the laboratories should be located at float plane bases and close to a local airport;

(c) Before any core storage facilities are constructed, the mining companies should be consulted with respect to desirable locations.

RECOMMENDED OPERATING PROCEDURES

1. Condensing of diamond drill core

As mentioned previously, for economic reasons no more than about 10 per cent of all core taken should be retained in storage. In order that the core retained may be of greatest value, rigid and systematic sampling procedures should be consistently followed. The suggestions given here are based on the experience of the Saskatchewan Department of Mineral Resources in operating its core storage laboratory at La Ronge, and on advice received from various geologists who kindly reviewed a preliminary draft of this paper.

(a) Before the core is condensed

A detailed written log should be prepared by a qualified geologist, with special attention being paid to features such as large structures that cannot be adequately represented by samples. Photographs, preferably in colour, should be taken of the core

(b) Condensing procedures

A specimen three to six inches long should be retained for each rock type present in the core and the depth interval of these specimens should be noted on the log. For long sections of a single rock type, one specimen six inches long should be collected for every ten to twenty feet of core. For mineralized zones where the core will be required for assay, it should be split longitudinally and a continuous portion retained in storage.

2. Storage of condensed core

Experience indicates that regular core boxes provide the most economical and convenient means for storing diamond drill core samples. In the event that lengthy air transportation is necessary to move the specimens from the field to the laboratory, they may be placed temporarily in plastic bags or cardboard boxes in order to reduce weight and bulk.

3. Filing of condensed core

The boxes containing the core samples should be fully labelled as to contents and placed on specially designed racks with identifiable compartments. A cross-reference card index system should be established with one card for each hole. The card should indicate the core rack identification number, number of drill hole, total footage cored, name and location of property, the azmuth and dip of the hole, date of coring. Also included on the card should be a brief summary of the rock types present, summary of the mineralization encountered, and reference to available assays and logs.

4. Collection and storage of outcrop samples

Type specimens should be collected of each of the geological rock units occurring in the area. Also representative suites of specimens should be obtained for each mineral showing, and these should consist of specimens of the adjacent wall rocks as well as of the actual mineralization. All specimens collected should be labelled according to the National Topographic Index System and be given a number. A card index system related to the numbers should be maintained indicating the name of the geologist who collected the specimen and the identification as to rock type. If the specimen comes from ground under disposition, this too should be indicated on the card.

ESTIMATED COSTS OF CORE STORAGE LABORATORIES

The figures presented here are based on the costs of constructing, maintaining and operating the Saskatchewan Department of Mineral Resources Precambrian Geological Laboratory at La Ronge. It is realized that these costs may not be typical of those to be encountered elsewhere as vastly different conditions exist in various parts of Canada.

The laboratory at La Ronge is a totally enclosed steel frame building consisting of a heated office portion and an unheated core shed. In addition to providing storage and examination facilities for 200,000 feet of AX diamond drill core or 350,000 feet of EX diamond core, the following services are provided all of which affect the capital and maintenance costs of the building:

Complete mining recording facilities

Resident geologist services

Library where maps, reports and assessment work may be examined by the public

Expediting services and storage space for equipment for eight geological survey parties

Capital Costs

Construction of the building was completed in 1965 at a total cost of about $145,000. This includes land acquisition fees, all contractors' charges, costs of all laboratory and office equipment, landscaping costs, and all other costs associated with the construction phase.

Maintenance Costs

The maintenance costs of the building are about $5,000 per year including light, heat, janitorial services, repairs to building and all equipment, snow removal, etc. It is apparent that the northerly location of the laboratory in an area of relatively severe climate and high snowfall increase the maintenance costs.

Operating Costs

The operating costs of the laboratory include the salaries of personnel at the laboratory - resident geologist, core technician, clerical staff. Also included are the costs of sampling, transporting and storing of core samples.

Excluding the salary of the resident geologist, personnel costs are about $4,000 per year. Transportation costs are about $4,000 per year, which includes the flying of the resident geologist to the field to sample cores and returning with the core samples.

Incidental expenses for core boxes, office and scientific supplies, etc. are about $2,000 per year.

Summary of Costs

From the foregoing it is apparent that the laboratory is costing about $15,000 per year to maintain and operate, excluding the salaries of the resident geologist and mining recorder. During the first two full years of operation, about 60,000 feet of core have been taken into storage.