INTERNATIONAL
UPPER MANTLE PROJECT

# Canadian Upper Mantle Report 1967


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FOR THE UPPER MANTLE PROJECT



COVER PICTURE: The Energy, Mines and Resources deep sea rock core drill being hoisted on board the CSS HUDSON.

GEOLOGICAL SURVEY

OF CANADA

CANADA

PAPER 67-41

# CANADIAN UPPER MANTLE REPORT, 1967

A report on the work of scientific groups in Canada on projects contributing to the International Upper Mantle Project, prepared on the occasion of the XIVth General Assembly of the International Union of Geodesy and Geophysics, Zurich, Switzerland

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# INTRODUCTION

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The Canadian Upper Mantle program was initiated in 1961, in response to guidelines established by the International Upper Mantle Committee. Co-ordinating committees were established and projects were designed to expedite the acquisition of knowledge and understanding of the earth's crust and mantle under Canada. This report summarizes some of the recent findings.

Previous reports have described the individual Canadian projects in some detail. In the preparation of this report the Committee decided to indicate not only the accomplishments of upper mantle studies in Canada during the past several years, but also to indicate some of the future goals which remain to be achieved.

Remarkable advances have been made in earth science studies in Canada during the period of the Upper Mantle Project. Although the current trend in research is toward more detailed and narrowly defined studies, Canadian scientists can begin to talk knowledgeably of the geological and geophysical properties of the *entire* Canadian crust. This is the result of the nearing completion of the first stage, reconnaissance geology of Canada and the companion strides being made in geophysical studies in Canada. The geological map of Canada has been revised. The aeromagnetic program of the Geological Survey of Canada has produced over 5,000 published maps which can now be used for tectonic analysis of large blocks of the Canadian crust and, with computer analysis, to interpret the properties of deeper sections of the crust. The regional gravity coverage is near completion and a meaningful gravity map of Canada is in preparation. Measurements of crustal thickness have increased remarkably in number - and add new appreciation of the complexity of the crust and mantle. A national heat flow network has been started. The isotopic age determination program of the Geological Survey of Canada and Canadian universities provides data on large regions of Canada and allows the delineation of tectonic events in time as well as in space.

The increased regional coverage has allowed the formulation of new concepts by Canadian scientists. R.J. Uffen has correlated the effect of reversals of the earth's magnetic field on the evolution of life. L.W. Morley and A. Larochelle have interpreted the remarkable alternating magnetic pattern of the ocean basins in terms of the movements of magma at depth (as did F.J. Vine and D.H. Matthews). J.T. Wilson has explained the development of the Atlantic Ocean in terms of continental drift. Other changes in thought are emerging as studies proceed. The simple layering of the crust and mantle is being forgotten. Abnormal crustal thickness, previously postulated only under mountain ranges, is now found in the centre of the continent. The correlation of gravity and seismic data commonly results in anomalous interpretations that can only be reconciled by assuming lateral inhomogeneities in the crust and mantle. This is indeed a period of increasing capability for geological and geophysical research, and for an accellerated growth in new knowledge. The reports which follow indicate the trends which have emerged, and the direction in which further research should be oriented.

# TECTONICS

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## I. INTRODUCTION

Tectonics involves the study and analysis of large areas of the crust in order to evaluate the nature and timing of the physical processes in the crust and mantle. It requires the integration of data from the whole realm of Earth Sciences. Seismic, gravity, and magnetic data outline the depth and character of crustal layers; aeromagnetic maps delineate structures and certain rock types; geochronology dates past plutonic and metamorphic events; stratigraphy, palaeontology, and sedimentary provenance studies reveal the former distribution and nature of uplifts, depressions, and faunal provinces; petrology, geochemistry, and isotopic studies provide data on the nature of volcanism and plutonism; structural studies determine the configuration of the rocks and ultimately lead to an understanding of how they were deformed. Finally a vast number of geological maps must be compiled, analyzed in various ways, and synthesized to produce regional, tectonic, palaeogeographic, metamorphic, and metallogenic maps.

This report involves two principal fields: tectonics in and around Canada and megatectonics, concerned with the whole of the earth's crust. The first section contains a review of the tectonics of Canada, a discussion of Canadian tectonic problems, and a summary of current projects. The second section deals principally with J.T. Wilson's contribution to the concept of continental drift and includes a summary by him of current research on continental drift and its implications.

Recent results from interdisciplinary studies in the Arctic, Appalachian, and Hudson Bay regions are reported elsewhere. The reporter may be accused of emphasizing the Cordillera over the other Phanerozoic orogens. This has resulted partly from his difficulty in communicating adequately with tectonics experts on parts of Canada outside the Cordilleran region. Consequently results of their work may not be fairly presented. A reason for emphasizing the Cordillera at this time, however, is that it represents one of the best-exposed orogenic belts in the world. Also it must be drawn to the attention of Canadian geophysicists that it is the most poorly known region, geophysically, in all of Canada.

The reporter acknowledges the help of D. Tempelman-Kluit who prepared Figures 1 and 2 and aided in other ways. He is also grateful for suggestions by J.W. Kerr, W.H. Poole, C.H. Stockwell, and H.P. Trettin.

References in which initials of the author are given refer to personal communications or to summaries in the part covering current projects in Canada.

## II. REVIEW OF TECTONICS OF CANADA

### A. Introduction

By the end of 1964 regional tectonic compilations and syntheses existed for only parts of Canada. The compilation of a tectonic map of Canada was in progress and resulted in a preliminary tectonic map of the Appalachian Region (Neale et al, 1961) and one of the Canadian Shield (Stockwell, 1964a). The map of the Shield outlined the structural provinces and supplemented an earlier review of Tectonics of the Canadian Shield (Stevenson, 1962). Certain Phanerozoic stratigraphic-structural provinces had been distinguished in the Arctic Archipelago (Thorsteinsson and Tozer, 1960) and later delineated for most of Northern Canada (Douglas et al, 1963). The tectonic framework was established for parts of the Cordillera (White, 1959; Gabrielse and Wheeler, 1961).

Since 1964 several tectonic compilations and syntheses of western Canada have been prepared, and those for all of Canada are nearly complete. The Alberta Society of Petroleum Geologists in December 1964 published the "Geological History of Western Canada" (McCrossan and Glaister, 1964). This impressive atlas and the accompanying text deal mainly with the Phanerozoic history of Western Canada south of latitude 60° with emphasis on the Plains and Western Canada Basin. The western Cordillera is discussed in less detail in this volume but is the principal subject of the Canadian Institute of Mining and Metallurgy Special Volume No. 8 "Tectonic history and mineral deposits of the Western Cordillera" (Gunning, 1966) that includes a tectonic map by W.H. White. Bally et al (1966) summarized the structural evolution of the southern Canadian Rocky Mountains on the basis of geological and seismic reflection data.

The tectonic map of Canada is currently nearing completion and that of the Canadian Shield has been published (Stockwell, 1965). Similarly a summary and synthesis of the geology of Canada by officers of the Geological Survey of Canada under R.J.W. Douglas is nearly finished. When these syntheses are concluded it will be possible to review the progress in regional tectonics and to appraise the direction of future research more readily than at present.

The following summary outlines the principal tectonic elements of Canada and briefly discusses some of their features that throw light on the behaviour of the upper mantle and the overlying crust during the development of the North American continent.

The tectonic framework of Canada (Figure 1) is characterized by a central craton comprising the central crystalline Canadian Shield, partly covered by a thin veneer of essentially undeformed strata, and bounded on the southeast, west and northwest by belts of deformed rocks of the Appalachian, Cordilleran, and Innuitian fold belts (orogens). The Canadian Shield is separated on the northeast by Baffin Bay, Davis Strait, and the Labrador Sea from a similar crystalline shield in Greenland.

## B. Canadian Shield

### (1) Structural Provinces

The Canadian Shield comprises several structural provinces. The character of the oldest provinces, Slave and Superior, suggests that granitic crust existed early in the Archaean about 3,200 my ago. The relationships of the younger provinces to the older indicate that much of the younger provinces are regions of redeformed older crust and not new additions to the continent. In fact the oldest provinces may once have been almost as extensive as the present Shield area.

Superior and Slave provinces. The oldest provinces are composed of large areas of gneisses and granitic rocks within which are less extensive linear belts and interlacing patterns of thick variously metamorphosed Archaean volcanic and sedimentary rocks. The southern part of the Superior province also contains small areas of undeformed sediments and volcanics. Chemical data (Wilson et al, 1965; Baragar, 1966; Goodwin, 1966) suggest that the typical Archaean volcanics, many of which are submarine, are mainly tholeiitic basalts that sequentially change to later calc-alkalic felsic phases. These authors and P.M. Clifford conclude that the volcanics were probably extruded through intersecting sets of fractures onto continents or into a near-continent orogenic environment, thus implying the existence of early Archaean sialic crust. This conclusion is supported by the occurrence in much of northwestern Ontario of Archaean clastic sediments, possibly older than 2700 my, notably rich in quartz and K-feldspar (Donaldson and Jackson, 1965). They were derived not from mafic volcanic terrain but rather from one rich in felsic volcanics, older sedimentary rocks, and granitic plutons. Furthermore the high degree of maturity of some of the Archaean sandstones suggests that they are the product of reworking through more than one orogenic cycle. Recent model lead and discordant zircon dates indicate that such sialic crust probably existed in North America more than 3,200 my ago and, moreover, that it was extensive. For example, model lead ages from sulphide

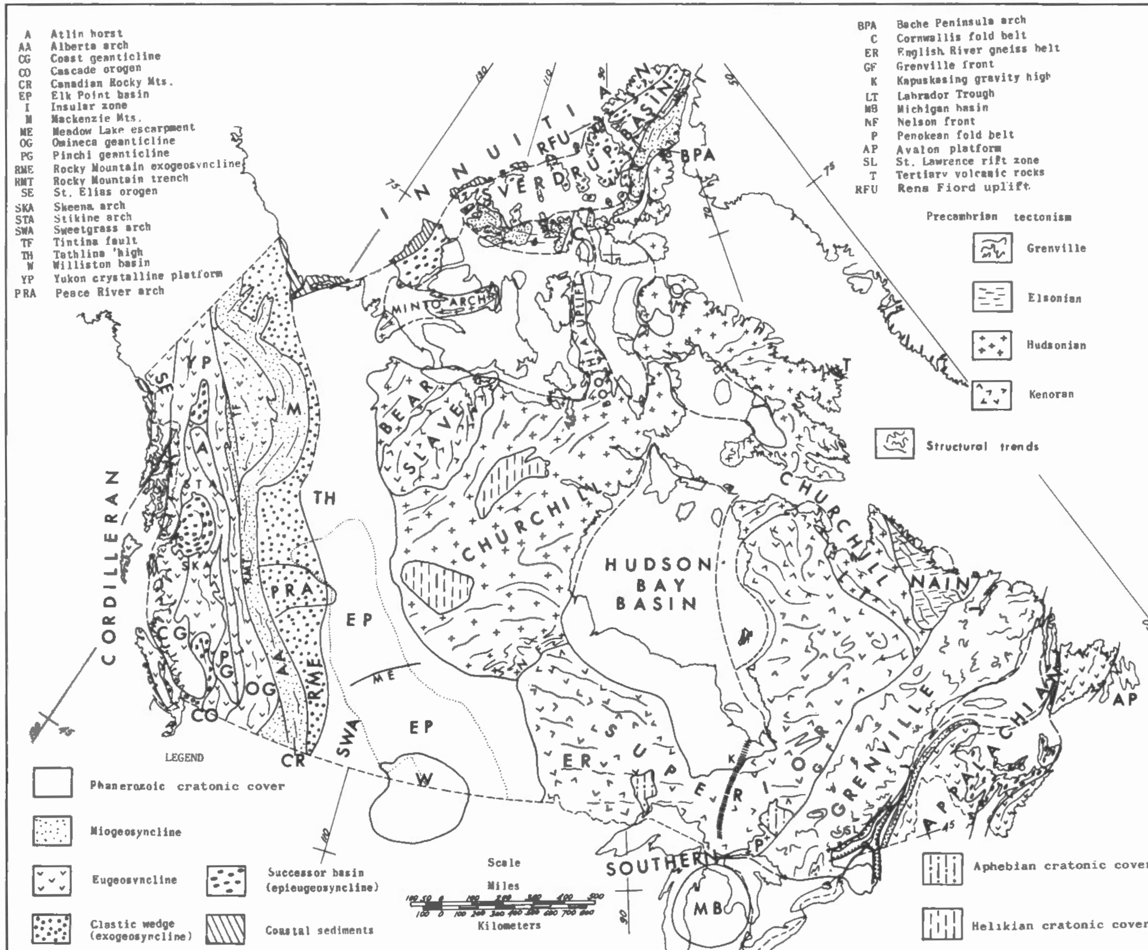


Figure 1. Map showing tectonic provinces of Canada.

deposits, regarded as coeval with Archaean volcanics of the character described above in the Superior province, range in age from 2,900 to 3,250 my (Slawson et al, 1963; Kanasewich and Farquhar, 1965; Roscoe, 1965). Model lead ages ranging from 3,000 to 3,550 my have been obtained from Ivigtut, Greenland and zircon ages of 3,100 and 3,300 my have been obtained from Montana (Catanzaro and Kulp, 1964) and Minnesota (Catanzaro, 1963) respectively.

The Slave and Superior provinces underwent deformation, metamorphism, and granitic intrusion during the Kenoran orogeny about 2,500 my ago. This orogeny created westerly trends in the southern part of Superior province, curvilinear trends east of Hudson Bay, and north-northwesterly trends in its northeasternmost part. Northerly trends prevail in the Slave province. In general the structures produced are somewhat less intricate and less complex than in the younger orogens. Recent studies in the western part of the Superior province indicate that early isoclinal folds in the Archaean rocks were apparently redeformed in response to the diapiric injection of granitic plutons (Brisbin, 1965; H.D.B. Wilson, 1965). Once the region was stabilized with the addition of granitic plutons it was thereafter repeatedly fractured and permitted the extrusion of presumed flood basalts and the emplacement of alkali-rich igneous complexes. The "Keewatin" greenstone belts in the southern part of the Superior province are commonly featured by a low metamorphic grade, slaty cleavage, and layered rocks in which the primary structures are preserved. Clastic sediments in these belts are characterized by turbidites and the coarser phases were derived in part from silicic terrains. Thus P.M. Clifford notes that the metamorphic and structural style is incompatible with deep burial and later resurrection and therefore indicates a mobile silicic crust and probably a high thermal gradient during the Archaean.

Bear, Churchill, and Southern provinces. The next younger provinces include the Bear, the Churchill (which fringes the Superior province on the northwest, north, and northeast) and the Southern province lying south of the Superior province. Thus, they almost surround the oldest provinces and in so doing truncate many of the older structural trends at a high angle. The younger provinces contain early Proterozoic (Aphebian) gneisses and volcanic and sedimentary rocks deformed and intruded during the Hudsonian orogeny about 1,700 my ago. Large areas in the Churchill province are underlain, not only by later relatively undeformed sediments and volcanics, but also by Archaean rocks deformed during the Kenoran orogeny and redeformed during the Hudsonian. Basement-cover response in such structurally complex areas has been studied by Ross and McGlynn (1965) near the boundary of Bear and Slave provinces. The structural trends over most of the Churchill province are generally northeasterly, but swing more northerly in the north. They are, however, particularly irregular in the southeastern part of this province where the Archaean rocks have been redeformed. Near the margins of the province the Hudsonian trends are linear or gently curving as they conform roughly to the boundaries of the older basement. Commonly these marginal zones are marked by a narrow, homoclinal strip that dips away from the older provinces and passes outward into the Hudsonian fold zones. The latter are characterized by axial planes and thrust faults that dip away from the older province. At other places the homocline is missing and the Hudsonian orogen meets the Kenoran along a metamorphic front, for example, the Nelson Front between the Churchill and Superior provinces in Manitoba, whose position was recently revised as a result of aeromagnetic studies (Kornik and MacLaren, 1966).

In the southern province Aphebian rocks of the Penokean fold belt in Minnesota are considered to have been deformed during the Penokean orogeny 1,700 to 1,800 my ago (Goldich et al, 1961, Petermann, 1966). Equivalent rocks occurring eastward in Canada were probably deformed at the same time during the Hudsonian orogeny (Stockwell, 1965). Young and Church (1966) and W.R. Church however, argue that the Huronian rocks are more than 2,100 my old and that the Penokean fold belt was also deformed some time before 2,100 my ago. They base their conclusion on the observation that the Nipissing diabase, dated by the Rb/Sr whole rock method at 2,155* my (Van Schmus, 1965), cuts earlier deformed Huronian rocks (Robertson, 1963). Other Rb/Sr whole rock isochrons on the Thessalon volcanic rocks within the Huronian and on the Sudbury "Series" (Van Schmus, 1965, Knight and Fairbairn, 1966) give ages of about 2,000 my implying that the Huronian is younger than 2,100 my and thus questioning the reliability of age of the Nipissing diabase.

Nain province. The Nain province east of the Labrador Trough is underlain by early mid-Proterozoic (Palaeohelikian) or older rocks intruded by large irregular plutons of granitic and anorthositic rocks and deformed during the Elsonian orogeny about 1,400 my ago (Stockwell, 1965a).

Grenville province. The Grenville province truncates the structural trends of the older provinces along the Grenville Front, which is mainly a metamorphic front but which is locally marked by faults or, as in Labrador, by a homocline. The Grenville province, once thought to be the latest addition to the Canadian Shield, is now regarded merely as the part of the Shield that has been most recently redeformed (Wynne Edwards, 1964). It is composed of late middle Proterozoic (Neohelikian) and older gneisses deformed during the Grenville orogeny about 900 my ago. The older gneisses represent the continuation into the Grenville province of elements of the Superior province, the Labrador trough, and the Nain province deformed during the Kenoran, Hudsonian, and Elsonian orogenies respectively and subsequently redeformed during the Grenville orogeny (Stockwell, 1964). In general, much of the Grenville province is metamorphosed to the granulite facies characterized by charnockitic rocks and anorthosites and hence was

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*Based on $\lambda_{Rb^{87}} = 1.39 \times 10^{-11} yr^{-1}$. If the calculations are based on the shorter $Rb^{87}$ half-life the ages would be reduced by approximately 6%.

probably once deeply buried. Only in the southwestern part, in the eastward continuation of the Superior province is the amphibolite facies developed (Osborne and Morin, 1962). The irregular structural trends, gneiss domes and depressions (dejective zones) so typical of the Grenville, result, according to H. Wynne-Edwards, from northeast-trending flow folds of the Grenville orogeny being superimposed on older structures. The flow folds have redeformed easterly-trending Kenoran basement structures in the southwestern parts of the province and are superimposed on the northerly-trending structures of the Hudsonian orogeny farther to the southeast and northeast. The characteristic association of intricately redeformed structures and granulite facies in the outermost and youngest exposed provinces of the Canadian Shield contrast strongly with the more regular structures and lower grade of metamorphism in the oldest and central portions of the Shield. It suggests that the marginal parts of the Shield only were deeply depressed and received a thick succession of superincumbent rocks. Subsequently the deeper structural zones were raised to the same level as higher structural zones of lower metamorphic grade in the central part of the Shield.

(2) Influence of Structures in the Precambrian Shield upon Cratonic Structures

The Precambrian basement beneath the cratonic cover shows considerable relief, for basins upon it contain Phanerozoic rocks separated by broad platforms, arches, and elongate areas of crystalline rocks. Much of the present pattern of basins and uplifts was established in the early Palaeozoic. Kanasewich (1966) emphasizes the broad conformity of the Precambrian basement surface in the central part of the craton with the Mohorovičić discontinuity. He concludes that the cause of vertical movements (epeirogenesis) must lie in the Upper Mantle possibly at the level of Gutenberg's low velocity layer and, moreover, that the Mohorovičić discontinuity has been locally depressed for long periods of time since the early Palaeozoic. The actual configuration of the basement relief resulting from this epeirogenesis was controlled commonly by structures in the basement. The timing of the epeirogenic movements cannot readily be correlated with orogenic episodes in the fold belts fringing the craton. Widespread interregional disconformities indicate cratonal emergence in latest Proterozoic and earliest Cambrian time, in the Middle Ordovician, from the Late Silurian to Middle Devonian, from the Late Pennsylvanian to the Early Permian, and from the Late Permian to the Early Triassic (Webb, 1965). The second and third periods of emergence just precede the Late Ordovician Taconic and Middle and Late Devonian Acadian orogenies respectively in the Appalachian orogen. The last two emergences cannot be related to a major orogeny except that the latest emergence just precedes the Middle Triassic Tahltanian orogeny in the Cordillera. On the other hand no widespread cratonal emergence preceds or correlates with the Upper Devonian to Middle Pennsylvanian Ellesmerian orogeny in the Innuitian and Cordilleran orogens, the Jura-Cretaceous Columbian orogeny in the Cordillera, and the Tertiary late Laramide orogeny in the eastern Cordillera and Sverdrup Basin. Even the time of movements related to local basins and uplifts is apparently not related to events in the fringing mobile belts.

The behaviour of the different basins and uplifts is quite variable. Some basins such as the Williston and Michigan Basins are roughly circular regions not associated with nearby rising highlands that subsided intermittently. They are typical autogeosynclines (Kay, 1951). Some uplifts such as the Boothia Uplift and the Bache Peninsula Arch in the Arctic Archipelago have risen intermittently and were never depressed more than the surrounding basins (Kerr and Christie, 1965; J.W. Kerr). The Minto Arch and Prince Patrick Uplift probably had similar histories. Other uplifts such as Peace River Arch, Tathlina 'high' and Alberta Arch were emergent in the early Palaeozoic but were depressed during the Mesozoic. The first two uplifts subsided beneath a Triassic autogeosyncline and later, together with the Alberta Arch, were further bowed down beneath the late Mesozoic Rocky Mountains exogeosyncline. The sediments in the latter were derived principally from uplifts in the west in the Cordilleran orogen.

The positions and shapes of Phanerozoic cratonal elements were controlled to a large degree by structures in the Precambrian basements. Stockwell (1965b) has pointed out that the Williston and Michigan Basins both lie on or near the probable continuation of the Nelson and Grenville Fronts respectively, and part of the margin of Hudson Bay Basin conforms to the boundary between the Churchill and Superior provinces. Elements such as the Peace River Arch and the faults within it, the Middle Devonian Meadow Lake escarpment, and some of the boundaries of the Middle Devonian Elk Point Basin (Grayston et al, 1964) and the facies boundaries in the Jurassic (Springer, et al 1966) all trend east-northeast parallel with similarly trending faults in the Shield. These faults, of which the East Arm fault near Great Slave Lake is an example, became reactivated during the Palaeozoic (Douglas and Duffell, 1962). Some northeasterly trends which extend into the Cordilleran miogeosyncline may reflect movement from the underlying basement. North-northeasterly Upper Devonian reef-trends in Alberta may have been controlled by movements in the basement parallel with Hudsonian structures of the Churchill province which extend southeastward under the cratonal veneer. Northwesterly trends of the Elk Point Basin may have been influenced by subsidence along northwesterly-trending faults in the Shield parallel with the extensive MacKenzie dyke swarm. The Boothia Uplift, basins and uplifts in northwestern Baffin Island (Trettin, 1965), and also the Minto Arch are aligned with local basement structural trends. The Cornwallis Fold Belt is an expression of the northward continuation of the Boothia Uplift beneath the miogeosyncline of the Innuitian orogen (J.W. Kerr).

Geophysical studies indicate that three distinct crustal layers exist within the craton and that the Mohorovičić discontinuity ranges in depth between 35 and 55 km and is thickest under basins in the craton (Kanasewich, 1966). The crust is thinnest in narrow belts coincident with gravity highs near the Nelson Front, along the English River gneiss belt, and along the Kapuskasing High. The latter may join the mid-continent gravity high in central United States (Wilson, 1965).

## C. Rifting of Northern North America

Kumarapeli and Saull (1966) have recently proposed that the St. Lawrence Valley fault system is coextensive with a well-defined pattern of seismic activity. The fault system, principally of Mesozoic age, is in a region of updoming and normal faulting and is associated with alkaline intrusives, carbonatites and kimberlites mainly of Cretaceous age although some may be older. Kumarapeli and Saull conclude that St. Lawrence Vally fault system is a major rift system analogous to the East African rift valley system. Moreover the authors propose that the Lake Superior fault zone, the Rough Creek - Kentucky River fault zone, and the normal fault zone in Texas and Oklahoma are possible extensions of the St. Lawrence system. A tract of seismic activity running from Lake Ontario to the Mississippi Embayment may also belong to it. They futher suggest that the St. Lawrence system may be connected with the mid-Atlantic Rift in the region of the Azores and imply that crustal tension in the St. Lawrence region may be genetically related to the opening of the Atlantic Ocean Basin.

J.W. Kerr has speculated on the rupturing of the Arctic craton and subsequent drifting and rotation of the Shield blocks in which rift directions were controlled by structural directions in the crystalline rocks.

## D. Phanerozoic Fold Belts Fringing the North American Craton in Canada

### (1) Tectonic Elements

The Phanerozoic mobile fold belts (orogens) fringing the northern North American craton are characteristically composed of an inner, essentially non-volcanic, miogeosynclinal belt bordering the craton and an outer, volcanic-bearing eugeosyncline, upon which are superimposed one or more later successor basins (King, 1966) or epieugeosynclines (Kay, 1951).

The miogeosynclinal belts typically contain carbonate and relatively mature clastic marine sediments derived largely from the craton and deposited on the adjoining more depressed shelves upon which were developed linear troughs and arches. In general, the shelves subsided rather more than the craton and accumulated a greater thickness of sediment. The miogeosynclinal belts in some places also contain younger, relatively rapidly deposited clastic sediments derived from uplifts in the

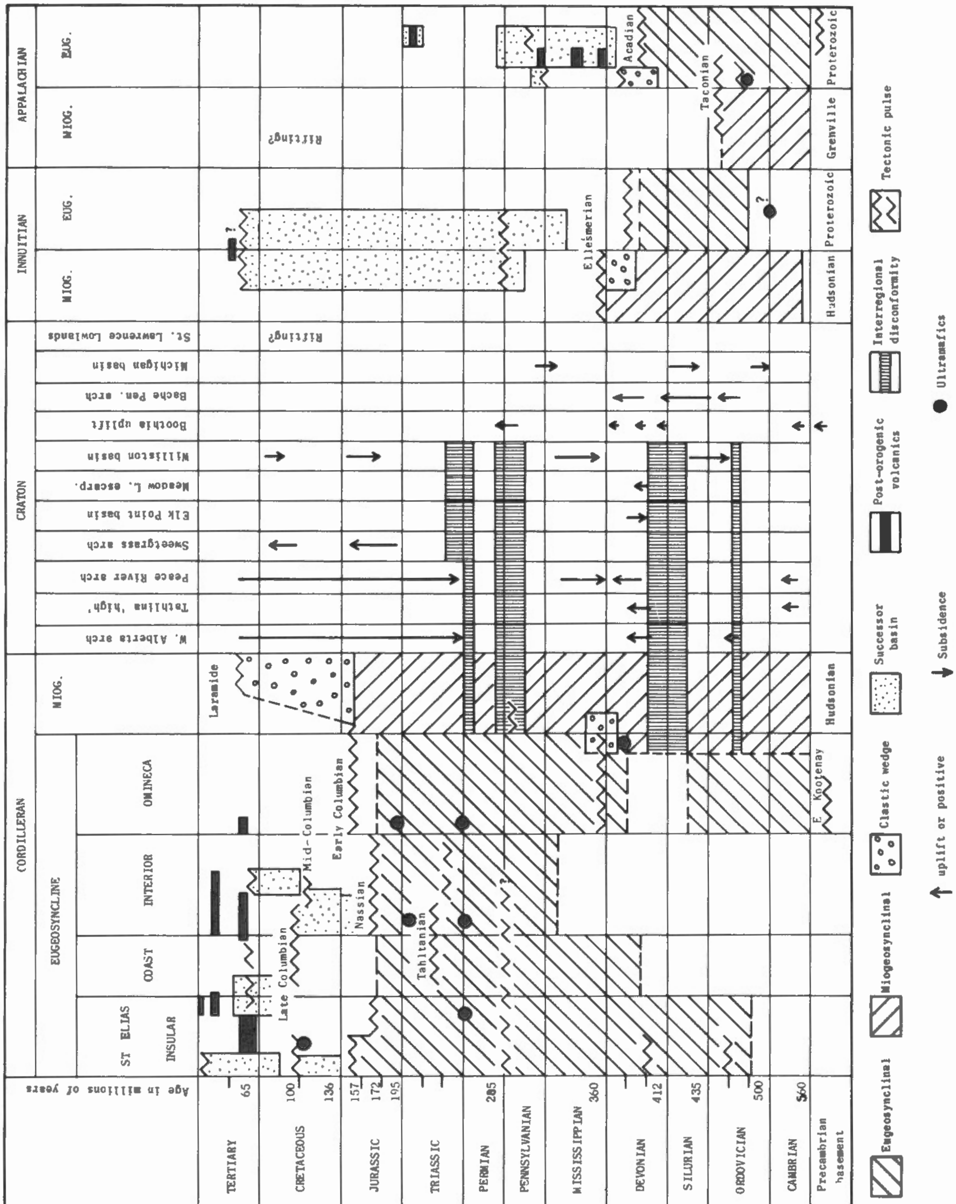


Figure 2. Chart of Phanerozoic tectonism.

eugeosyncline. These clastics formed parts of clastic wedges (King, 1951) that spread onto and depressed the craton under an exogeosyncline (Kay, 1951).

The eugeosynclinal belts typically are distinguished by thick assemblages of volcanic rocks, ranging from basalt through andesite to rhyolite; rapidly deposited clastic marine sediments; and local accumulations of carbonate and chert. Basalts commonly were extruded as great submarine piles. Andesitic and felsic rocks are principally products of explosive volcanism and may have been parts of island arcs. If so, some in the Cordilleran orogen were built on older siliceous sedimentary terrain. Soda-rich volcanism prevailed at times in some eugeosynclinal belts. Part of the Insular Zone of the Cordilleran eugeosynclinal belt received thick piles of spilitic basalt in Middle and early Upper Triassic time, sodic andesites in the Middle Jurassic, and sodic basalt and sodic rhyolite in the Tertiary (Brown, 1965). In the northern part of the Innuitian eugeosynclinal belt felsic and andesitic keratophyres were extruded in Late Silurian and Early Devonian time and spilites and basalts during the early Middle Devonian (H.P. Trettin). Ultramafic rocks are restricted to these eugeosynclinal belts, where in places they are spatially and temporarily associated with basaltic volcanics as well as along thrusts and faults bounding major structural blocks. The former tectonic relief in these mobile belts is outlined by the lateral gradation of fine-grained sediments in the troughs into coarser detritus, locally associated with thinner rock sequences interrupted by unconformities, on the margins of the geanticlines. The latter, and not the deeply depressed intervening troughs, are the favoured sites for both regional metamorphism and the emplacement of granitic rocks. The metamorphism which commenced during or slightly after the deformation in the geanticlines generally persisted some time after the major deformation ceased (Wheeler 1966; Price and Mountjoy 1966; Taylor and Schiller, 1966).

The superimposed successor basins comprise thick successions of marine and non-marine, locally rapidly deposited, clastic sediments and minor volcanic rocks. In several cases the basins are partly bounded by normal faults. The basins are developed mainly on a previously deformed eugeosynclinal succession, as in the Appalachian and Innuitian orogens, but in the Innuitian orogen the successor basin also overlaps the folded miogeosyncline (Thorsteinsson and Tozer, 1960).

In the Cordilleran orogen the successor basins are in part unconformable on older fold belts and in part conformable with older troughs. Furthermore they are syntectonic in that the adjoining Omineca Geanticline was being deformed and uplifted while the basins received clastic sediments.

The youngest tectonic assemblages in the younger orogens are of two types: (1) a post-orogenic suite of continental clastic and volcanic rocks in fault troughs and associated with extensional zones of normal faults. Examples are the Cenozoic sections of the Cordillera in which the volcanics vary from basalt to rhyolite but contain much flood basalt, and the Triassic of the Appalachians; (2) coastal clastic sediments of latest Tertiary age on the Arctic Coastal Plains and along the Pacific margin. Locally in the St. Elias orogen, marine Pliocene sediments have been tilted, faulted, and uplifted nearly 5,000 feet above sea-level (Plafker and Miller, 1957; Miller, 1957).

(2) Structures of the Miogeosynclinal Belts.

The miogeosynclinal belts and the clastic wedges where they are superimposed on them are generally featured by shallow, thin-skinned deformation that apparently does not involve the Precambrian basement. In fact large areas of miogeosynclinal rocks in the Cordillera and perhaps in the Appalachian orogens have been detached and moved relatively from the underlying shelves onto the craton. The typical structures are sinuous folds whose axial planes dip away from the craton and thrust faults that are locally folded but commonly also dip away from the craton. Thrust faults, however, are sparingly developed in the Innuitian miogeosynclinal belt. Where competent strata such as carbonate and sandstone are dominant the rocks have developed concentric folds by flexural slip, but in sequences of shale and shaly limestone, similar folds produced by shear prevail. Concentric folds have wave lengths apparently related to the thickness of the dominant members in the succession (Currie et al, 1962) and by the nature of their geometry they are associated with thrust faults (Price, 1967) and regional sliding over the basements (décollement).

The southern Canadian Rocky Mountains of the Cordilleran miogeosynclinal belt have been intensively studied both on the surface and by seismic reflection techniques and the results are highly instructive concerning the nature and amount of deformation in the marginal part of a fringing orogen. Bally et al (1966) have shown that the Precambrian basement dips gently and uniformly westward from 15,000 feet below sea level at the inner edge of the orogen to nearly 40,000 feet below sea level at the Rocky Mountain Trench, which roughly marks the eastern margin of the eugeosyncline. The structure in the Canadian Rockies is featured by numerous sub-parallel thrust faults which are generally westerly dipping and concave-upward. Some faults, however, are folded. The faults are most numerous in the Foothills or eastern part of the Rockies where they are developed in weak strata of the Mesozoic clastic wedge but are less abundant in the more competent Palaeozoic miogeosynclinal rocks. The faults commonly follow weak shaly layers for a long distance but locally step across an intervening competent sequence from one weak layer to another (Douglas, 1950) and eventually merge downward into major sole faults and then in turn into the basement décollement. Various lines of evidence indicate that the first thrusts formed in the west and that progressively younger thrusts developed farther to the east in lower sequences that were overridden by the earlier formed thrust sheets. As the younger, lower thrust sheets stepped from one incompetent horizon to another higher one or were otherwise folded the older overlying thrust sheets were folded also. The miogeosynclinal sequence was thus thrust eastward over the underlying platform and craton shearing off the Palaeozoic cover. The amount of shortening above the basement is estimated to be about 50 per cent or probably more than a hundred miles. Seismic data have also demonstrated that west-dipping normal faults, bounded on the west by east-dipping tilted strata, results not from gravity faults that intersect the basement but rather from back-sliding down a concave-upward thrust fault thus rotating the once-horizontal overlying strata to an eastward dip. Such faults are termed listric faults (Bally et al, 1966).

The structures in the Mackenzie Mountains in the northwesternmost Cordillera are featured by less asymmetry and less shortening than those in the Rockies and also by transcurrent faults that may have been controlled to some degree by movement in the basement (Goodman, 1951; Gabrielse, 1967) but Bally et al (1966) consider the structural style to be only a variation of that displayed in the Rockies.

(3) Structures in the Eugeosynclinal Belts

Structures of the eugeosynclinal belts are not well understood for several reasons. The structures are complex and of more than one generation; the stratigraphy is difficult to decipher; key relationships are commonly obscured by regional metamorphism, emplacement of granitic rocks, and the masking cover of epieugeosynclinal and post-orgenic deposits.

The structure of the Innuitian eugeosynclinal belt is not well known. It is currently being studied by Christie (1967) and Trettin (1967). Structures in the northwestern part of the Appalachian eugeosynclinal belt have been directed northwestward over the miogeosynclinal belt. P.R. Eakins considers that in the southwestern part of the belt deformation in the soft rock stage began shortly after the deposition of some formations. It was followed by at least two periods of folding accompanied, during the first, by gravity sliding to the west. The second resulted in the Sutton Anticlinorium and probably involved intrusion or granitization deep in the core of the structure. Similarly in northwestern Newfoundland, Rodgers and Neale (1963) consider that two klippes of eugeosynclinal rocks now lying on cratonic cover arrived there as a result of gravity sliding in Middle Ordovician time. Structures in the central part of the belt trend northeasterly and have steep to vertical dips.

One of the best exposed eugeosynclinal belts lies in the Cordilleran orogen. The structure of the Cordilleran eugeosynclinal belt is dominated by the Omineca and Coast Geanticlines that merge northwestward into the Yukon crystalline platform and have persisted more or less since mid-Palaeozoic time. These two geanticlines were repeatedly the principal sites of medium-grade regional metamorphism, of by far the greatest amount of granitic emplacement, and of the most intense deformation. The Omineca Geanticline lies in the axial zone of an 'alpine-type' orogen, whose marginal zone of thrust sheets is in the miogeosynclinal belt which has already been described. The core of the axial zone is represented by gneiss-dome complexes that occur in culminations. They are enclosed by low- to medium-grade metamorphic rocks that appear to form two, and possibly more, back-folded nappes that override thrust sheets in the marginal zone to the east. In a general way the structural profile of the axial zone is crudely in the form of an asymmetric downward narrowing prism whose west side slopes steeply and east side more gently.

The Rocky Mountain Trench separating the axial and marginal zones is apparently a somewhat linear erosional tract partly controlled by normal faults (Leech, 1966) or faults that actually may be listric faults (Bally et al, 1966). It is apparently not influenced by a flexure in the basement since seismic data indicate no flexure there, nor is it a rift, nor the site of a transcurrent fault. Tintina fault in the northern Cordillera has a similar setting but Roddick (1965) considers that about 250 miles of righthand displacement has taken place along it.

The Interior Zone between the geanticlines is structurally heterogeneous. It is dominated by a disconnected central rib of irregularly deformed Palaeozoic rocks outlining the Pinchi Geanticline and Atlin Horst and by the transverse arches that largely controlled the disposition of the late Mesozoic syntectonic basins. The eugeosynclinal troughs north of the Skeena Arch contain mainly Mesozoic sedimentary rocks that were variably folded and faulted and locally involved gravity sliding off the rising Atlin Horst (Souther and Armstrong, 1966). South of this arch the Mesozoic troughs are less constricted and contain thick sequences of volcanic rocks that were fractured and faulted rather than folded, implying that little or negligible crustal shortening took place in the Mesozoic rocks of the southern Interior Zone.

The Coast Geanticline is underlain mainly by the Coast Plutonic Complex, composed principally of granitic rocks, and is featured by a northwest-trending gneiss-migmatite core. Its structure is not well known. Structures in the western part of the complex north of the Skeena Arch and in its eastern part just south of the arch are overturned to the west. Elsewhere the foliation dips vertically or nearly so (Roddick et al, 1966).

The Cascade orogen, which lies en echelon southeast of the Coast Complex, is somewhat like an asymmetric downward-narrowing prism in cross-section. Its gneiss migmatite core, possibly a continuation of that in the Coast Complex, is flanked by a zone of steep west-dipping thrusts on the east and variably east-dipping thrusts on the west (Misch, 1966).

Two structural elements of the Pacific margin are represented in Canada. (1) The St. Elias orogen is part of the fold belt bounding the Gulf of Alaska and is the youngest in the northern Cordillera. It is also a downward narrowing prism in cross-section, comprising a core of crystalline rocks and flanking zones thrust outward from the central axis (Gabrielse and Wheeler, 1961). The orogen is bounded on the east by the Shakwak fault whose early history involved normal and thrust movements (Muller, 1967) but is now apparently part of the Denali System that elsewhere is characterized by right-hand transcurrent movement. The southwestern flank of the orogen contains southwesterly directed thrusts involving strata as young as Pliocene (Plafker and Miller, 1957). (2) The Insular Zone embracing the major islands off the Pacific coast contains thick assemblages of Mesozoic volcanic rocks that, like those in the southern Interior Zone, are merely warped and faulted (Brown, 1966). The Insular Zone is bounded on the west by the Queen Charlotte fault, an apparently steeply east-dipping structure, that has exhibited recent right-hand movement, and truncates the north-northeast trending magnetic anomalies related to the East Pacific Rise. It is interpreted as a transform fault by Wilson (1965) and Vine (1966).

It is apparent that there is a crude structural symmetry to the Cordilleran eugeosynclinal belt. The most intensely deformed zones, the Omineca Geanticline in the east and the Coast Geanticline and associated orogens in the west, comprise structural prisms of opposing asymmetry. The tectonic movement in the Omineca Geanticline has been mainly up and to the east whereas that in the western deformed belts has been principally up and to the west.

Assuming that the craton was stationary, then more than a hundred miles of shortening in the miogeosynclinal belt implies that the Omineca Geanticline underwent an even greater displacement eastwards. Furthermore since the southern Interior Zone shows seemingly little shortening, then more than half the Cordillera must have been moved eastward considerably more than a hundred miles (Bally, et al, 1966). On the other hand the apparent persistence of the Omineca and Coast Geanticlines from the Late Triassic, perhaps even from the mid-Palaeozoic, and the repetitive subjection of these elements to metamorphism and granitic emplacement during this period suggests that they may overlie fundamental heat zones. This conclusion implies, in turn, that the geanticlines have been relatively 'in place' or autochthonous. If the second conclusion is reasonable then the eastward directed tectonic transport of the rocks in the Omineca Geanticline and the miogeosynclinal belt may have resulted from westward movement and underthrusting of the continent (Charlesworth, 1959).

The apparent steep upward and westward tectonic movement required to account for the asymmetric structural prisms in parts of the Coast Geanticline and its associated orogens near the Pacific margin need explanation. Even though such movement is not reflected in the Insular Zone these structures are probably related to the differential movement between the Pacific Ocean Basin and the North America Cordillera.

(4) Structures of Successor Basins

The structures of the successor basins are simpler than those of the older tectonic elements. In the deformed successor basins in the Appalachian orogen the structures are largely related to the movement along faults of blocks of older rocks, including the Precambrian. During certain periods non-marine sedimentation prevailed in some troughs while the adjacent blocks were raised, whereas at other times sedimentary rocks were folded as a result of gravity sliding of the rising blocks (Fyson, 1967).

Folds and thrusts in the Sverdrup Basin in general conform to the trend of Palaeozoic folds, whereas in some of the Cordilleran syntectonic basins folds conform to the basin boundaries and were apparently influenced by the pre-existing relief. Easterly directed gravity sliding is common in the western part of the Bowser Basin between Skeena and Stikine Arches (Souther and Armstrong, 1966). Faulting, however, is the principal mode of deformation in the Tyaughton Trough east of the Cascade orogen.

(5) Basement Beneath Eugeosynclinal Belts of the Phanerozoic Orogens

Various lines of evidence suggest that the Phanerozoic orogens were not direct additions to the continent but were built at least in part upon older basements. The nature and age of the basement is variable and whether it extended entirely beneath the eugeosynclines is not known. Precambrian rocks occur at intervals within the Appalachian eugeosynclinal belt. Those of the Grenville province occur in western Newfoundland (Williams, 1964) but in southeastern Newfoundland the basement consists of latest Precambrian siliceous sediments and felsic and basic volcanics of a pre-Appalachian orogen intruded by the Holyrood granite now dated as 574 ± 11 my by the Rb/Sr method (McCartney et al, 1966). Following this latest Precambrian orogeny the region remained a relatively stable platform or shelf that was little affected by the Palaeozoic orogenies recognized farther west (Williams, 1964). The presence of crystalline Precambrian rocks overlain unconformably by Proterozoic rocks rich in felsic and basic volcanics farther southwest in the central and southeastern part of the eugeosyncline suggests that it was underlain by an extensive siliceous basement.

J. T. Wilson (1966) has suggested, however, that the Lower Palaeozoic sediments in the southeastern part of the eugeosynclinal belt, which are characterized by a Cambrian fauna of an 'Atlantic realm', may have been deposited along the northwestern margin of the European continent. According to this hypothesis all the exposed basement rocks in the Canadian

Appalachians except those in western Newfoundland would initially have been part of the European basement.

In the Innuitian orogen, crystalline basement exists along the northern coast of Ellesmere Island well into the core of the eugeosynclinal belt. The basement is considered to have undergone recrystallization in Early Cambrian or Proterozoic time (Blackadar, 1960).

Although Precambrian basement is not now exposed in the Cordilleran eugeosynclinal belt, sialic crust probably underlay parts of the eugeosyncline in late Precambrian time and earliest Palaeozoic time. Gabrielse (1967) suggests that in late Precambrian time the present Yukon crystalline platform was a source area for quartzose and feldspathic grits that now extend over much of central Yukon. Moreover the occurrence in southeastern Alaska of Ordovician and early Silurian andesitic volcanics (Buddington and Chapin, 1929) and Late Ordovician granites (Lanphere et al, 1964,1965) suggests that sialic crust existed in earliest Palaeozoic time nearly as far west as the present continental margin. It is apparent therefore that the eugeosynclines in the orogens fringing the northern North American craton were deposited not on oceanic crust but upon the edge of the continent. The parts of the Phanerozoic orogens that remain thus represent parts of the continental margin that were depressed, redeformed, and possibly thickened, but do not signify the addition of new orogens to the continent from the oceanic crust.

## (6) Crustal Layers Beneath the Phanerozoic Orogens

The young orogens lie on crustal layers that vary in depth and character both along and across the trends of the fold belts. In the Appalachian orogen (Ewing et al, 1966) the Mohorovičić discontinuity is depressed from a depth of about 35 km beneath the edge of the craton to as much as 45 km in the core of the eugeosyncline but then rises to about 35 km in the southeastern part. This depression of the Mohorovičić discontinuity is accompanied by the development of an intermediate layer having a compressional wave velocity (Vp) ranging from 7.35 to 7.52 km/sec and a complementary increase in the Vp of the underlying upper mantle from about 8 km/sec on the edge of the eugeosyncline to 8.50 to 8.69 km/sec in the core. In the Innuitian fold belt, the crust is apparently 38 km thick under the geosynclinal belt and thins to 30 km under the continental shelf (Roots, 1965).

Very few crustal studies have been carried out in the Cordilleran orogen. Results from profiles across the southernmost Canadian Cordillera (Kanasewich, 1966) indicate that the orogen as a whole does not have a crustal root, although a local root may exist at a depth of about 50 km beneath the Coast Geanticline. The crust beneath the Canadian Rockies is considered to be 30 to 50 km in thickness. In the Interior Zone the granitic layer appears to extend to the Mohorovičić discontinuity at about 40 km depth but, according to W.R.H. White, 300 miles (500 km) to the northwest it rises to a depth of

27 km; the crust thins rapidly west of the Pacific margin to 10 km. The compressional wave velocity in the upper mantle varies from 8.25 km/sec under the craton to 8.0 to 8.2 km/sec in the Interior Zone and to 7.81 km/sec beneath the Coast Geanticline and under Vancouver Island. It increases to over 8 km/sec off the Pacific margin (White and Savage, 1965).

(7) Time of Tectonism in the Phanerozoic Orogens

The principal Phanerozoic tectonic assemblages and tectonic pulses are summarized in Figure 2. The culminating orogenies in each of the fold belts migrated with time. The early phases took place in the interior of the eugeosynclinal belt, succeeding phases occurred progressively closer to the miogeosynclinal belt, and the latest phases were generally restricted to the miogeosynclinal belt. Appalachian data are largely from Poole (1966); Innuitian data from Douglas *et al* (1963), Kerr and Christie (1965), and Trettin (1966, 1967); Cordilleran information from Gunning (1966), Gabrielse (1967) and current work by J.O. Wheeler.

*Appalachian orogen*. The earliest tectonic event in the Appalachian orogen, excluding Middle Ordovician emplacement of ultramafic rocks, was the northwestward gravity sliding of eugeosynclinal rocks onto the craton in the late Middle Ordovician. In the Late Ordovician, part of the Appalachian orogen was deformed and uplifted during the taconic orogeny. Other parts of the fold belt, however, continued to receive sediments. During the Acadian orogeny in Middle and Late Devonian time almost the entire eugeosynclinal belt including the latest Precambrian pre-Appalachian orogen and its cover were deformed and intruded by granites. A welt associated with early stages of this orogeny arose in the core of the eugeosyncline and in Early and Middle Devonian time shed debris northwestward to a clastic wedge.

Subsequently in the Late Devonian a successor basin, locally subdivided by uplifts, developed upon the Acadian fold zone. Deposition of clastics was accompanied by movement of fault blocks and some folding. Tectonism essentially ceased by Middle Pennsylvanian time although non-marine sedimentation continued into the Permian. In Late Triassic time a fault-trough, which received clastics and basalt, was established over the most intensely deformed part of the Late Palaeozoic successor basin.

*Innuitian orogen*. Although the later record from the eugeosyncline is missing the two geosynclinal belts in the Innuitain orogen apparently prevailed longer than in the Appalachian fold belt and lasted until Late Devonian time. The Middle and Upper Devonian clastics in the miogeosyncline, however, were derived from a source to the north now covered by the Sverdrup Basin and are apparently characteristic of a clastic wedge.

In the eugeosynclinal belt Trettin (1967) established that northeastern Ellesmere Island was the site of a trough from Middle Ordovician to Late Silurian time. Volcanic, ultramafic, and granitic rocks are restricted to the region to the northwest, whereas the trough itself received marine and deltaic clastics from an intermittently positive source to the north in the Arctic Ocean. Carbonates were deposited to the southeast.

Although local folds were developed in early Palaeozoic time in association with the periodic rise of the Boothia Uplift, Bache Peninsula Arch, and Rens Fiord Uplift the Innuitian orogen was not deformed until the Ellesmerian orogeny. The time of this orogeny cannot be closely dated. The eugeosynclinal belt was apparently deformed by an early phase in late Middle and Late Devonian time (Trettin, 1967) whereas the miogeosynclinal belt was deformed after the clastic wedge derived from the eugeosynclinal region was laid down - hence some time between the latest Devonian and mid-Pennsylvanian. The folded Lower Palaeozoic rocks were then succeeded by the exceedingly thick Sverdrup successor basin whose basalt beds vary from Upper Mississippian to Middle Pennsylvanian age. Although evaporites occur near the base of the succession in Mississippian and Permian beds the Sverdrup basin assemblage is dominantly clastic and derived, in the Mesozoic, largely from the south and east (Douglas et al, 1963).

Although some local folding took place in the basin between Pennsylvanian and Permian time the whole basin itself was not deformed until mid-Tertiary time following the deposition of Paleocene - Eocene strata. The folding was accompanied by the injection of numerous gypsum and anhydrite diapirs.

Gabbro sills are found in rocks as young as Upper Cretaceous but they may be younger since similar dykes cut folds presumably formed in the mid-Tertiary.

Cordilleran orogen. The southern half of the miogeosynclinal belt persisted as such from Cambrian to early Upper Jurassic time. The northern half, however, received much clastic sediment during the late Palaeozoic, probably as clastic wedges. The latter were related apparently to an Early Mississippian orogeny that took place primarily along the length of the Omineca Geanticline and also to a Pennsylvanian (?) orogeny in northernmost Yukon.

The eugeosynclinal belt was a mobile volcanic belt from at least Early Ordovician to Middle Jurassic time. It was less extensive in Early Palaeozoic time than later, for in the Late Devonian, just prior to the Early Mississippian Ellesmerian orogeny, a marked eastward overlap took place and thick volcanic piles, accompanied by emplacement of ultramafic rocks, developed upon the former miogeosyncline.

Several tectonic pulses took place in different parts of the eugeosynclinal belt at different times. The earliest pulse apparently took place in southeastern Alaska in Late Ordovician time and was accompanied by the emplacement of granitic rocks. Southeastern Alaska underwent another pulse in Late Devonian time that shortly thereafter exposed large areas of granitic rocks to erosion (Brew et al, 1966). The orogeny equivalent to the Ellesmerian, formerly named Cariboo by White (1959), is roughly contemporaneous with the Antler orogeny in the Basin Range of the western United States. This orogeny marked the beginning of the Omineca Geanticline in the northern Cordillera but apparently not in the southern Cordillera where relatively little clastic sediment was associated with the orogeny and no clastic wedge was developed.

Evidence is accumulating from current investigations, notably by geologists at the University of British Columbia, that some deformation may have taken place sometime between the Pennsylvanian and the Permian but apparently little or no clastic debris was associated with it.

Following the Early and Middle Triassic pulses of deformation and plutonism that constitute the Tahltanian orogeny the three geanticlines became established. Until the Nassian orogeny in Middle Jurassic time the tectonic elements such as the geanticlines and adjoining troughs trended northwesterly. Volcanic centres at the edges of the geanticlines shed flows and debris to the adjoining troughs. With continued uplift granites were unroofed and abundant debris deposited in the troughs. During the early Middle Jurassic, volcanism flourished south of Skeena Arch but not to the north. Finally, with the Nassian orogeny, the eugeosynclinal belt was segmented with the emergence of the northeast trending Skeena and Stikine arches and the rising of the Atlin Horst. At the same time the thick volcanic piles of the Insular Zone were warped, faulted, and injected with granite along the faults.

The culminating deformation of the eastern Cordillera - the Columbian orogeny - began in the southern part of Omineca Geanticline in Late Jurassic time almost contemporaneously with the type Nevadan episode in the western Sierra Nevada of California. Various lines of reasoning suggest that deformation during the early Columbian phase extended into the miogeosyncline and, as would be expected from the sequence of thrusting, the deformation migrated eastward and culminated in the mid-Tertiary as a late Laramide episode. It is so indicated on Figure 2.

The miogeosynclinal regime ended abruptly in Late Upper Jurassic time contemporaneously with the early Columbian episode. It marked the beginning of the deposition of a great clastic wedge in the Rocky Mountain exogeosyncline that was derived from the eastward migrating uplift developed during the deformation spanning the Columbian and Laramide orogenies. Thus later uplifts involved earlier formed parts of the clastic wedge.

Synchronously with the early Columbian episode in the Omineca Geanticline, and with a concurrent one in the northern part of the Insular Zone, clastic sediments were deposited in successor basins whose disposition was controlled by the geanticlines and arches. Some of these together with the adjoining Coast Geanticline and the Cascade and St. Elias orogens, underwent deformation and plutonism in mid-Cretaceous time during the late phase of the Columbian orogeny. The major deformation in much of the northern Cordillera took place during the mid-Cretaceous. By this time most of the Cordillera was emergent and late successor basins became smaller - no more than intermontane troughs.

Except for the St. Elias Mountains and local disturbances in the Insular Zone and in the Coast Geanticline, the Tertiary was a time for extensional tectonics in the Central Cordillera. Mixed volcanic and clastic rocks were deposited in fault-troughs in early Tertiary time and flood basalts in late Tertiary time.

The last orogenic episode occurred in the late Pliocene and involved thrusting, folding, and uplift of the St. Elias Mountains facing the Gulf of Alaska. This activity was roughly contemporaneous with the uplift of the Coast Mountains in Canada.

Quaternary tectonics are characterized by (1) the evolution of volcanic centres that are commonly aligned and therefore possibly located along faults, (2) right-handed predominately strike-slip faulting in the St. Elias orogen and Insular Zone, and (3) in common with other parts of Canada, by rapid rebound following melting of Pleistocene ice.

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## III. CURRENT PROBLEMS AND DIRECTION OF FUTURE RESEARCH

Most of the problems concerning the tectonics of Canada are created simply by incomplete knowledge. In many cases suggestions based on scanty data need to be tested by yet further data. Much of this additional information will come not from structural studies alone but from a combination with other fields of Earth Science such as seismology, gravity, magnetism, geochronology, isotope geology, petrology, stratigraphy and sedimentology. The recommended approach is a comprehensive interdisciplinary study such as is being carried out currently in parts of the Canadian Shield, the Arctic, Hudson Bay, and Appalachian regions. In other cases, perhaps, the contributions toward solving a broad tectonic problem will provide a sufficient stimulus to undertake certain studies in, say, petrology, sedimentology, or isotope geology.

The problems selected for consideration have been arrived at without an opportunity to discuss them with tectonicists elsewhere in Canada. Others may well have different suggestions. Nevertheless the following presentation no doubt will stimulate others to recognize problems neglected here and to advance ways of attacking them.

The principal tectonic problems fall into several broad categories concerning: (1) the oldest crust, (2) continental crust, (3) the fringing mobile belts, (4) continent-ocean basin interface, and (5) continental drift. These are discussed below.

### A. The Oldest Crust

The problems related to the oldest crust are its age, its extent, and its character. Sparse model lead ages on galena and discordant lead-uranium dates on zircons suggest that the crust is older than 3,000 my and that it may be fairly extensive. It would be desirable, therefore, to search for suitable rocks that might be expected to provide these very old ages and to date them. Eventually enough "old" ages may be obtained whereby the age of the oldest crust could be statistically determined and a better estimate made of its extent.

The nature of the oldest crust can be arrived at partly by continuing the present program of detailed isotopic, chemical, and petrologic studies on Archaean volcanic rocks, and partly by a greatly increased effort to study intensively the clastic sediments associated with these volcanics in the manner advocated by Donaldson and Jackson (1965). They propose not only that Archaean sediments receive greater petrographic and chemical study but that much more emphasis should be put on quantitative investigations using readily observable parameters. This approach will lead to the recognition of lateral facies changes and, coupled with directional primary structures, will delineate source areas. Quantitative data permits an evaluation of the composition of the source area which, in turn, provides information on the composition of the oldest crust. If silicic crust was relatively widespread in earliest Archaean time, as present scant data suggest, then the concept of continental growth by progressive accretion from a volcanic crust needs revision.

## B. Continental Crust

The problems concerning the continental crust in general involve the tectonic nature of the Precambrian crust, the age, nature, and extent of the continental basement under the Phanerozoic orogens and the relationship between the crustal layers and tectonic relief on the craton.

It has been pointed out by Stockwell, Clifford, and others, that the younger provinces of the Precambrian Shield commonly contain more intricate structures and much more extensive regions of high-grade metamorphic rocks than the older provinces. This apparently indicates that recurrent deformation and the greatest depression and crustal thickening occurred near the margins of the continents in later Precambrian time, followed by subsequent uplift that brought deep-zone metamorphic rocks to the surface. The validity of these generalizations could be readily tested by a compilation and analysis of the significant metamorphic and structural data. This information could be best portrayed by the preparation of maps of the Canadian Shield (and elsewhere) indicating the distribution of various kinds of metamorphic facies and different kinds of tectonic style. The importance of the latter is emphasized by Stockwell (1964) and also by Clifford. Quoting Stockwell ... "The orogens of the Shield characteristically cover very broad regions quite unlike the mountain chains of later times. Another difference is the long time interval between deposition of sediments and their involvement in orogeny (about 400 my in two instances), as contrasted with the close time sequence of geosynclinal deposition, sinking, and mountain building in younger rocks. Still another difference is the very extensive overlapping of a younger orogen on an older one and this occurs in regions not likely ever to have been the site of intervening geosynclinal deposition. On the whole, the thesis that the orogenic development of the Shield differed from that of younger rocks seems worth considering and, it may be suggested, resulted from deep crustal or subcrustal movements unrelated to the sinking of geosynclinal belts."

Ultimately it would be worthwhile to know the configuration of the crustal layers beneath the continent well enough so that they could be contoured and be compared directly with the relief of the Precambrian basement on the craton.

Precambrian basement is exposed in the Appalachian and Innuitian orogens and there its age and character is reasonably well known but whether it extended completely beneath the eugeosyncline is not known. In the Cordilleran orogen the existence of Precambrian basement can only be inferred locally and its former extent is unknown. Later plutonism in the eugeosynclinal belts probably mobilized, destroyed, or otherwise masked any Precambrian basement that may have been present. Therefore it seems that such basement, if it existed, can only be recognized from isotopic studies on Phanerozoic igneous and plutonic rocks that may have incorporated such basement.

The importance of being able to infer if the Precambrian basement extended entirely beneath the eugeosyncline concerns whether or not the Phanerozoic orogens were built on the depressed margin of the continent or whether they represent accretionary additions to the continent. Moreover, the concept of later "oceanization" of continental crust can never be evaluated until the former extent of continental crust can be reliably estimated.

## C. The Fringing Mobile Belts

The fundamental problems regarding the fringing mobile belts concern the relationship of the crustal layers beneath these belts to the tectonic architecture in the upper crust and the deformation within it.

The first step, of course, is to know the character and disposition of the crustal layers beneath the mobile belts by continuing seismic, gravity, and magnetic studies. It is of particular interest to know if there are differences in the character and the level of crustal layers beneath the geanticlines, the intervening troughs, and the successor basins. It is worthwhile knowing if there are differences in heat flow between these tectonic belts because the geanticlines are the favoured sites for regional metamorphism, granitic emplacement, and uplift.

It is obvious that ultimately the nature of the deformation in the upper crust must be understood. This goal is at present some distance off. First, the structurally complex mobile belts must receive a great deal more intensive structural study, aided in regions of layered rocks by seismic reflection studies similar to those that proved so successful in the Rocky Mountains. Eventually it may be possible to determine the movement patterns that developed during the various deformations and then to investigate the possible causes.

The kinds of structural investigations being carried out in the Rocky Mountains whereby movement patterns are being established in certain thrust sheets, and those combined with palaeomagnetic data from volcanic rocks and dykes, are the sort of studies to emulate. Palaeomagnetic studies are particularly applicable to areas where great regional bending may have taken place. Programs like those of Norris and Larochelle in the Mackenzie Mountains and northern Yukon should be applied to the western Cordillera.

## D. Continental Drift

Interdisciplinary studies in the Arctic and Appalachian regions and of the mid-Atlantic Ridge are dealing directly with the problems of continental drift. The discussion of these problems and the research that should be undertaken are given elsewhere.

The following section emphasizes the sorts of investigations of Canadian geology that are contributing to the understand of continental drift. The study of diabase dykes of the Canadian Shield under W.F. Fahrig of the Geological Survey of Canada is an excellent program providing data whereby palaeomagnetic pole position of dykes in Canada can be compared with pole positions determined from dykes of the same age in other continents. Isotopic dating of dyke swarms also indicates periods of crustal tension and rifting.

Stratigraphic and sedimentalogical studies in the Arctic by Kerr, Trettin, and others have been extremely fruitful in indicating past movements of the crust and of continental blocks. Sources of Lower Palaeozoic sediments in the northern Innuitian orogen are inferred from continental sources where ocean now lies. Consequently continental drifting or foundering are implied thus opening up additional fields of inquiry.

Stratigraphic and structural studies are being conducted in Newfoundland with a view to direct comparison with the Irish Caledonides (Kay, 1966). It is obvious that Appalachian geology should be reviewed in the light of J.T. Wilson's suggestions that the Atlantic Ocean may have closed in the early Palaeozoic and opened again in Late Jurassic time.

The coincidence of the culminating orogenies in the Cordillera beginning in the Late Jurassic with the supposed opening of the Atlantic Ocean has been remarked by Bally et al (1966) and by Wilson (1966). It is not yet clear whether these two events are related but the idea is worthy of speculation.

## E. Publications

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1965: Archaean sedimentary rocks of North Spirit Lake area, Northwestern Ontario; Can. J. Earth Sci., vol. 2, pp. 622-647.

Kay, Marshall
1966: Newfoundland structures and continental drift; Bull. Can. Petrol. Geol., vol. 14, pp. 613-620.

Stockwell, C.H.
1964: Tectonic map of the Canadian Shield; Int. Geol. Congress, 23rd session, 1964.

Vine, E.J.
1966: Spreading of the ocean floor: new evidence; Science, vol. 154, p. 1405.

Wilson, J.T.
1966: Did the Atlantic Ocean close and reopen? Nature, vol. 211, p. 676.

## IV. SUMMARY OF CURRENT PROJECTS IN CANADA

It is not possible to record the many mapping projects that provide the data necessary for broader structural syntheses. The projects reported here are, however, representative of structural studies having significance to the Upper Mantle Project but do not include interdisciplinary studies reported elsewhere in this volume.

### A. General

#### (1) Tectonic Map of Canada

C.H. Stockwell, Geological Survey of Canada, with cooperation of and contributions by the Geological Association of Canada, Alberta Society of Petroleum Geologists, and various Provincial governments.

The map indicates the time at which rocks were involved in orogenies. Folds, faults, bedding, foliation, dykes, volcanic centres, basement contours, etc. are also shown. Extensive use has been made of aeromagnetic and gravity data. The map will be published on a scale of 1:5,000,000. The manuscript for the whole of Canada is nearly completed. Preliminary tectonic maps have been published for the Canadian Appalachian region (Neale et al, 1961) and for the Canadian Shield (Stockwell, 1964, 1965a, 1965b).

Neale, E.R.W., Potter, R.R., Beland, J., and Poole, W.H.
1961: A preliminary tectonic map of the Canadian Appalachian region based on age of folding; Bull. Can. Inst. Mining Met. vol. 54, pp. 687-694.

Stockwell, C.H.
1964: Tectonic map of the Canadian Shield; Int. Geol. Congress, 23rd session, 1964.

Stockwell, C.H.
1965a: Tectonic map of the Canadian Shield; Geol. Surv. Can., Map 4-1965.

Stockwell, C.H.
1965b: Structural trends in the Canadian Shield; Bull. Am. Assoc. Petrol. Geol., vol. 49, pp. 887-893.

(2) New edition of "The Geology and Economic Minerals of Canada"

The "Geology of Canada" is currently being completely revised by R.J.W. Douglas and officers of the Geological Survey of Canada and is being greatly enlarged in order to incorporate the spectacular increase of geological knowledge gained over the past 10 years. This volume contains much basic geological data in text form, on various sorts of maps, correlation charts, and restored and structure sections as well as summaries and syntheses. It will be an invaluable source book for analysis, correlation, and dating of tectonism within Canada and also for comparative studies with other parts of the world.

Douglas, R.J.W.
1967: Geology and Economic Minerals of Canada; Geol. Surv. Can., Ec. Geol. Series No. 1.

B. Cordillera

(1) Southern Cordilleran Structure Project (J.O. Wheeler, Geological Survey of Canada *et al*)

A project to study the structure of a belt across the Cordillera in southern British Columbia was instigated in 1964 by the National Advisory Committee on Research in the Geological Sciences. The belt under study extends northeastward from the coast near Vancouver across the Coast Plutonic Complex, Cascade orogen, the Interior Mesozoic Volcanic province, the southern extension of the Pinchi Geanticline, the Shuswap Metamorphic Complex, Selkirk Mountains and Dogtooth Range, and the Rocky Mountains.

The objective of the study is to obtain an integrated picture of the form of the structures and the relationships in time and space between individual structures and between structural belts, thus leading to an understanding of the structural development of the southern Cordillera.

Field studies began in 1964. Field work in the Cascade orogen has been completed by K.C. McTaggart and R.M. Thompson (University of British Columbia) and by J.A. Coates (Ph.D. candidate, University of Washington) and is currently being done by T. Richards (Ph.D. candidate, University of British Columbia) and B.E. Lowes (Ph.D. candidate, University of British Columbia). These studies are supplemented by independent investigations, now complete, by W.J. McMillan and J.W.H. Monger (theses projects at University of British Columbia).

M. Schau (Ph.D. candidate, University of British Columbia) is currently engaged in structural studies in the Upper Triassic volcanics of the Interior Zone. W.K. Fyson is continuing structural studies in the transition zone between the Shuswap Metamorphic Complex and the highly deformed late Palaeozoic rocks to the west. Elsewhere in the Shuswap Metamorphic Complex field studies have been completed on the west side of Frenchman's Cap gneiss dome by W.J. McMillan (Ph.D. candidate, University of British Columbia), on the south side of the dome by J.T. Fyles (B.C. Department of Mines and Petroleum Resources), and east of the dome along the east margin of the Shuswap Metamorphic Complex in the Revelstoke salient by J.V. Ross (University of British Columbia).

P. Simony (University of Calgary) and his students are carrying out a stratigraphic and structural investigation in the northern Dogtooth Range west of the Rocky Mountain Trench.

The entire southern Rocky Mountains south of Jasper have now been mapped by the Geological Survey of Canada on Operation Bow-Athabasca under R.A. Price and E.W. Mountjoy, and in the Kananaskis area by G.B. Leech. This work has been supplemented by detailed studies by H. Bielenstein in the Rundle thrust sheet and by D.G. Cook in the Stephen-Dennis fault zone (both are Ph.D. candidates at Queen's University), and by an independent study of a gneiss terrain that straddles the Rocky Mountain Trench at latitude 52°30'N by C.A. Giovanella (Ph.D. candidate, Stanford University). Current work reveals that apparent normal faults are particularly abundant in the western Main Ranges and Western Ranges of the Canadian Rockies. N.C. Ollerenshaw is currently continuing his structural studies in the Foothills around the "Panther Dome".

A seismic refraction profile was run in 1966 by the Dominion Observatory under W.R.H. White from the mouth of Fraser River to Revelstoke. It is hoped that a reverse profile will be run in the near future. Experimental detailed aeromagnetic maps were made of a strip of rugged, mountainous terrain from the late Palaeozoic rocks of the Interior Zone to the east side of the Shuswap Complex. Further geophysical work is anticipated in the future.

Bielenstein, H.V.
1967: Structural analysis of the Rundle Thrust Sheet, Southern Rocky Mountains; Geol. Surv. Can., Paper 67-1, part A, pp. 100-101.

Coates, J.A.
1966: Manning Park area, Cascade Mountains; Geol. Surv. Can., Paper 65-1, pp. 55-56.

Coates, J.A.
1967: Manning Park area (92H) Cascade Mountains; Geol. Surv. Can, Paper 67-1, part A, pp. 56-57.

Fyson, W.K.
1966: Structures in the Mt. Ida, Cache Creek, and Monashee Groups, Shuswap Lake area; Geol. Surv. Can., Paper 66-1, p. 58.

Leech, G.B.
1967: Cretaceous Strata in the west face of the Rocky Mountains; Geol. Surv. Can., Paper 67-1, part A, pp. 72-73.

Lowes, B.E.
1967: Chilliwack Groups, Harrison Lake Area; Geol. Surv. Can., Paper 67-1, part A, pp 74-75.

McMillan, W.J.
1966: Ratchford Creek map-area; Geol. Surv. Can., Paper 66-1, p. 74.

McMillan, W.J.
1967: Ratchford Creek area; Geol. Surv. Can., Paper 67-1, part A, p. 75.

Ollerenshaw, N.C.
1965: Burnt Timber Creek map-area, Alberta; Geol. Surv. Can., Map 11-1965.

Ollerenshaw, N.C.
1966: Geology of the Marble Mountain and Fallentimber West map-areas; Geol. Surv. Can., Paper 66-1, p. 115.

Ollerenshaw, N.C.
1967a: Lake Minnewanka East map-area, Alberta; Geol. Surv. Can., Paper 67-1, part A, p. 104.

Ollerenshaw, N.C.
1967b: Lake Minnewanka West map-area, Alberta; Geol. Surv. Can., Paper 67-1, part A, pp. 104-105.

Price, R.A. and Mountjoy, E.W.
1966: Operation Bow-Athabasca, Alberta and British Columbia; Geol. Surv. Can., Paper 66-1, pp. 116-121.

Price, R.A.
1967: Operation Bow-Athabasca, Alberta and British Columbia; Geol. Surv. Can., Paper 67-1, Part A, pp. 106-112.

Ross, J.V.
1966: Structural studies, Mt. Revelstoke area; Geol. Surv. Can., Paper 66-1, pp. 85-86.

(2) Structural Studies at University of British Columbia

J.V. Ross and P. Kellerhals have undertaken sample structural studies in parts of southern British Columbia from late Palaeozoic rocks west of the Shuswap Metamorphic Complex, within the complex, and in the northern Slocan and Kootenay Arc belt east of the complex. Polyphase deformation is related to unconformities within the Late Palaeozoic and early Mesozoic stratigraphy.

W.J. McMillan and J.W.H. Monger contributed to an understanding of the structural geology of the west side of the Cascade orogen emphasizing the role of an upthrust crystalline wedge on Vedder Mountain and of early northwesterly directed recumbent folds and thrust in the Chilliwack area.

MacMillan, W.J.
1966: Geology of Vedder Mountain near Chilliwack, B.C.; M. Sc. Thesis, University of British Columbia.

Monger, J.W.H.
1966: Stratigraphy and structure of the type-area of the Chilliwack Group, Southwestern B.C.; Ph.D. Thesis, U.B.C.

(3) Structural studies in the Precambrian of the Rocky Mountains

H.A.K. Charlesworth, University of Alberta, and students.

(4) Mesoscopic subfabric studies in Southern Rocky Mountains (R.A. Price, Geological Survey of Canada).

Some preliminary results of a reconnaissance study of mesoscopic subfabrics illustrate their tectonic significance.

A movement picture can be established for the deformation that occurs within an individual thrust plate during its development and translation. Kinematic relationships between and among the interlocking thrust plates can be studied.

Within a broad area centred along the prominent structural re-entrant that crosses the Rocky Mountains near Fernie, British Columbia, two different movement pictures occur in superposition. Both north- and northwest-trending kinematic axes can be recognized in the mesoscopic subfabrics of rocks which, on a megascopic scale, have either a northwest or a north-trending fabric axis.

The mesoscopic subfabrics associated with transverse faults in parts of the Front Ranges outline a movement picture which indicates that they are not tear faults related to the translation of the thrust sheets, but instead are older gravity faults whose orientation may be controlled by the fabric in the Hudsonian basement extending beneath the mountains from the Canadian Shield:

Price, R.A.
1967: The tectonic significance of mesoscopic subfabrics in the southern Rocky Mountains of Alberta and British Columbia; Can. J. Earth Sci., vol. 4, pp. 39-70.

(5) Structural analyses in some Cordilleran Coal Mines (D.K. Norris, Geological Survey of Canada).

Mesoscopic analysis of extension faults, contraction faults, and interbed slip has been undertaken in some coal mines in the southern Rocky Mountains.

Investigation at the A-North Coal Mine, Michel, British Columbia indicates that slickenside striae on bedding-surface deformation discontinuities and shear surfaces within the A seam provide a kinematic pattern consistent with that of the transport and deformation of the Lewis Thrust plate. Contact faults have a preferred direction of dip (southwest) whereas extension faults may dip in either direction. The disposition of faults is independent of the joint subfabric.

Mesoscopic analysis of three extension faults in Number 4 coal seam, Canmore, Alberta, has revealed that the fault surfaces are not planes. Observations on the variability of the acute angle between the faults and the bedding, the erratic variation of the net slip along the faults, and systematic difference in the pitch of slickenside striae on a given fault indicate the need for lateral slip on the relatively active block toward the extremeties and normal slip at the centre of even the simplest fault.

Studies of interbed slip in several mines reveal that the preferred direction of slip commonly lies at an angle of 10 to 15 degrees to the *ac* fabric plane where *a* and *b* fabric axes are in the plane of layering and *b* is defined parallel to the local strike. There has been strike-slip movement on these discontinuities that may be sympathetic to motion in the principal thrust surfaces which underlie (and overlie them). Variation in pitch of tens of degrees within a few feet on structurally and stratigraphically continuous planar bedding surfaces must indicate real and temporally distinct directions of relative transport. Slickensides can be and are preserved from more than one kinematic pattern. They indicate that the orientation of the *ac* (deformation) plane is variable in space as well as time, but rests with preferred orientation measurably divergent from the *ac* fabric plane.

Norris, D.K.
1965a: Structural analysis of part of A-North Coal Mine, Michel, British Columbia; Geol. Surv. Can., Paper 64-24.

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1966: Interbed slip in some Cordilleran coal mines, Geol. Surv. Can., Paper 66-1, pp. 114-115.

(6) Tectonic Analysis of the Northern Cordillera (D.K. Norris and A. Larochelle, Geological Survey of Canada).

The project was initiated in 1966 to investigate the tectonic significance of changes in structural trend among the mountain ranges of the northern Cordillera. The objectives are threefold: 1) to establish the kinematic and dynamic significance of the structural fabric of the rock mass in relation to these changes in trend; 2) to establish the control of the pre-Laramide shape of the sedimentary basin and its contents on the final deformational pattern in the northern Cordillera; and 3) to establish the sequence of intrusive and extrusive events in relation to orogenies and epeirogenesis in the area.

Samples were collected of dykes, sills, and lava flows in sedimentary rocks of Proterozoic and early Palaeozoic age from the Canadian Cordillera between latitudes 58° and 66° N. A total of 138 samples were obtained from 27 localities and the number of oriented specimens at each locality ranged from 1 to 6, depending on structural conditions.

(7) Granites in Canada Project (J.E. Reesor, Geological Survey of Canada, et al).

This project has resulted in several detailed plutonic and structural studies that have contributed to a better understanding of polyphase deformation in the core of the axial zone of the Eastern Cordilleran orogen. Studies on the Valhalla and Thor-Odin gneiss domes have revealed that early recumbent folds, now isoclinal, were accompanied by the injection of sheets of granite gneiss. These early structures were redeformed by northerly-trending (Cordilleran) structures and upward diapiric movement of the cores of the domes that locally spilled out as tongue-shaped lobes. Hyndman's work near the edge of the Shuswap Complex indicates that early recumbent structures also affected early Mesozoic rocks.

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Reesor, J.E.
1966: The Thor-Odin gneiss dome, Monashee Mountains, southern British Columbia; Geol. Surv. Can., Paper 66-1, pp. 78-80.

## C. Western Canada

(1) Crustal Studies (E.R. Kanasewich and G.L. Cumming, University of Alberta).

Bouguer and isostatic gravity studies have been made of the crustal section from the plains into the Rocky Mountains and compared with seismic refraction and, locally, reflection data. It appears that density variations in the upper mantle are necessary to interpret the observed data. Lateral variations in the upper 500 km of the mantle have been found by long range refraction studies carried out at the University of Alberta, so density variations are plausible also. It appears that the cause of epeirogenesis must lie in the upper mantle and that substantial vertical movement of large crustal blocks is plausible in tectonically active areas. If central British Columbia has been raised 10 to 15 km since the Mesozoic, as crustal data suggests, then such vertical motion and consequent gravitational gliding tectonics may be a contributing factor to overthrust faulting in the Rocky Mountains.

Cumming, G.L. and Kanasewich, E.R.
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1966: Deep crustal structure under the plains and Rocky Mountains; Can. J. Earth Sci., vol. 3, pp. 937-946.

## D. Arctic Canada

(1) Control of Granitic Basement upon Deposition and Deformation of Sediments (J.W. Kerr, Geological Survey of Canada, Calgary, Alberta).

The Canadian Arctic Islands offers an exceptional opportunity to study the control which the granitic basement exerted upon Late Precambrian to present day depositional and structural history. Narrow, relatively positive basement features provided clastic sources, or allowed shallow carbonate buildups flanked by deeper water, and thereby influenced facies patterns. Differential basement uplift and subsidence was transmitted upward to the overlying sedimentary column, thereby also controlled its structure.

Four relatively positive basement features project north or west from the Precambrian Shield as gently upwarped arches and partially fault-bounded uplifts. Their positions were influenced by basement anisotropy and may reflect the gneissic grain. They are but the manifestation of several types of differential movement of the basement (a) a positive element raised slightly while flanking regions depressed, (b) a positive element stationary while flanking regions depressed, and (c) a positive element depressed slightly while flanking regions depressed greatly. At no time were the arches or uplifts depressed relative to flanking regions, except locally in grabens that probably were associated with relative uplift.

These principles are illustrated by the structural history of Bache Peninsula Arch on Ellesmere Island, Boothia Uplift, and probably also by Minto Arch and Prince Patrick Uplift.

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1960: Summary account of structural history of the Canadian Arctic Archipelago since Precambrian times; Geol. Surv. Can., Paper 60-7.

## E. Canadian Shield

### (1) Tectonic Studies at the University of Manitoba (H.D.B. Wilson, W.E. Brisbin, D.H. Hall).

The geology-geophysics group at the University of Manitoba has been attempting to work out the nature and history of the Precambrian crust by combining regional geology, magnetic, seismic, and gravity data. The study has covered a large block of northwestern Ontario, the Superior-Churchill structural boundary in northern Manitoba, and the orogenic belt between Lake Superior and James Bay. The work on the Superior-Churchill boundary has been reported in several publications.

The general method has been to operate a continuing program of observation, compilation, and interpretation of data for each of the above disciplines, then to attempt to fit the data from two disciplines together, gradually extending to include all four disciplines.

Precambrian Shield Structure in Northwestern Ontario.

Geology-Magnetic: This combination shows that the Archaean greenstone-sedimentary belts form a continuous interlacing pattern indicating that the Archaean province in northwestern Ontario was covered by a continuous volcanic-sedimentary sequence which was folded and metamorphosed during the intrusion of vertically rising granitic diapirs. This is a very different concept than a series of parallel volcanic belts separated by granite. Earlier geologic mapping did not separate the highly metamorphosed gneissic volcanic-sedimentary series from the granitic rocks.

The combination of regional geology and magnetic pattern also outlined the English River gneissic belt. This belt is 400 miles long, with an average width of 40 miles. It is composed of granite and high-grade metamorphic paragneiss, bounded by fault contacts against the more usual low grade metamorphic volcanic-granitic Archaean shield.

Sixty large, late alkalic or alkaline circular plugs were located cutting the Archaean rocks. These plugs range in age from 2,600 to 1,000 million years old, and along with the diabase dikes form the post-orogenic igneous activity after the Superior province of the Shield became stabilized.

Geology-Gravity: A Bouguer gravity high coincides with the English River gneissic belt although the average surface rock density is lower within the gneissic belt than beyond it.

Bouguer gravity highs also coincide with major east-west trending areas of highly metamorphosed volcanic-sedimentary formations, whereas regional Bouguer lows coincide with areas where the volcanic-sedimentary formations are weakly metamorphosed. This may be caused either by thin granitic crust in the highly metamorphosed areas and thick granitic crust in the weakly metamorphosed areas; or by heat driving off volatiles from the highly metamorphosed areas, thus causing an overall density increase in the granitic crust.

The apparent east-west trends of the volcanic-sedimentary belts in the Superior province in northwestern Ontario are due principally to the east-west metamorphic belts rather than to the strike of the volcanic-sedimentary belts which is predominantly northeast and northwest.

Combination with Seismic Studies: Explosion seismic mapping of crustal structure using head and refracted waves as wide angle reflection generated by explosions in lakes have indicated two boundaries, one at the top of the mantle and one within the crust, the latter presumably representing the top of the intermediate layer.

The English River gneissic belt coincides with marked flexures on the two seismic boundaries. The top of the intermediate layer has a pronounced monoclinal flexure dipping to the north with a depth difference of approximately 9 km from the south to the north side of the belt. The top of the mantle on the other hand has a pronounced anticlinal upwarp of approximately 5 km beneath the English River gneissic belt.

Regional Magnetism: New methods of digital filtering of aeromagnetic maps are being applied to extract the long wave length anomalies that are suspected to be due to crustal structure. The anomalies are being compared with contour maps of induced and remanent magnetization of surface rocks prepared from surface measurements.

Interpretation: It is not yet possible to prepare a completely integrated model which satisfies all the data, but work is continuing and certain models considered originally are gradually being eliminated or modified to fit the new data. A set of papers is being prepared to describe the progress to date.

<u>Project Pioneer</u>

A single volcanic-sedimentary belt adjacent to the English River gneissic belt has been chosen for detailed geological mapping. Petrographic and geochemical research, gravity, magnetic, seismic, electrical, and radio-active surveys are being carried out in the same area to attempt to get as complete a picture as possible of a smaller area within the large regional area under study. This work is being carried on jointly by the Manitoba Mines Branch and the University of Manitoba. Field work started during the summer of 1966 and will be carried on through 1968.

(2) <u>Studies of crustal behaviour in the Precambrian</u> (Paul M. Clifford, McMaster University).

Mapping of "Keewatin" greenstone belts shows a persistent association of low metamorphic levels, a highly individual sedimentary development, and a characteristic tectonic style. The structural style and the metamorphic styles are incompatible with ideas of deep burial and later resurrection and indicate a rather more mobile crust, probably a higher thermal gradient, and the availability of abundant silicic material in the Archaean. It seems plausible to interpret the distribution of volcanic centres as indicating fracture zones and their intersections in the pre-volcanic crust. It also seems likely that the notion of a Kenoran orogeny analogous to say the Alpine orogeny is misleading.

Clifford, P.M.
1967: Crustal character in early Precambrian time; <u>Geol. Soc. Amer</u>. Northeastern Section meeting, March, 1967.

(3) Measurement of absolute stress (J.E. Blanchard, Dalhousie University).

A number of measurements of absolute stress have now been made in the Canadian Shield. These measurements indicate the forces are compressive and the horizontal stresses are several times greater than the vertical stresses. While the magnitudes may be in error, it is significant that the measurements indicate compressive forces.

(4) Penokean orogenic belt (W.R. Church, University of Western Ontario).

In the region north of Lake Huron and Georgian Bay, folded Huronian rocks extend for some 250 miles between Sault Ste. Marie and the Sudbury area (Young and Church, 1966). The region can be conveniently subdivided into two areas: The Bruce Mines - Blind River area of gently folded Huronian; and the wedge-shaped area extending from Spragge to Wanapitei Lake (the Espanola Wedge) which constitutes the main fold belt of the Penokean orogen in Ontario. In the latter area the Huronian exhibits a complex history of polyphase folding, metamorphism, and igneous intrusive activity (Card, 1964; Church, 1966; Robertson, 1966), which includes the following events:

a) Intrusion of gabbroic rocks

b) Main phase folding and faulting

c) Intrusion of gabbro-granophyre sheets, and northwest to west-northwest trending quartz-diabase dikes; formation of Sudbury-type intrusion breccias

d) Regional thermal metamorphism, polyphase minor folding and granite intrusion.

Although the detailed structural and metamorphic history of the Huronian has yet to be worked out it seems probable that all these events form part of the Penokean orogeny which, on the basis of whole rock age determinations on Nipissing diabase-granophyre intrusions of the Blind River area, took place c.2,100 my ago (Van Schmus, 1965). This age for the Penokean orogeny is also suggested by a Rb-Sr age of 1,940 my for a post-tectonic pegmatite intruded into the folded and metamorphosed Huronian of Michigan (Aldrich and Davies, 1960), and a K-Ar age of 1,995 my (Leech, et al, 1963) for a west-northwest trending, post-folding diabase dike intrusive into the Huronian of the Blind River area (Frarey, 1962).

An age of c.2,100 my for the Penokean orogeny agrees well with that adduced for the Inverian orogeny of Scotland, the Karelian orogeny of Scandinavia, and possibly the Ketilidian orogeny of Greenland.

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Card, K.D.
1964: Metamorphism in the Agnew Lake area, Sudbury District, Ontario, Canada; Bull. Geol. Soc. Amer., vol. 75, pp. 1011-1030.

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1966: The status of the Penokean orogeny in Ontario; Abst., Ninth Conf. on Great Lakes Research, Chicago, p. 25.

Frarey, M.J.
1962: Geology Bruce Mines, Ontario; Geol. Surv. Can., Map 32-1962.

Leech, G.B., Lowden, J.A., Stockwell, C.H. and Wanless, R.K.
1963: Age determinations and geologic studies; Geol. Surv. Can., Paper 63-17, p.74.

Robertson, J.A.
1966: The relationship of mineralization to stratigraphy in the Blind River area, Ontario; Geol. Assoc. Can., Spec. Paper No. 3, Precambrian Symposium, pp. 121-136.

Van Schmus, R.
1965: The geochronology of the Blind River-Bruce Mines area, Ontario, Canada; J. Geol., vol. 73, pp. 755-780.

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1966: The Huronian system in the Sudbury District and adjoining areas of Ontario: a review; Proc. Geol. Assoc. Can., vol. 17, pp 65-82.

## (5) Grenville Front

An independent study is being made by R.T. Cannon, of McGill University, of the Killarney gneisses southeast of the Grenville Front. The gneisses have a polyphase deformational history more complex than previously considered within the Grenville province. In addition polyphase deformation has also been established in the Huronian adjacent to the Front; this is also complex but more clearly defined than within the above gneisses. Work with M.J. Frarey of the Geological Survey of Canada on the Grenville Front itselt is also in progress to try and establish the nature and function of this complex zone in relation to the structural and metamorphic history of the adjacent blocks. The Front is clearly a major deep-seated, tectonic feature with a complex history and shows many unique features in the present area which are being currently evaluated.

Frarey, M.J.
1967 Lake Panache and Collins Inlet map-areas, Ontario; Geol. Surv. Can. , Paper 67-1, part A, pp. 135-137.

In the vicinity of Sudbury the Grenville Front is partially obscured by faulting and shearing and partially by a quartz diorite pluton (1,400 - 1,700 my by Rb-Sr). The quartz diorite emplacement was controlled by structures in the Huronian. Grenville structures are very much more complicated. It is now clear that the assumption of a metamorphic transition as advocate by Phemister is incorrect. The zone of feldspathization he postulated is, in fact, an unambiguous intrusive body, significantly older than the "Grenville" metamorphism, and some at least of the metamorphism here also is much older than the Grenville.

Henderson, J.R.
Tectonic history of the Grenville Front south of Sudbury; thesis in preparation, McMaster University.

Kwak, T.A.P.
Metamorphism of "Grenville" rocks near Wanapitei; thesis in preparation, McMaster University.

Spaven, H.R.
1966: Granite tectonics in part of Eden Township, Sudbury District, Ontario; M. Sc. Thesis, McMaster University.

(6) Structural Studies in the Grenville Province of Southwestern Quebec (H.R. Wynne-Edwards, A.F. Gregory, P.W. Hay, C.A. Giovanella, and E.W. Reinhardt).

In 1964 the Geological Survey of Canada initiated a project of reconnaissance geological mapping in the Grenville province, aided by aeromagnetic data. In that year, 13,000 square miles north of Montreal and Ottawa were completed, providing a cross-section of the Grenville province about 170 miles long. The plutonic and high-grade metamorphic rocks of this area can be divided on the basis of their structure, texture, and composition into 5 tectonic categories determined by their role during the Grenville orogeny. From the oldest to youngest they are: (I) a pretectonic, basement complex, (II) a pretectonic metasedimentary group, (III) a pretectonic, plutonic, intrusive group, (IV) a syntectonic, plutonic, intrusive group, and (IV) a post-tectonic family of diabase dykes.

The first three categories were deformed and recrystallized during the events of the Grenville orogeny and are respectively represented by (I) quartzo-feldspathic and amphibolitic gneisses covering over half the area, and concentrated to the north, (II) quartzite, marble, and layered paragneisses concentrated to the southwest, and (III) anorthosite, gabbro, mangerite, quartz monzonite, and related green-rock migmatitic complexes concentrated to the southeast. These rocks are inferred to be of Archaean, Aphebian (Lower Proterozoic), and Palaeohelikian

(Middle Proterozoic) ages respectively.

The structure results from northeast-trending flow folds of the Grenville orogeny superimposed on east-west trending structures in the basement complex to the northwest, and on north-south trending structures in the rocks to the southeast, these older trends being interpreted as the result of the Kenoran and Hudsonian orogenies in that order. There thus appears to be a record in this part of the Grenville province, as earlier predicted by Stockwell (1964), of continued tectonic overprinting of Archaean rocks (Figure 3). The Kenoran, Hudsonian, Elsonian, and Grenville disturbances each appear to be represented, and each contributed new rocks to the sum total present, and modified all pre-existing rocks by deformation, metamorphism or both (Figure 4). Thus, far from composing a new segment of the continental crust added about 950 my ago, as has been suggested on the basis of the numerous radiometric age determinations of this approximate date, all but 5 per cent (categories IV and V above) of the exposed rocks in the Grenville province are much older than this, and over 50 per cent (category I above) are inferred to be Archaean in age, and are compositionally the correlatives of rocks in the Superior province about 40 miles west of the area studied. These results provide a tectonic framework to which rock units elsewhere in the Grenville province may be referred. The Grenville province is among the best exposed areas of deep-zone crustal structure, so that its step-like tectonic evolution (Figure 4) may have wide significance.


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1966: Mont Laurier and Kempt Lake map-areas, Quebec (31J and 31 O), A preliminary report of the Grenville Project; Geol. Surv. Can., Paper 66-32, 32 pages.

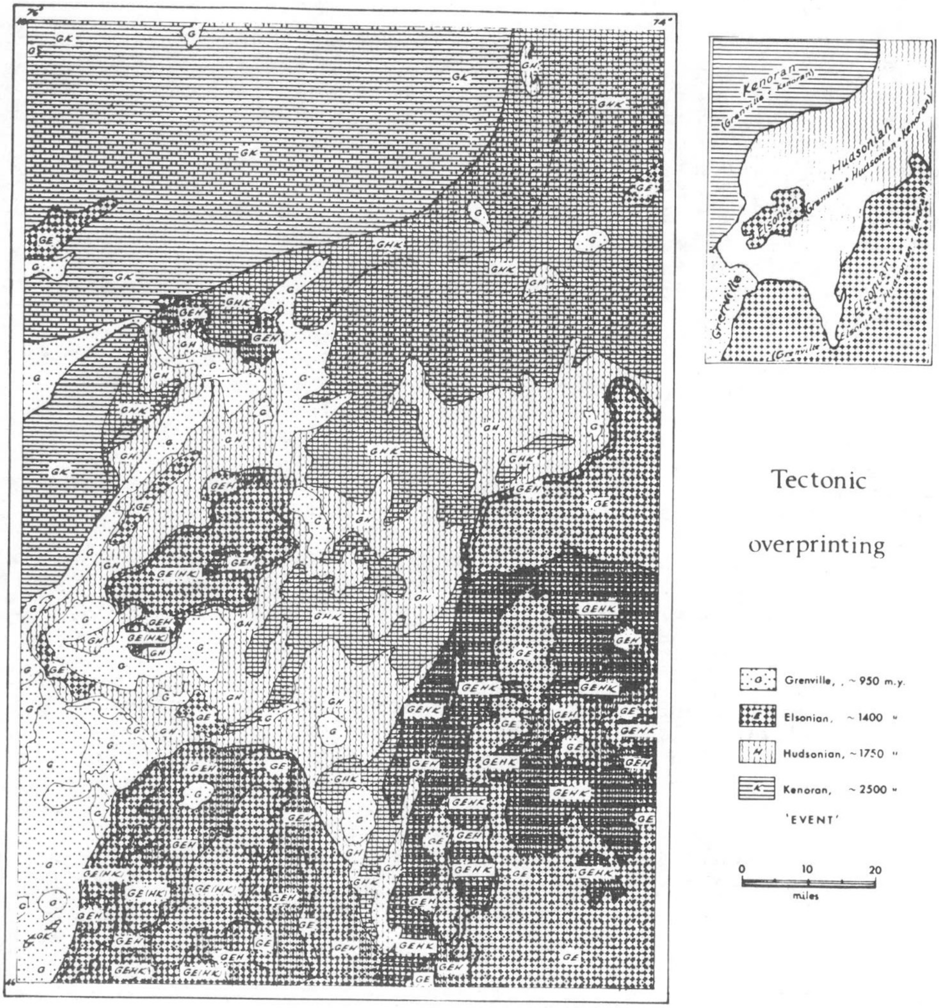


Figure 3. Pattern of tectonic overprinting produced by superimposed events of the Kenoran, Hudsonian, Elsonian, and Grenville disturbances in Mont Laurier and Kempt Lake map-areas, Quebec. The smaller map is a much simplified version showing where the effects of the various tectonic events are dominant.

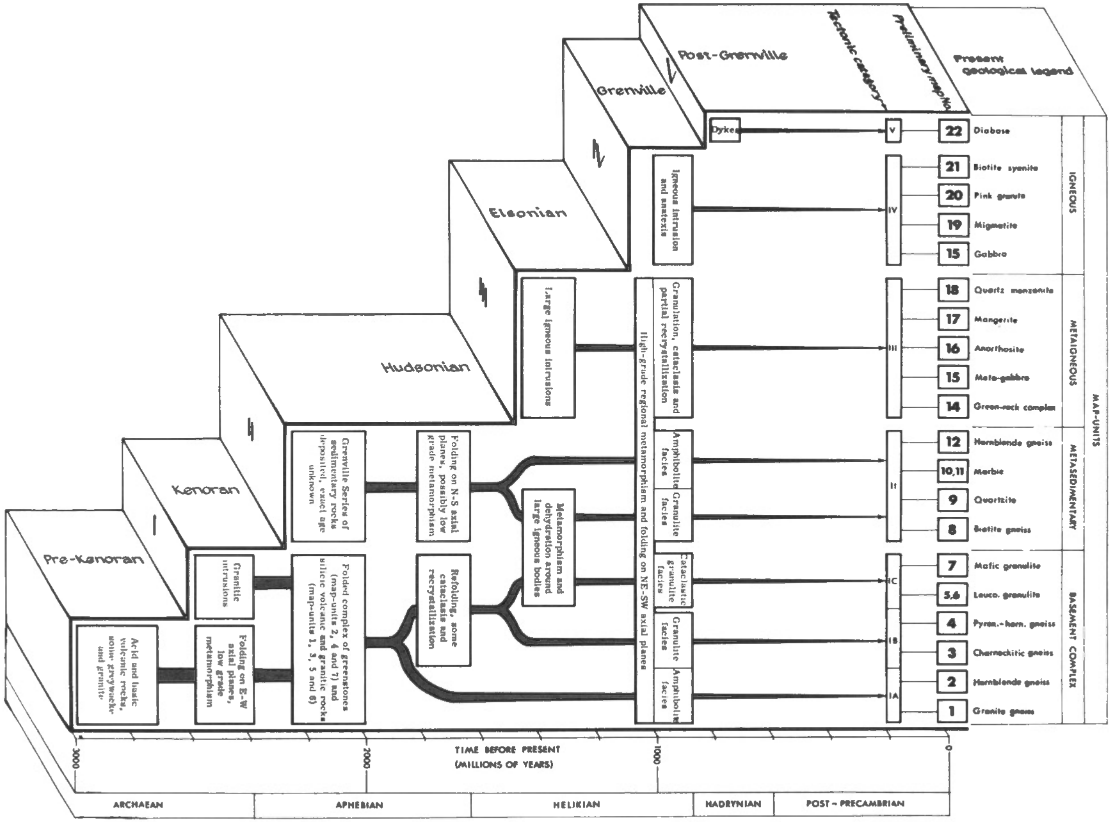


Figure 4. Geological evolution of the rocks of Mont Laurier and Kempt Lake map-areas showing the progressive growth of the present geology (represented by the map legend to the right of the diagram) by a series of steps in which older rocks were reprocessed and new rocks were added, beginning in the Archaean and ending in the Late Proterozoic.

Wynne-Edwards, H.R.
in press: Tectonic overprinting in the Grenville province, Southwestern Quebec; Can. J. Earth Sci.

F. Appalachian Region

(1) The Taconic Klippen of Western Newfoundland (R.K. Stevens, University of Western Ontario)

Two Taconic klippen, each approximately 100 miles long and 20 miles wide, consisting of Cambro-Ordovician sedimentary rocks and ophiolites, rest on a Cambro-Ordovician platform of miogeosynclinal sequence in western Newfoundland. The klippen are composed of a variety of sedimentary rocks, including coarse lime-breccias, deltaic deposits and flysch, such that the assemblage cannot be classified as strictly miogeosynclinal or eugeosynclinal. The ophiolites represent a major pre-tectonic phase of basic igneous activity.

Although the allochthonous rocks are believed to have been transported westwards from central Newfoundland by gravity sliding (Rodgers and Neale, 1963), no satisfactory source area has been identified.

Zones of chaotic structure, resembling certain facies of Alpine wildflysch were generated during the Taconic sliding. There is evidence to suggest, however, that the wildflysch associated with the ophiolites was formed as a result of pre-Taconic sliding of the ophiolites prior to the final emplacement of the klippen. At least some of the ophiolites appear to have had a complex history of movement within the geosyncline.

Rodgers, J. and Neale, E.R.W.
1963: Possible "Taconic" klippen in Western Newfoundland; Am. J. Sci., vol. 261, pp. 713-730.

(2) Tectonic Comparisons Between Fleur de Lys Orthotectonic Belt of Northeastern Newfoundland and Moine - Dalradian Group of British Caledonides (W.R. Church, University of Western Ontario).

In 1965 quartz-eclogites of classic type were found for the first time in North America (Church, 1966), in psammitic schists of the Fleur de Lys Group of the Burlington Peninsula, northeast Newfoundland. Their occurrence is of interest because such rocks are not known from any other region of the Appalachian mountain system, whereas similar rocks do occur in psammitic schists of the Moine Series of the west of Ireland (Church, 1966). Furthermore the Fleur de Lys Group occurs in a similar structural position to that of the Moine-Dalradian Series (Group) of the British Caledonides. Both occur immediately to the southeast of the northwest foreland region of Cambro-Ordovician shelf deposits, and to the northwest of a sequence of less highly metamorphosed lavas and sediments of a central mobile belt. Since it is now generally accepted that the folding and metamorphism of the Moine-Dalradian of the British Caledonides occurred prior to the deposition of the Lower Ordovician of the west of Ireland, present work is directed towards determining whether a similar relationship exists between the Fleur de Lys Group of the Burlington Peninsula and the lower grade metamorphic rocks of the Baie Verte and Mic Mac Groups bordering the Fleur de Lys to the southeast. Results of preliminary studies suggest that the earliest phases of deformation and metamorphism of the Fleur de Lys, with which the formation of the eclogites is associated, occurred prior to the earliest phase of deformation recognizable in the Baie Verte Group. If correlation of the Baie Verte Group with the Lower Ordovician Snooks Arm Group of the Notre Dame Bay region proves justifiable, a pre-Lower Ordovician age for the folding and metamorphism of the Fleur de Lys Group would be strongly suggested and the similarity of the Fleur de Lys and Moine-Dalradian amplified. Alternatively a Taconic (post-Wilderness stage) age for the folding and metamorphism of the Fleur de Lys might be taken to indicate, assuming continental drift, that lateral migration with time has occurred of the main phases of folding and metamorphism from east to west along the Caledonide - Appalachian mountain belt.

Church, W.R.
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Church, W.R.
1966: Geology of the Burlington Peninsula, Northeast Newfoundland; Abst. Geol. Assoc. Can. Ann. Meeting, Halifax, pp. 11-12.

(3) Southwestern Appalachians, Sutton Region (P.R. Eakins, McGill University)

Deformation in the soft rock stage began shortly after the deposition of some formations, indicating crustal unrest during the geosynclinal phase of the mountain building. At least two phases of folding followed, the first probably involving gravity sliding to the west. The second phase resulted in the Sutton anticlinorium, and probably involved granitic intrusion or granitization deep in the core of the structure.

## G. Megatectonics and Continental Drift

J.T. Wilson has recently investigated several aspects of tectonics of the ocean basins in relation to continental drift. His own report of progress in this and related fields, which gives a brief account of his own contributions and emphasizes the exciting challenges that face earth scientists today, follows -

"A few recent papers, the most significant of which are still only available as preprints, suggest that we are on the verge of a great and revolutionary advance in our knowledge of the earth.

Until now the most profitable studies in all branches of geoscience have been to collect data. Because there has been no fundamental theory of the earth's behavior, prediction has been impossible and speculation idle. The basic trouble has been a lack of agreement upon the extent of past movements in the earth. Although folding shows that some motion has occurred, the natural view has been to minimize this and in particular to hold the continents fixed. This assumption has not been satisfactory, because it has not served to explain geology well. At best our idea about such matters as mountain building are still vague. If our basic assumption that the earth as a whole has been fairly rigid is wrong, our ideas need revision and much of what has been written about historical and structural geology, tectonics, petrogenesis and physics of the earth is out of date.

Fifty years ago, A. Wegener (1) pointed out three reasons for believing that parts of the crust are being displaced relative to other parts by movement over some mobile layer. These points were the excellent fit of some opposite coasts, the rise of land after ice sheets melted and the displacement of climatic zones of the past. Most geologists and geophysicists did not accept these views, but Wegener's arguments were never wholly dismissed. Several recent discoveries bear on the problem. The earth's magnetic field is reversing every few hundred thousand years (2,3). The palaeomagnetism locked in rocks at the time of their formation suggests that large displacements of the crust have taken place (4). As M. Ewing and H.W. Menard and their colleagues have done so much to show, the mid-ocean ridge is the greatest mountain system on earth, quite different from continental mountains and not explained by existing theories of a rigid earth (5). The crust may be growing and expanding away from it (6,7). The geometry of fractures formed between moving crustal plates demands new kinds of faults, named transform faults, with quite different properties from normal, transcurrent or thrust faults (8).

The present advance stems from the suggestion by F.J. Vine and D.H. Matthews (9) at Cambridge and independently by L.W. Morley and A. Larochelle (10) that if the ocean floors are spreading and if the earth's magnetic field is reversing then every reversal should be discernable in magnetic anomalies over oceans.

F.J. Vine and J.T. Wilson (11) discovered off California the first example of a ridge which appears to be expanding and used it to illustrate the theory. They interpreted the anomalies to deduce the age, total displacement and rate of motion along the San Andreas rift, which is a transform fault.

F.J. Vine in a long paper has shown (12) that the magnetic anomaly patterns of the ocean basins can be precisely explained if reversals of the earth's field influence the magnetization of lavas poured out along expanding mid-ocean ridges. The rates of expansion are quite steady, being 1.9 cm/yr south of Iceland, 6 cm/yr off British Columbia and 9 cm/yr in the South Pacific. This interpretation has been accepted by E.A. Godby et al (13) and also by J.R. Heirtzler at Lamont who is attempting to extend it to all oceans.

This method promises to give a precise picture of where every continent lay at the time of every reversal (about every million years) back to Jurassic time. If this is true the later history of continental drift changes from being a vague and dubious hypothesis to being a numerically precise design for recent geology.

Doubt that the mid-ocean ridge is expanding is further removed by an abstract now in press for the next meeting of the Geological Society of America. L. Sykes (14) of Lamont has measured the direction of motion of earthquakes along offsets in the mid-ocean ridge. Theory shows that they should be in opposite directions for transcurrent and transform faults. The mechanism of about twenty earthquakes on mid-ocean ridges have been studied and he concludes that "The sense of strike motion is in agreement with that predicted for transform faults and for various hypotheses of ocean-floor growth; it is opposite to that expected for a simple offset of the ridge crest along fracture zones.

At the symposium on 10th and 11th October, 1966, held in connection with the 200th Anniversary of Rutgers University, the idea of continental drift was gaining acceptance and with it the view that the history of continental motion for the past hundred million years is recoverable in great detail.

That drift was going on before the Mesozoic era seems probable and J.T. Wilson (15) has recently applied this idea to suggest that an early Atlantic Ocean closed during the Paleozoic and has reopened again since the Jurassic.

If the view that drift is occurring is accepted, earth science will have gained a proper theoretical basis and great progress will be possible. Most of the present textbooks will be out-of-date. It will be very unwise to write any general report for the Upper Mantle Project or any accounts of large regions in shields or mountains without realizing that rocks now contiguous may bear no relation to one another, that the off-shore sources of old sediments may have been carried far away and that the sources of igneous rocks need not have remained beneath them. This question is the most crucial one before the Upper Mantle Project."

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1965: Convection in a non-Newtonian mantle, continental drift, and mountain building; Phil. Trans. Roy. Soc. London, vol. A258.

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Research undertaken by J.T. Wilson (Institute of Earth Sciences, University of Toronto) and his associates is listed below.

(1) Continental Drift and Transform Faults

J.T. Wilson has suggested that continental drift should give rise to a new class of faults, not properly recognized before and named by him "transform faults". He points out that movements in the earth's crust are concentrated in fold belts, mid-ocean ridges and major faults with large movements. These features and the seismic activity along them appear to end abruptly and are transformed into another feature. At the point of transformation the horizontal shear motion along the fault ends abruptly by being changed into an expanding tensional motion across a mid-ocean ridge or rift with a change is seismicity or the fault may terminate where oceanic crust moves down under an island arc. Thus the mobile regions of the earth form a continuous network which divide the surface into several large rigid plates. He has predicted twelve possible new types of transforms and has identified six of them in ocean basins. The sense of movement on some types of transform faults is the reverse of that expected by transcurrent faulting.

Wilson, J.T.
1965: A new class of faults and their bearing on continental drift; Nature, vol. 207, p. 343-347.

(2) Interpretation of Magnetic Anomalies over Ocean Basins

The polarity of the earth's magnetic field is known to be reversing every few hundred thousand years. Vine and Matthews (1963) and independently L.W. Morley and A. Larochelle, have pointed out as a consequence, that, if the ocean floors are spreading away from mid-ocean ridges, the basalts formed there should form strips parallel with the ridge. They should also be magnetized alternately in the normal and reversed directions. They concluded that this might be so from study of a few profiles of the magnetic field variations in the Indian and Atlantic Oceans respectively. Vine and Wilson (1965) and Wilson (1965) provided the first interpretation of a magnetic map of an area which illustrated this theory. In doing this for the region off the Pacific coast of North America they were able to suggest the age of the beginning of the present stage of activity of the San Andreas fault (10 to 11 my ago), the total displacement across it (400 km), the position of the submarine extension to the north and its average rate of movement (4 to 6 cm per year).

Wilson, J. Tuzo
1965: Transform faults, oceanic ridges, and magnetic anomalies southwest of Vancouver Island; Science, vol. 150, pp. 482-485.

Vine, F.J. and Wilson, J. Tuzo
1965: Magnetic anomalies over a young oceanic ridge off Vancouver Island; Science, vol. 150, p. 485.

(3) Fracture Zones, Submarine Ridges, and the Spreading of Oceans.

The great fracture zones on the ocean floors appear to be transform faults. Assuming them to be so, their properties and the pattern of some chains of aseismic volcanic islands have been interpreted by J.T. Wilson to show the possible directions of flow in the upper mantle. The pattern can explain the northward movement of the southern continents away from Antarctica since the rupture of Gondwanaland. An explanation for the origin of some submarine ridges follows and predictions have been made upon where to look for some uncharted submarine ridges and what their directions, alignments, offsets, and ages should be.

Thus it has been proposed that the start of a new pattern of drifting may involve a break through an ocean basin, which becomes a ridge. This is suggested as the origin of the Lomonosov Ridge in the Arctic Basin and of the Florida-Bahamas Ridge. Another ridge down the Pacific called the ICSU Line has been identified and held to be of this nature and to divide the Pacific into younger and older halves. To provide additional information for testing this hypothesis of the origin of Florida, R. Grasty has started to date volcanics and basement rocks obtained from deep well cores in Florida and Georgia.

Field work to check a prediction based upon drift has been undertaken by D.B. Clarke who investigated Tertiary basalts in Baffin Island in 1964 and 1965 and moved to West Greenland in 1966. Basalts in each region are very similar in petrology and age (about Paleocene).

Wilson J.T. and Clarke, D.B.
1965: Geological expendition to Capes Dyer and Searle, Baffin Island, Canada; Nature, vol. 205, pp. 349-350.

Wilson, J.T.
1965a: Submarine fracture zones, aseismic ridges and International Council of Scientific Unions Line. Proposed western margin of the East Pacific Ridge; Nature, vol. 207, pp. 907-911.

Wilson J.T.
1965b: Convection currents and continental drift; Phil. Trans. Roy. Soc. London, vol. A258, pp. 145-167.

Wilson, J.T.
1966: Some rules for continental drift; Roy. Soc. Canada spec. publ. no. 9, pp. 3-17.

(4) Did the Atlantic Ocean close and then reopen?

To the old speculation that the Atlantic Ocean has opened since the Jurassic period has been added the concept that in Cambrian and Lower Ordovician time an earlier ocean existed which separated 'Atlantic' and 'Pacific' faunal realms, and was the site of island arcs. Subsequently the ocean slowly closed. The meeting of the North American and European continents resulted in the Palaeozoic orogenic episodes. The shedding of clastic wedges from the uplifted regions at the junction of the continents, and the subsequent continental post-orogenic volcanic and sedimentary assemblages are common to both continents in late Palaeozoic and early Mesozoic time. This interpretation involving recurrent continental drifting implies that a series of major faults through the Atlantic Provinces of Canada and the New England States of the United States mark the line of closure of a former Atlantic Ocean. Geological evidence for this has been discussed and the geophysical data is now being assembled and interpreted.

J.T. Wilson has also drawn an analogy between patterns formed between two colliding ice sheets and that of structures in the Caribbean and Scotia areas. It is proposed that the Antilles arc forms the top of a great finger raft of lithosphere advancing relative to Mexico and northern South America. This crustal motion may have been produced by the growth of the mid-Atlantic Ridge and East Pacific Ridge. The mechanism suggested would require that the faults through Bartlett Trough and northern Venezuela be transform faults and accounts for the anomalously thick crust in the eastern Caribbean and normal oceanic crust in the Gulf of Mexico.

Wilson, J. Tuzo
1966a: Are the structures of the Caribbean and Scotia Arc regions analagous to ice rafting?; Earth and Plan. Sci. Lett. vol. 1, pp. 335-338.

Wilson, J. Tuzo
1966b: Did the Atlantic Oean close and then reopen?; Nature, vol. 211, p. 676.

# SEISMOLOGY

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In previous reports in this series the standard seismological network, array seismology studies, program in Canadian seismicity, P- and S-wave studies of earthquake mechanisms, surface wave research, programs involving the study of the character of body wave signals and crustal seismic refraction studies have been described.

The author has been asked in this report to give a brief review of the state of knowledge in the field, to emphasize progress and results in the upper mantle seismological program in Canada in a non-specialized manner, and to indicate his ideas on the direction of future research in the immediate years ahead. Since seismology covers such a wide field, and since in the past it has been largely a matter of personal choice as to which programs in seismology would be reported under the aegis of the upper mantle program, the terms of reference must necessarily be interpreted in a somewhat restricted manner. It is proposed therefore to discuss only those features of Canadian work in seismology which have been heretofore outlined in upper mantle progress reports. At each stage general progress in recent years will be outlined in a non-specialist manner. In addition some views as to the direction of future work, and some personal ideas of the immediate problems will be indicated.

The reader is referred to the National Report for Canada, Seismology and Physics of the Earth's Interior, 1963-1966, for a full technical account of the work in Canada either underway or completed during that interval. This report to the International Union of Geodesy and Geophysics, Association of Seismology and Physics of the Earth's Interior, will be available for the 14th General Assembly, Zurich, Switzerland, 1967. It contains a complete bibliography of approximately 150 papers published by Canadians in seismology during the interval 1963-1966. A number of these papers are listed in the Canadian Contributions to the Upper Mantle Project at the end of this Report.

# I. CANADIAN SEISMOLOGICAL NETWORK

Investigations of the mechanism of earthquakes, the seismicity of the earth and further refinement by seismological research of models of the internal structure of the earth require a cooperating world-wide network of modern seismological observatories as a basic research infrastructure. Optimally the spatial distribution of elastic waves should be completely determined in a frequency range from about 100 cycles per second to one cycle per hour. Economic and practical considerations limit the observations available from a major network to the frequency range 10 cycles per second to about 1 cycle per 100 seconds.

## A. First Order Canadian Seismological Network

The status of the first order standard seismological network operated in Canada by the Department of Energy, Mines and Resources is shown in Figure 1. Twenty-three first order stations are in operation with well calibrated three component short and long period instrumentation. A vault has recently been constructed, but not yet instrumented, at Churchill, Manitoba, and two additional stations are planned. This will bring the total of such stations in Canada to 26.

With a few exceptions each station is instrumented with three orthogonal short period seismographs, each consisting of a 1-second Willmore Mark II seismometer coupled to a 0.25 second galvanometer, and three long period orthogonal Press-Ewing Columbia seismometers at either 15 or 30-second periods coupled to 90 second galvanometers. At each station the three short period systems are very approximately matched, as are the long period systems. Minute marks are controlled by a crystal chronometer, checked daily against radio time signals either automatically or by manual operation.

Network seismograph calibration is by the Willmore Bridge steady-state method and is absolute. The calibrations are believed to be reliable to within a few percent and this, in general, is supported by repeated observations and theoretical study.

The network contributes in three major ways to international cooperation in seismology:

(a) The stations at Alert, Mould Bay, Resolute, Coppermine, Frobisher and Ottawa report their readings to the U.S.C.G.S. on a daily basis by radio to Ottawa and thence by teletype to the U.S.A. The stations use a special code which allows a simple check on consistency. In addition to P-times, five Arctic station telegrams report the maximum peak-to-zero ground amplitude and period in the first 5 seconds of the P-wave

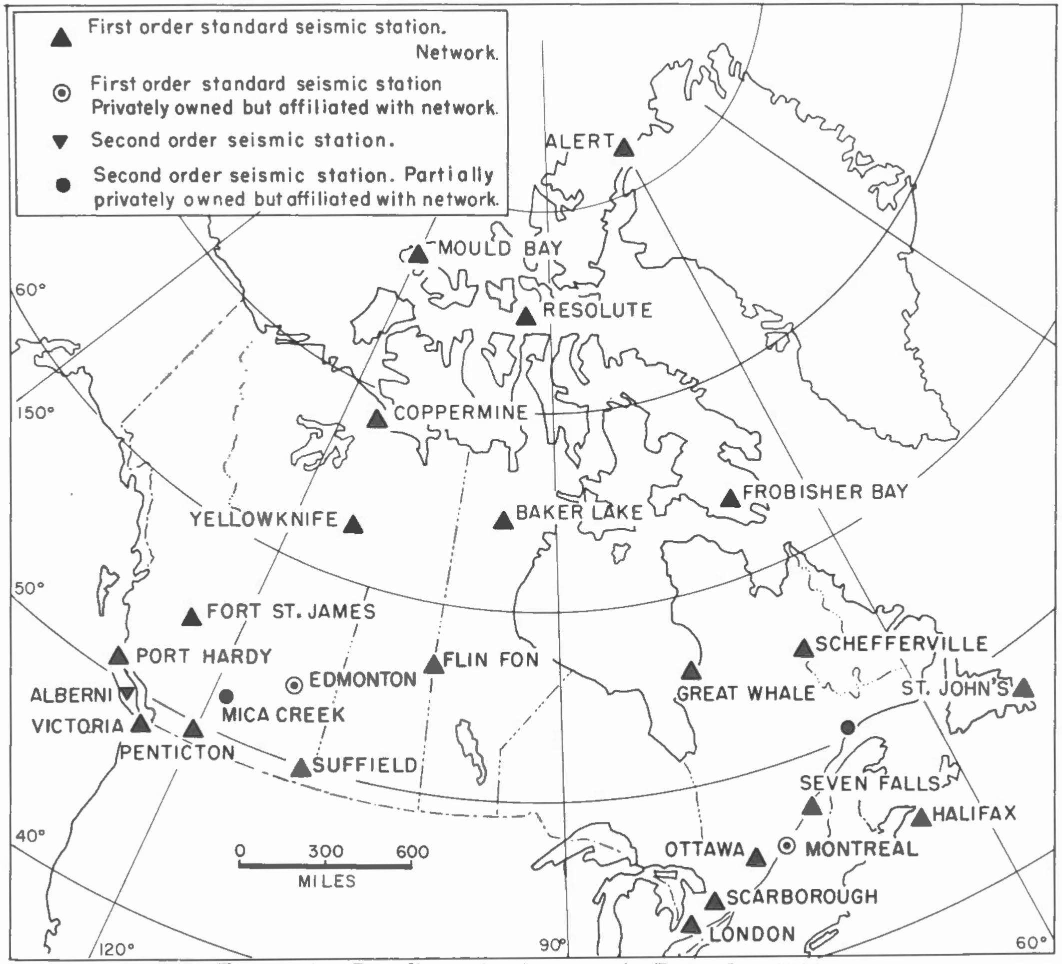


Figure 1. Canadian seismic network, December 1966.

train, provided the maximum peak-to-peak amplitude exceeds 4 mm. In addition copies of the Victoria and Edmonton phase sheets are airmailed to the U.S.C.G.S. weekly. These results are all used in the preliminary epicentral and magnitude determinations of the U.S.C.G.S.

(b) P-arrival data including directions of first motion for all stations are punched on cards, which are sent in station-month blocks to the International Seismological Research Centre in Edinburgh, well within a year of the initial generation of the data, in order to contribute to the definitive epicentral determinations of the Centre. This service is offered to other international and national agencies. The data in punchcard form is used to generate the seismological bulletin with a chronological sort and print-out.

(c) From July 1, 1966, all Canadian seismograms have been microfilmed with those of the world-wide standard seismic network of the U.S.A. in the record centre expressly designed and equipped for high quality seismological purposes in the U.S.A. The data is handled in observatory-month blocks, and the data flow is uniform and continuous to the assigned camera. In this way high quality reproductions of Canadian Seismograms can be made widely available to the international seismological community in an inexpensive and efficient manner for a large number and variety of research purposes. Prior to July 1, 1966, a microfilm file of all Canadian seismograms was maintained in Ottawa using the facilities of the National Archives of the Government of Canada, and is available in a similar way.

The Canadian standard network, as planned at the beginning of the Upper Mantle Project, is now reaching completion. The number of stations has quadrupled in the last four years.

Problems which remain include those of increasing the technical competence of record interpretation at the stations themselves. This problem is complicated by the isolation of most of the stations and the consequent rapid staff turn-over, and by the fact that it is not economically possible to locate seismologists at more than a very small number of stations. Other requirements for the immediate future include the addition of higher gain, narrow band-pass long period instrumentation at a small number of sites, and the addition of a visual recording seismograph at a number of stations.

Meanwhile, research is actively proceeding at the Dominion Observatory on the next generation of standard seismic station instrumentation, with tape recording acquisition of data, instruments with a greater dynamic range, and the devising of programs and techniques for multiple real-time data handling on a digital computer. Portable well-calibrated FM magnetic tape recording seismographs have been developed jointly with the Arctic Institute of North America. Three sets of such equipment in two versions have been constructed: each allows five days of unattended field recording of three components at two different levels of amplification. Techniques have been developed for editing the tapes, and conversion of data samples to a digital tape file using the CDC-3100 computer of the Department of Energy, Mines and Resources. In addition experiments have been undertaken by A.M. Bancroft and P.W. Basham in extracting the long period information from the recorded signal. So far only analogue techniques have been studied: these show that the system noise is sufficiently low that for a typical shallow earthquake at an epicentral distance of $90^{o}$, the surface wave maximum would produce a signal-to-noise ratio of 1 for a magnitude 5 earthquake. The results using two second seismometers are thus as good as typical photographic installations to periods as long as 20 seconds. This result has considerable significance for the future development of surface wave studies including temporary stations without necessitating expensive permanent vaults such as are required for the usual long period seismographs used in this work.

Here it should be noted that E.R. Kanasewich and M.D. Burke of the University of Alberta are developing a digital recording facility to record seismic and other data from the Edmonton vault, which is more than 20 miles distant from the University, on digital magnetic tapes at the University. A small commercial digital computer is being used to format the tapes.

A major gap in the Canadian network of seismic observatories is the absence of one or more strain seismograph installations. This gap imposes severe restrictions on Canadian contributions to such studies as those of the separation and identification of the higher modes of fundamental vibrations of the earth, and needs rectification. In addition, more fundamental studies of the natural seismic background and microseisms are needed: the level of noise, its variation in time and character with location need study. The effects of geological and topographic structure require investigation.

## B. Second Order Canadian Seismic Observatory Network

The standard station network described above is supplemented for local seismicity studies by three single component, short period vertical seismographs at Alberni, B.C., Mica Creek, B.C., and Sept Isles, P.Q. In addition visual recording seismographs are operated at Ottawa and Victoria. Each of the stations is being equipped in a uniform manner with hot wire visual recording, and modern electronic seismographs with low operating costs.

## II. LOCAL SEISMICITY

Considerable progress can be reported in the study of Canadian seismicity. In recent years W.E.T. Smith at the Dominion Observatory has completed a study of the known earthquake history of Eastern Canada. The results have been issued in two volumes, one covering the period 1534-1927, and the other covering the period 1928-1959. The area considered includes northeastern North America and its adjacent waters east of longitude 85°W and bounded by the 40th and 60th parallels. An instrumental magnitude has been assigned to each shock in the later work. In the earlier period an instrumental magnitude was assigned from a study of the probable intensity of the shocks. Epicentral maps and catalogues, and isoseismal maps of six of the largest earthquakes have now been published. A similar summary has been prepared by W.G. Milne of the Observatory for the earthquakes of western Canada. In addition, more recent Canadian earthquakes up to 1963 have been catalogued, and instrumental data for them published by W.G. Milne and W.E.T. Smith. Local earthquake coverage in Canada has now been quantitatively assessed.

A great deal of research into seismicity is underway in Canada. The results have in general been surprising, and in some ways disappointing. For example, W.E.T. Smith has studied the correlation between earthquake epicentres for 1500 or so earthquakes in eastern Canada and known faults in the area. He has demonstrated that earthquakes of eastern Canada are felt to unusually large distances, but no geological explanation for this is forthcoming. Other work has shown that it is not a consequence of abnormal focal depths.

A noticeable feature of the Canadian work is the increase in the number of Arctic earthquakes both recorded and located instrumentally, once the new Arctic standard seismic network was installed. This result was known before a recent series of some 2000 micro-earthquakes was recorded in the spring of 1965 at the Mould Bay seismic station. W.E.T. Smith, W.T. Piché and the author have studied this series, and defined the concentrated volume of energy release at or near the PreCambrian basement, a few km from Mould Bay. The magnitude-frequency occurrence relationship was found to favour the tectonic release of energy, and particle motion and energy studies have been made. The sequence to date is unique in Canada, but it is obvious that future experiments to search for such effects elsewhere along a number of old and previously inactive faults should be carried out.

W.G. Milne has continued his studies of the seismic regionalization of Canada. Extreme value theorem statistics is now being applied to the estimation of earthquake risk in Canada for a proposed revision of the seismic zoning map of Canada, planned for 1967. After various trials with ground amplitude and acceleration which led to great difficulties because of the abnormal distances out to which eastern Canadian earthquakes are felt, W.G. Milne is now using the empirically determined intensity-distance relationships of W.E.T. Smith, and the earthquake catalogues to predict return periods for different intensities and predicted intensities for given intervals.

Meanwhile, interdisciplinary studies of the seismic regionalization of Canada are taking place within the Department of Energy, Mines and Resources. A.C. Hamilton has published a summary of the information on recent tectonic activity in Canada assembled by the appropriate committee members. Although preliminary analysis of geomorphological, tide gauge, releveling and gravity data indicate that post-glacial crustal rebound and tilting has been and is occurring on a regional scale, no way of using this information to supplement seismicity analyses for the regionalization of eastern Canada has yet emerged. Geological evidence of crustal movement prior to the last glaciation has been removed in eastern Canada by the glaciation itself. Despite the lack of practical success in correlating the various geophysical data, the work is continuing and expanded programs are underway for both releveling and geodetic surveying for possible evidence of current horizontal motion in three interesting areas of Canada, across the St. Lawrence River, across Robeson Channel separating Ellesmere Island from Greenland, and across Georgia Strait between Vancouver Island and the mainland of British Columbia.

The principal problems remaining are thus (a) producing a satisfactory explanation for the observed seismicity of the old and large stable block of eastern Canada, (b) elucidating the relationship, if any, to the local geology now that good determinations of hypocentres are possible, and (c) defining the relationship, if any, to the isostatic recovery still occurring in eastern Canada. On the west coast it is clear that the principal feature of the earthquakes is their occurrence in the circum-Pacific belt. However, better determination of focal depth in both regions is necessary; and the abnormal intensity-distance relationship in eastern Canada still defies quantitative explanation.

The increasing refinement of observations of local earthquakes has reached the point where local variations in travel-time curves need more precise determination. The practice, to date, of using an average travel-time curve and applying it to observations throughout Canada is almost certainly inadequate. Consequently, work is underway to delineate more precisely regional differences in travel-time curves.

A rather similar research problem which needs investigation in Canada is the possibility of the occurrence of swarms of small earthquakes in the region of northern British Columbia where there is sound geological evidence for very recent volcanic activity. It is hoped that equipment under development for after-shock studies can be adapted for useful field experiments in this region in the near future.

New methods of examining the mechanism of small local earthquakes are necessary. Most Canadian earthquakes have been too small for the usual methods, involving the distribution of radiation patterns throughout the entire earth, to be of use in elucidating the mechanism.

Although probability theory can be applied to the estimation of seismic risk with some degree of assurance in Canada, the specific predictive problem is completely unsolved. Experience in the more active seismic areas, and recent studies undertaken in Japan and in the U.S.A., suggest that a Canadian program to study the possibility of prediction would require the integration of seismic data, gravity data, information on electrical conductivity, magnetic effects, geodetic observations, observations of tilt, strain observations and observations of stress in Canada. At the present time, although some effort in some of these fields is underway and an attempt has been made to examine the available data from the point of view of seismic regionalization, no large scale new program in the predictive field has yet been either studied or proposed in Canada.

## III. ARRAY SEISMOLOGY

In 1962 the United Kingdom Atomic Energy Authority, in cooperation with the Canadian Department of Energy, Mines and Resources, established at Yellowknife, N.W.T., a medium aperture seismic array for purposes of research and development. Nineteen evenly spaced seismometers are connected in the form of an asymmetrical orthogonal cross, each arm being 22.5 km in length. In addition to the main array, a cluster has been added around one pit. Initially the data from the array was used only by the United Kingdom Atomic Energy Authority group in its research program for the detection and identification of explosions. However, early in 1966, digital processing of the Yellowknife array output became possible in Ottawa using the CDC-3100 computer of the Department of Energy, Mines and Resources, largely in non-prime time. D.H. Weichert, E.B. Manchee and K. Whitham have described both the technical details of the technique used and the results of a number of automatic detection experiments conducted digitally at twice real time speeds. Unit weight delay-and-sum followed by cross correlation was employed for detection, but both linear and non-linear analogue outputs have been reformed and made available automatically. This work followed two earlier Canadian papers describing the array, and analyzing different methods of possible signal processing.

A number of different modes of FM tape output search are possible: a free search mode, and fine-scan digital experiments have been devised. Signal-to-noise ratio improvement has been studied, and the results published on epicentral determination accuracy and the detection probability level of the array for different modes of processing.

Additional work is now in progress on the processing of events with propagation paths in the upper mantle, on the formation of a digital file of selected events, and on signal stacking techniques.

The Department of Energy, Mines and Resources has on order, for delivery during 1967, a 16K word (24 bit) computer, a DDP-124, for Yellowknife Array processing inside the Division of Seismology, thereby avoiding the present difficulties in working in non-prime time through a general computing facility.

To date the Canadian program of research and evaluation of seismic arrays has not contributed appreciably to the question of signal diagnostics, although it is hoped to do so in the future as the research section expands. The feasibility of an automatic bulletin has, however, been demonstrated, and in cooperation with other arrays, it would now be of interest to examine the problem of hypocenter determination made automatically from a small number of array observations. In addition a wealth of optimum-phased seismograms have been computed, which can be used to identify later arrivals and for travel time and amplitude studies. Meanwhile, an intensive effort is going into a determination of travel-time curves inside a distance of $30^{\circ}$. For this purpose the array has the great merit of having great sensitivity, generating signals with a high signal-to-noise ratio, and producing not only travel time information, but also the slopes associated with later arrivals. Using chemical explosions inside Canada, it should be possible to clarify some of the problems involved in seismic wave propagation in the top 200 to 300 km of the mantle, and search for deep reflections at the base of the low velocity layer (about 200 km), at the top of the C layer (about 500 km) and at the base of the C layer (about 950 km).

## IV. EARTHQUAKE MECHANISM STUDIES

Recent Canadian studies have led to objective methods, using a digital computer, of determining nodal planes from the initial directions of P-waves observed at all distances and azimuths from large earthquakes. The program has evolved since 1962. K. Kasahara, A.J. Wickens and J.H. Hodgson have been involved in this continuing research at the Dominion Observatory. Recently, all earthquakes from 1922 to 1962, for which data could be found in the literature, were examined with the final computer program. A.J. Wickens and J.H. Hodgson have assembled a catalogue of these redetermined solutions, which includes a mathematical estimate of their precision. A.E. Stevens and J.H. Hodgson have been conducting a study of the results contained in the catalogue.

A.E. Stevens has continued her work on the use of S-polarization angles to study earthquake mechanism. She has derived a set of algebraic equations which can be used to select between the focal models Type I and Type II for a given earthquake. The results for most earthquakes, published to date and principally in the Aleutian and Kamchatka regions, indicate Type II mechanisms.

While visiting the Observatory in Canada, K. Kasahara also studies focal mechanism by computing the seismograms to be expected for a given deep focus earthquake with a Type I or a Type II source. Comparison of the computed and observed seismograms showed the Type II source to be the better focal model.

J.C. Savage, now at the University of Toronto, has studied the elastic radiation from rupture by using the phase spectrum. He has demonstrated that a sequence of phase jumps, overlooked in previous studies, may suggest that some of the fault length solutions obtained by the directivity method may be in error.

Dislocation theory has been studied at the Universities of Toronto and British Columbia. M. Chinnery continued his theoretical studies of stress changes and displacements accompanying transcurrent faulting and published a series of papers on his results. J.C. Savage and L.M. Hastie have calculated the vertical surface displacement for several earthquakes associated with dip-slip faults. They have compared the observed surface deformation produced by the great Alaskan earthquake of 1964 to the surface deformation calculated from dislocation theory and concluded that a low angle thrust fault best fits the data. This contradicts earlier studies which suggest that the Alaskan shock was associated with a near vertical reverse fault. J.C. Savage and a number of his students are continuing their work on mechanisms, investigating the use of the equivalent force couple as a measure of earthquake magnitude.

A new development in Canada was initiated during 1966 by J.C. Savage of the University of Toronto. He and his students used an array of five geophones on the surface of the Athabaskan glacier and two in bore holes at 60 and 150 metres depth, in an attempt to measure "icequakes". An analysis of this data is underway. Clearly, the experiment models the fundamental dilemma associated with the existence of deep focus earthquakes. It should be most instructive to determine whether "icequakes" can occur at depth inside a glacier where creep is known to occur.

A number of model studies have also been undertaken at Canadian universities on elastic waves generated by internally induced tensile fractures in a glass plate. J.C. Savage and H.S. Hasegawa have published the results of such experiments.

In the earthquake mechanism problem the size of any fracture, the speed of propagation, its orientation, the volume of rock involved and the rate of strain accumulation must be determined. It is clear that present procedures which use the radiation pattern in one manner or another can give only some of this information, and then only under certain severe restrictions regarding earthquake size and the number and distribution of the available observations. Further work on the integration of observations from surface waves is essential.

The work now underway in establishing the validity of the solutions presently in the literature should finally establish unambiguously the major axes of regional tectonic stress. However, the tectonic and physical problems still remain of quantitatively explaining these and the predominance of strike-slip faulting.

In addition, further work is required to investigate the possibility of mechanisms other than faulting, to study the time variations of the focal mechanism, and in particular to study deep focus earthquakes in order to examine whether their mechanism might be in any way different and produced by a phase or volume change. Why earthquakes are confined to the outer 720 km of the earth is still not completely understood.

## V. SURFACE WAVE STUDIES

With the rapid development of the Canadian standard seismic network, it is now possible for surface wave dispersion and attenuation studies to be conducted for a variety of geological provinces and paths. Several years ago Raleigh waves generated by several Russian nuclear explosions were recorded at Canadian seismograph stations, and group and phase velocities to Alert, Mould Bay, Resolute, Ottawa, London and Penticton determined by G.G.R. Buchbinder of the Dominion Observatory. Phase velocities between Alert and Resolute, Mould Bay and Penticton and Mould Bay and Victoria were computed. A crustal model between Alert and Resolute was determined.

Since that time a seismogram digitizer has been developed at the Dominion Observatory for the routine processing of surface waves on photographic seismograms. K. Pec, working at the Dominion Observatory, has published dispersion tables for Love waves propagating in a wedge and in a single layer with a linear gradient of shear velocity. The dispersion equations were deduced from the condition of constructive interference in both cases. The domain of existence of Love waves in a wedge-shaped layer has been discussed. Important effects on the dispersion curves are produced by small angles of inclination ($<5^{\circ}$), but in the possible range of linear gradient of shear wave velocity in the earth's crust, any effects are not marked.

A.J. Wickens and K. Pec have recently developed a package of programs leading towards the routine determination of crust-mantle models from digitized seismograms. The programs are used to determine the degree of contamination of the surface wave trains. The same workers have studied the inverse problem of determining structure from the dispersion curve using a digital technique based, following a first approximation calculation, on the principle of steepest descent. Corrections are applied sequentially to shear velocities and density respectively for the Love waves being studied.

Their first studies with this package of programs have involved the generation of crust-mantle profiles through west central North America along a line from Mould Bay, Canada, to Tucson, Arizona, U.S.A., using Love wave dispersion, and six continuous sections on a near north-south line. They are now testing the solution obtained by the acquisition of reversed surface wave data. The programs are also being applied to produce contour maps of dispersion throughout different areas of Canada. It now appears likely that a major areal analysis should be possible within a comparatively short length of time.

At a number of universities, model studies on surface waves have been undertaken. The attenuation of Raleigh waves to determine whether the mechanism is linear or non-linear has been studied by H.S. Hasegawa and J.C. Savage at the University of British Columbia. N. Thapar of the University of Western Ontario has studied Raleigh wave propagation over a perturbed elastic half-space and across a perturbed boundary between a layer and a half-space. He is conducting experimental checks of the theoretical results on two dimensional seismic models. In addition L. Mansinha at the University of Western Ontario has started a number of studies involving fractures and elastic wave radiation from fractures. The Raleigh into shear wave conversion of the end of a fracture is being studied in two dimensional ultrasonic models.

Now that the computational procedures have been developed, enormous advances in the application of surface waves to Canadian problems should be possible in the immediate future, and the lag of observations behind theory reduced. The investigation of the existence of and velocity limits for a low velocity layer in different tectonic provinces remains one of the most interesting geophysical problems in Canada: the density, distribution and instrumentation of the stations of the standard seismic network allows regional studies to depths of 200 to 300 km. Although there is general agreement concerning the existence of a low velocity layer (at least for S), detailed opinions vary widely and its relationship to tectonic processes is virtually a matter of pure speculation. It is, however, accepted that the top of the low velocity channel is considerably shallower under oceans than under continents.

In the more distant future, it seems quite likely that the instrumental advances outlined earlier will allow the possibility of comparatively inexpensive, temporary, unattended recording seismographs at a number of locations in order to substantiate or further investigate any of the results obtained from the permanent network stations. In particular, more detailed crustal studies may be possible using this technique.

Both data analysis and theory require extension to include presently unexplained surface wave phases, including the so-called mantle guided waves. Q for P- and S-waves needs examination as an indication of the physical state of the mantle.

## VI. STUDIES ON THE CHARACTER OF BODY WAVES

Some fifty years of experimental seismology have been necessary to define travel-time curves for the principal body wave phases. In recent years studies of the slope of travel-time curves, using amplitude variations with distance and studies of attenuation have become very important. It is, however, clear that there is a better understanding of surface waves than of the signal character of body waves at present. This is a consequence of the fact that in body wave work, ray theory has usually been employed.

Recently the Dominion Observatory and the University of British Columbia, in cooperation with the Arctic Institute of North America, has conducted research into the character of body waves. These studies initially arose out of an investigation of the effect of site on the records produced by a seismograph. Over the last three years they have developed considerably in complexity and sophistication, and problems of crustal deconvolution of P-wave signals are now actively being studied in Canada.

M. Ichakawa and P.W. Basham studied P-wave amplitude anomalies, and showed from spectral studies that significant effects could be reproduced by low velocity upper crustal layers. They demonstrated that the different apparent recording abilities of stations could be explained by a combination of shallow crustal effects operating on the signal amplitude and the local noise properties: the properties of the local noise were, however, most important in the straightforward detectability problem.

T. Utsu extended these studies with detailed spectral calculations on P waves recorded at four Canadian Arctic stations, Coppermine, Mould Bay, Resolute and Alert, from Alaskan earthquakes. Both long and short period records were used. He determined crustal models at these stations by best-fit analysis of the vertical to radial horizontal spectral amplitude ratios to theoretical models obtained from the theory of signal reverberation in a horizontally layered system of perfect elasticity.

One surprising feature of the work of Utsu was that crustal models from surface wave studies and from seismic refraction studies did not fit the experimental spectral observations, and that appreciable unexplained transverse signals were found. His work was from photographic seismograms and this limited some aspects of the analysis possible.

During 1964 and 1965 A.M. Bancroft and P.W. Basham among others developed the FM tape recording seismographs mentioned earlier: in 1965 these were used for several months to record teleseisms over flat-lying sediments of central Alberta. Twelve to fifteen teleseisms with unified magnitude greater than 5.5 were recorded at each of three pairs of stations, one station being common to all pairs, namely in the Edmonton (Leduc) vault. The station pairs formed a line approximately perpendicular to the Rocky Mountain front, each successive pair having a greater difference in sedimentary and possible crustal thickness. Velocities in the area are well defined in the sedimentary sequences from oil exploration well-logging work. The experiment could thus be considered as a controlled seismic experiment designed to obtain high quality seismic three-component data over flat sedimentary formations, as well defined in structure and velocity as those anywhere in Canada. Field tapes were converted to a digital file of 40 earthquakes and one nuclear explosion in station pair form.

R.M. Ellis of the University of British Columbia joined P.W. Basham at the Dominion Observatory between March and August 1966 to interpret the digital file. Extensive numerical experiments have been performed both in the frequency and time domains, and with extensive digital filtering to concentrate on the 0.25 - 3 cycles per second passband. They found that the particle motion exhibited marked departures from that predicted by the theory for horizontal layers with both large transverse components and consistent deviations of the calculated azimuth from the true azimuth observed. Vertical to radial horizontal spectral ratio studies have been made and compared with theoretical curves based on independent evidence. They conclude that crustal deconvolution in the sedimentary area does not appear feasible, and the explanation for this is now under study.

The University of British Columbia is planning the use of three portable tape recording seismographs in a study of the effects of the crust on body wave signals received in different geological areas of Canada. Meanwhile, the Dominion Observatory has obtained similar field data within 200 km of the Yellowknife Array, using a tripartite network of tape recording seismographs for a very limited field season. H.S. Hasegawa is about to undertake the analysis of these records, which should lead to an understanding of the possibilities of crustal deconvolution in a shield area.

Similar studies have been made by G. Leblanc with spectral analyses of the short period first arrivals of the April 13, 1963, Peruvian earthquake.

It is obvious that only a beginning has been made on this very fundamental problem. If we are ever to be in a position to compute a theoretical seismogram at any point on the earth for an arbitrary disturbance in a model of any reasonable degree of complexity, with some degree of confidence in the results, it seems that a solution of the inverse problem should be at least partially possible. To do this, research such as that described above is required on the nature of the wave trains. It seems likely that in order to understand the conversion processes taking place in a non-horizontally layered crust, a tripartite network of very closely spaced stations is essential. It should also be clear that such studies could also lead to potentially valuable information on attenuation in the crust, and attenuation in the upper mantle. In this respect they should contribute to the understanding of possible lateral variations regionally within the upper mantle. Finally, it seems clear that such studies should help to elucidate the magnitude anomalies well demonstrated for certain paths from certain events: an example would be the low magnitudes recorded in the interior plateau of British Columbia from the nuclear explosion, Long Shot, in the Aleutian Islands. At the present time the explanation for these anomalies is not known.

Finally, if we are elucidate the time varying mechanism at a focus, we need to apply deconvolution effects for the crust, and corrections for mantle attenuation. It is an interesting observation that with the present state of knowledge, it is not known beyond doubt whether this is feasible from any of the stations of the Canadian standard seismic network. When the experimental and theoretical programs, now underway, are completed, the situation should be much clearer. Meanwhile, R. Yole is examining and compiling all available geological information for each of the Canadian network stations.

## VII. SEISMIC CRUSTAL AND UPPER MANTLE STUDIES USING CHEMICAL EXPLOSIONS

The Upper Mantle Project has probably had its greatest impact on Canadian University programs in seismology in the area of refraction crustal studies. Recently, however, additional considerable interest has developed in deep seismic reflection techniques, and in long range seismic observations from chemical explosions. In the latter work complex travel-time curves are obtained observationally at very long ranges and, from these, structure in the upper mantle to depths of a few hundred kilometers is deduced.

The large expansion in activity mentioned above has led in the recent years to cooperative international and cooperative programs, they are conducting independent and continuing programs of primary interest to themselves.

Increasing equipment sophistication is evident. Many groups record data on FM analogue magnetic tapes in the field, and at least one university (the University of Alberta) has some field digital recording equipment. All universities, however, now have access to analogue to digital conversion facilities. This increasing equipment sophistication has led to, and also been the consequence of, increasing studies on the amplitude of signals, their spectra, studies of particle motion, angles of emergence, and so on. In turn this emphasis on extracting the maximum possible information from the complex field studies has led to theoretical advances particularly on the nature of head waves, calculations of synthetic seismograms, and the study of crustal Q values.

In most of these studies, the integration of the seismic results with the gravity, magnetic and any available heat flow information and with the regional geology has been attempted. The results have largely been most surprising: clear cut correlations are extremely difficult to observe, and as often as not, the topography of the Mohorovicic discontinuity deduced from seismic observations is not in very satisfactory agreement with that deduced from an analysis of the Bouguer anomalies, compensated so far as is possible for crustal effects and using simple density and velocity relationships. Similarly in different tectonic provinces, the crustal models obtained are difficult to relate clearly to the geology. We have examples of the reported existence and non-existence of intermediate layers in the Shield areas and we have examples of a wide variability both regionally and locally in the Moho topography, with a more or less uniform upper mantle P-wave velocity: we have other examples of changes in both crustal thickness and in local upper mantle velocities in the same tectonic province. No clear cut correlation between depth, upper mantle velocity and/or the existence of a basaltic layer is evident in Canadian results summarised in Figure 2. Upper mantle $P_n$ velocities in Shield areas appear higher than earlier believed.

As mentioned above, there has been increasing emphasis on observations at longer ranges in the last year or so, with the hope of obtaining structure at greater depths. We expect high pressure phase transitions in the range from 200 - 600 km. It should be obvious that there are serious problems in this work. Firstly, large and efficient chemical explosions are required to obtain adequate signal to noise, particularly in the many arrivals observed from distances of about 2000 km. In addition this sort of work is best done with observations and shots at locations where the crust is well calibrated by orthodox crustal seismic studies. Finally, it must be emphasized that because of the large penetration depth involved, there is of course a fundamental problem of the lack of resolution in experiments of this kind, no matter how well conducted and recorded.

At the other extreme, increasing interest is being expressed in the possibility of obtaining deep reflections from both the Conrad and the Mohorovičić discontinuities. Using patterns of shots and seismometers in order to optimize the desired signal-to-noise ratio, the University of Alberta has demonstrated, beyond reasonable doubt, that observations of reflections from the Conrad discontinuity can be obtained. The technique is, however, rather expensive for the precise but rather limited information obtained. It appears that future development in this country will almost certainly require a judicious mixture of the long range seismic refraction studies, supplemented in an adequate way by deep reflection studies. In addition, there is increasing evidence that in some parts of the Cordillera and possibly in the Appalachian System, there may be sufficient local variation in upper mantle velocity, over distances of a few hundred kilometers, that it may be almost impossible even in principle to conduct meaningful seismic refraction studies of the mantle. This is because the scale-length of an adequate profile, or a scale-length typical of an areal experiment, may well exceed the length over which the parameter being measured is indeed constant. In this case considerable rethinking of our techniques and our methods of analysis in these areas will be necessary.

The University of Toronto has continued a very active program of regional studies of the crust: as part of this, more than 1000 deep crustal seismic refraction profiles have been compiled in a standard format and organised in summary form for different tectonic units. This information is being kept up to date as an authorized permanent geophysical service.

Before outlining the major programs and activities of recent years, it might be useful to summarise some of the outstanding problems. These are:

(a) the elucidation of interdisciplinary relationships, particularly those with the gravity and magnetic field

(b) the necessity for reconciling seismic crustal observations with crustal models obtained from the shorter period surface waves, for example, or from calculations on the signal character of teleseisms: these different techniques where applicable under certain conditions of uniformity must lead to consistent answers, but, to date, there is nowhere in Canada where it can be demonstrated in a clear cut manner that these different techniques do lead to the same unambiguous result.

(c) the relationship of seismic investigations of the crust to crustal geology certainly needs clarification. It is accepted as a matter beyond debate that measurements of crustal thickness and upper mantle parameters should cast light on the development and evolution of the crust. While not questioning this as a general statement, since regional structure must persist into the upper mantle where there is no isostatic balance, it appears to the author reasonable to question whether the observations of head waves in the top few kilometers of the upper mantle are really leading to a clearer understanding of the major structural blocks. The nature of the Mohorovicic discontinuity is still not known.

(d) the necessity for decreasing the ambiguity in interpretation of crustal seismic data. The Hudson Bay cooperative experiment provides a good example of the fact that there can be considerable differences in solutions obtained by different workers. Any comparison of the crustal structures derived by different authors is made difficult by the varied interpretative techniques used, and by subjective elements in the choice and application of these techniques. The same experiment can be used to demonstrate that the overall design of large scale crustal seismic projects probably needs further thought.

(e) the requirement to measure, understand and use the later arrivals, converted phases and so on, to conduct amplitude studies, and to understand better the nature of head waves. This in turn very often requires more careful attention to seismograph calibration than has been the case in the past.

(f) the requirement to study shear waves in order to obtain the maximum possible physical information on the interior of the earth: it appears likely that observations of shear waves out to different distances may be directly diagnostic of conditions of uniformity, and the attenuation of S waves requires study with that of P.

(g) the data from long range observations must be firmly integrated with shallow seismic data.

(h) the study of the possibility of anisotropic wave propagation.

It should be clear that the author believes that at the present time seismic crustal studies cannot be regarded as a routine surveying procedure, that both the design of field experiments and the methods of interpretation require improvement and that much remains to be achieved in order to understand the tectonic significance of the results more fully.

The remainder of this section will be devoted to a brief account of some of the outstanding programs, both cooperative and otherwise, in which Canadian groups have been involved in the last few years. Further details can be obtained in the reference given in the introduction to this article.


Figure 2. Map showing depth to the Mohorovičić discontinuity and the Pn velocity (km/sec). The symbol C indicates one or more intermediate layers. When no symbol is used no intermediate layer has been reported. When the interpretation changes along a profile, S indicates the simple, and C the complex parts. Reversed profiles end in solid dots; unreversed lines are open-ended. Data for December 1966.

## A. Cooperative Programs

(1) Lake Superior Experiment 1963-1964. In this experiment, the University of Toronto, the University of Alberta, the University of Manitoba, the Dominion Observatory and the Polar Continental Shelf Group cooperated with the American groups in observing two refraction lines fired in the lake.

Mr. Berry and G.F. West of the University of Toronto published a time-term interpretation of the crustal structure from the data of the 1963 project. A very substantial basin was found with a maximum depth of more that 50 km under the eastern side of the lake, and a more normal 35 km thick crust under the western side. Their work has been backed up with theoretical studies of the amplitude of refracted arrivals. R.F. Mereu of the University of Western Ontario has published results from the Lake Superior experiment, and so has A.M. Bancroft of the Dominion Observatory who concentrated on providing a physical explanation for the long range observations of the Lake Superior shots.

(2) Hudson Bay Experiment, 1965. The Hudson Bay region is in the center of a continental shield area and an important location for a comprehensive regional study including a major crustal refraction program.

G.D. Hobson of the Geological Survey of Canada coordinated a major crustal refraction program in 1965 conducted jointly by the Geological Survey of Canada and the Bedford Institute of Oceanography of the Department of Energy, Mines and Resources. Nine university and government crews recorded data at stations on the periphery of Hudson Bay. Stations on shore used conventional long range refraction instruments, while telemetering sonabuoys, developed and maintained by Dalhousie University were monitored by instruments aboard C.S.S. Hudson at a central location in the Bay. Forty-one charges, 1800 or 3600 pounds in size, were detonated electrically on the sea floor. A number of papers are now appearing on the results. It is hoped that these will be published together in a single issue of the Canadian Journal of Earth Sciences, and thus provide a framework for the examination of the crustal seismic method: some indication of the ambiguities may be obtained from an analysis of the differences in interpretation reported by different groups as a consequence of the assumptions used in their interpretation, and the data either used or rejected. One thing, however, is clear. Appreciable undulations in the Moho have been mapped with extremes from perhaps 25 km to 40 km, and the preferred $P_n$ velocity is quite high for a shield area: different groups report values between 8.23 and 8.29 km/sec.

The Hudson Bay shots were recorded widely on the standard seismic network described earlier in this article. K.G. Barr of the Dominion Observatory has attemped to define layering in the mantle to approximately 300 km depth from a study of the seismograms obtained over a range from 500 to more than 3000 km. He discusses in some detail the evidence from this work against a prominent low velocity P layer. These results are the most extensive yet available on long range propagation in Canada and, despite the difficulties in reading the records, represent the most direct deep sounding observations to date in Canada. Doubtless experiments in the future will substantially modify the conclusions which have been drawn, particularly since the analysis to date has necessarily averaged along paths through a variety of tectonic provinces.

(3) Early Rise, 1966. This was an American program of thirty-eight 5-ton shots at a substantially fixed shot point in Lake Superior during July, 1966. The Universities of Alberta, Manitoba, Western Ontario and Toronto took part in the project, each with their own research interests, but supplying first arrival data to a common U.S.A.-Canada pool. Details are availa-elsewhere, but it perhaps should be noted that the University of Alberta, in this experiment, used a digital recording seismometer for the first time. Many of the Canadian groups were primarily interested in time-distance information at comparatively long ranges. Analyses of travel-time curves, cusps, etc., are now underway and it appears that there may be substantial differences on different azimuths from the shot point.

The same shots were used by the University of Toronto at more orthodox distances of less than 600 km in order to study the return to normal thickness of the crust east of Lake Superior.

## B. Independent Programs.

(1) University of Alberta. The University of Alberta (E.R. Kanasewich, G.L. Cumming and students) has determined crustal thicknesses at several locations in western Canada by shooting reversed refraction profiles east and west from Suffield over a distance of 500 km. A three year program has produced a reversed profile from Swift Current, Saskatchewan, to Vulcan, Alberta, with one-way observations beyond the Rocky Mountains. In the plains of southern Alberta and the mountains of south-eastern British Columbia the thickness is about 45 km and in eastern Alberta about 47 km. In western Saskatchewan crustal thickness decreases to 43 km. Upper mantle velocities are close to 8.2 km/sec and there is no evidence for any substantial root under the Rocky Mountains.

Evidence has been reported for three layers in the crust below the sediments: the velocities are 6.1, 6.5 and 7.2 km/sec. Large and rapid changes in the velocity of the crust immediately beneath the sediments could occur.

(2) University of Manitoba. Mapping of crustal structure using head, and refracted waves, as well as wide-angle reflections generated by explosions in lakes, has been completed by D.H. Hall, W.C. Brisbin and Z. Hajnal in the Kenora district of Ontario and the adjacent portions of Manitoba east of Lake Winnepeg, in an area bounded by latitude 49°N and 51°30'N and longitudes 93°W and 96°30'W.

Two boundaries are indicated: one at the top of the mantle and one within the crust, the latter presumably representing the top of the intermediate layer. This boundary varies from 13 km depth at the south of the area to 23 km depth in the trough-like structure in the northern part of the area. The structure of this boundary shows correlation with surface geological and gravity features. The Mohorovicic discontinuity varies from 35 to 40 km depth below the surface.

The project is continuing to the west to span the basin of Lake Winnepeg, Manitoba.

(3) The University of Toronto. Following the earlier cooperative programs in Lake Superior, the University of Toronto (G.F. West) has started its own program on the upper refractor of Lake Superior. To date six intermediate scale seismic refraction profiles have been obtained to study the depth of what are probably Middle Keewenawan sediments. A magnetic survey carried out at the same time is being used to estimate the depths of the Middle Keewenawan volcanics.

(4) Dalhousie University. For the last five years J.E. Blanchard, M.J. Keen and their students have conducted extensive marine refraction profiles along the eastern seaboard of Canada. Refraction lines have been completed parallel to the edge of the continental shelf, at the foot of the continental slope parallel to the continental margin and along the center and flanks of the Appalachian geosyncline. The results obtained have been quite striking: crustal thickness varied from 14 km at the foot of the continental slope to between 40 and 45 km beneath the Gulf of St. Lawrence. Considerable variation in upper mantle wave velocity has been reported, together with considerable local variation in the existence of an intermediate layer. At one time it was believed that a thick crust with an intermediate layer and a high upper mantle wave velocity was associated with the central part of the major geosyncline, but subsequent experiments on the continental shelf suggest the structure is more complicated.

In addition, the same group has made theoretical studies of crustal absorption and synthetic seismograms.

Observations have been conducted over the Sohm abyssal plain. In addition to the deep marine seismic activity reported, the same group has conducted a great deal of both shallow marine seismic work to study sedimentary formations, and sparker surveys.

(5) Bedford Institute of Oceanography. Prior to 1966 BIO personnel cooperated both with Dalhousie University and other branches of the Department of Energy, Mines and Resources in marine seismic programs, but had not conducted independent surveys. In September 1966 the first attempt was made to obtain deep seismic refraction profiles independently in the Baffin Bay area. Results from this experiment are now being reduced.

(6) Geological Survey of Canada. In addition to coordinating the Hudson Bay shoot, the Geological Survey of Canada has conducted reflection and refraction profiles near Flin Flon, Manitoba, to examine whether seismic techniques are able to detect interfaces between PreCambrian rock units. They have reported at least one reflection event at a depth of approximately 15 km, which they identify as the Conrad discontinuity.

(7) Dominion Observatory, including the Polar Continental Shelf Project. Until 1965 the Polar Continental Shelf Project seismic group operated under the scientific direction of the Dominion Observatory, which in addition maintained until 1964 a small crustal group in Ottawa and a small crustal group on the west coast in Victoria. In 1965 the Ottawa groups were re-organized and brought together, with research terms of reference extending throughout all Canada and not restricted to the Arctic. In 1967 the Victoria-based section will also be transferred to Ottawa.

Refraction seismic surveys were conducted during 1962-1965 in the Arctic Islands. An intermediate velocity and an average Moho depth of 38 km, with a reversed $P_n$ velocity of 8.2 km/sec has been reported in a section through the Franklinian geosyncline and the Sverdrup Basin. Further west in the vicinity of Prince Patrick Island an upper mantle wave velocity of approximately 8.2 km/sec has been deduced with an average estimated depth to the Moho in the region of 36 km. At the present time an experiment is planned by K.G. Barr and M.J. Berry for the spring of 1967 northwest from Prince Patrick Island in an attempt to obtain a true Arctic Ocean reversed profile.

On the west coast explosion refraction studies have been conducted by this group. In areas adjacent to Vancouver Island, a most unusual structure has been determined. An intermediate layer with a velocity of about 6.8 km/sec exists in the coastal area. There is some evidence that this layer is considerably more than 40 km thick, perhaps reaching 51 km. The unreversed $P_n$ velocity is 7.7 km/sec.

W.R.H. White, M.M. Bone and W.G. Milne, in a paper in press, have given a preliminary interpretation based on first or second arrival data of seismic refraction surveys conducted by the Dominion Observatory in the interior of British Columbia between 1964 and 1966. A reversed profile along the interior plateau from Quesnel to Merritt with an unreversed extension to the U.S. border shows an undulating mantle crust boundary with an average thickness of 30 km. No intermediate layer has been reported and the upper basement velocity is uniform at 6.1 km/sec. Either a transition from subnormal to normal $P_n$ velocity takes place north of Clinton, or a uniform $P_n$ velocity of 8.0 km/sec is required throughout much of the interior region of British Columbia, with a crust thinning towards the north of the interior plateau, and to the west across the interior ranges and plateaus. The results suggest that the upper mantle low velocity layer must be at shallow depth in central British Columbia.

A large scale crustal project has been completed by K.G. Barr in the Yellowknife area during August 1966. This project was designed to calibrate the Yellowknife Array, to provide crustal time terms of points scattered over an area of 150,000 square miles and to produce a reverse profile 500 miles long through Yellowknife and Uranium City. Ten temporary recording crews were involved, of which two were supplied by the University of Alberta. Seventeen large shots were successfully recorded at most stations. Reduction of the data is now proceeding.

(8) Pacific Naval Laboratory. A.R. Milne has published the results of an unreversed seismic refraction profile conducted at the southern rim of the Canada deep.

## C. Deep Reflection Studies

The University of Alberta between 1964 and 1966 has recorded near vertical incidence deep reflecting events along three different lines in Southern Alberta. Predesigned systems of geophones and shot-hole patterns have been synthesized into an effective filter. Signal processing techniques have been used to enhance the signal-to-noise ratio, and a synthetic seismogram program has been developed and applied to the problem. A strong reflection at 11.6 seconds (the Conrad discontinuity) has been continuously correlated over 30 km, enabling average vertical velocity and depth to be calculated. Structural relief of 9 km and dips over 20$^{\circ}$ have been established over the section. Other reflections are evident suggesting the deeper crust may be too complex for resolution by refraction methods. In addition to seismic reflection, gravity and magnetic results have been obtained to support the interpretation of the existence of a high angle fault in the Conrad. Further work is planned.

## D. Shallow Refraction Work and Reflection Surveys

It is not possible in a report of this type to review the extensive work undertaken both commercially in the study of sedimentary sections for oil exploration or of bedrock conditions for engineering purposes, or for a variety of research purposes by government and university groups. It should, however, be noted that the seismic section of the Geological Survey under G.D. Hobson has been extremely active in this field. The report mentioned in the introduction to this article should be studies for further information on this very valuable work.

# MAGNETISM

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## I. SUMMARY OF PRESENT CANADIAN KNOWLEDGE

### A. Magnetic Surveys

Magnetic surveys and magnetic charts provide basic information for many geophysical investigations, ranging from studies of the fluid motions in the earth's core to the influence of the solar wind on the outer boundaries of the magnetosphere. For the Upper Mantle Project, the anomalies in the geomagnetic field revealed by magnetic surveys are of great importance, because they are a function of the composition, temperature, and structure of the earth's crust, and of the mantle in regions where the depth to the mantle is not too great.

The coverage of Canada by magnetic surveys is probably more complete than that of any other area of comparable size. Figure 1 shows the distribution of some 18,000 observations of the direction and intensity of the geomagnetic field which were used in the construction of the magnetic charts of Canada, epoch 1965.0, by the Dominion Observatory. Most of the measurements were made at altitudes of 6,000 to 15,000 feet using the three-component airborne magnetometer developed by the Dominion Observatory. Twenty percent of the data were supplied by the U.S. Coast and Geodetic Survey, and Project Magnet of the U.S. Naval Oceanographic Office.

The distribution of points on Figure 1 is reasonably uniform and the density, with one point per 700 square miles on the average, is generally satisfactory for the preparation of charts showing the direction and intensity of the geomagnetic field over the whole country. These smoothed charts show the part of the magnetic field due to electric currents flowing deep inside the earth in the liquid core. Much more closely spaced observations are necessary to delineate the anomalies originating in the magnetic part of the crust, which extends to a depth of only 10 to 15 miles.

Of more direct concern in geophysical investigations of the earth's crust and upper mantle are the results from low-level detailed aeromagnetic surveys, similar to those carried out commercially in the search for oil and minerals. Here only the total intensity, and not the direction, of the field is measured,

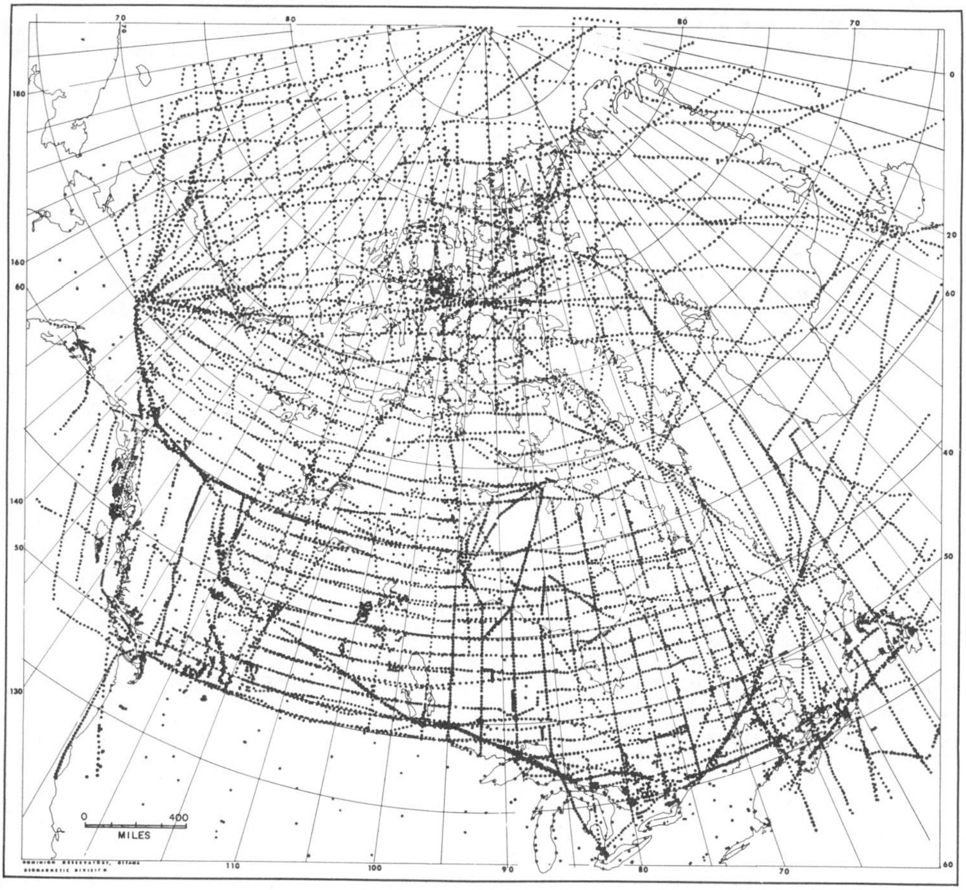

Figure 1. Distribution of magnetic observations used in construction of magnetic charts of Canada, epoch 1965.0.

with the aircraft flying 1,000 feet above the terrain in a pattern of parallel flight lines usually spaced one-half mile apart. The Geological Survey of Canada began flying such surveys and publishing detailed aeromagnetic charts in 1948. The rate of coverage was vastly increased in 1961, with the implementation of agreements between the federal government and the governments of the various provinces to share the costs of four-year contracts under which commercial surveying companies carry out the surveys and prepare the maps for joint government publications. The Geological Survey of Canada is responsible for coordinating this program, and for control of the quality of the work done under contract.

Figure 2 shows the areas which have been covered under the federal-provincial plan as well as work done earlier by the Geological Survey. An idea of the magnitude of this project can be gained from the fact that some 5,000 aeromagnetic map sheets, at a scale of 1:63,360, have been published at this time. There are of course many aeromagnetic surveys financed by industry which are not shown in Figure 2, since their results have not been released for publication. The Figure also shows total intensity surveys made by ship-towed magnetometer in Hudson Bay and in the Grand Banks region. Most of this work was carried out in conjunction with investigations by seismic and gravity methods, and is reported more fully in other sections of the Report.

Many magnetic surveys of more restricted areas have been made by various Canadian university groups. Mention should be made of the total intensity surveys in the Great Lakes carried out by the Great Lakes Institute in connection with their limnological studies.

Extensive total intensity surveys by ship-towed magnetometer have been made by the Bedford Institute of Oceanography. These are reported in Part III. A particularly interesting group of high-sensitivity total field aeromagnetic surveys of a reconnaissance nature have been carried out jointly by the National Aeronautical Establishment of the National Research Council and the Geological Survey of Canada. This work is reported in detail elsewhere in the Report.

## B. Interpretation of Anomalies

The difficulty of studying the short-wavelength magnetic anomalies originating in the earth's crust from widely spaced observations has already been pointed out. However, airborne and ship-towed magnetometers do give continuous information on the magnetic field along the path followed, and much can be learned about the sources of anomalies from isolated magnetic profiles, at least in a statistical sense. Well known methods of determining depths of sources have been extensively applied by the Geological Survey in Hudson Bay and the Arctic Archipelago, and have provided useful estimates of the depth of the basement rock beneath thick sedimentary cover. More sophisticated methods

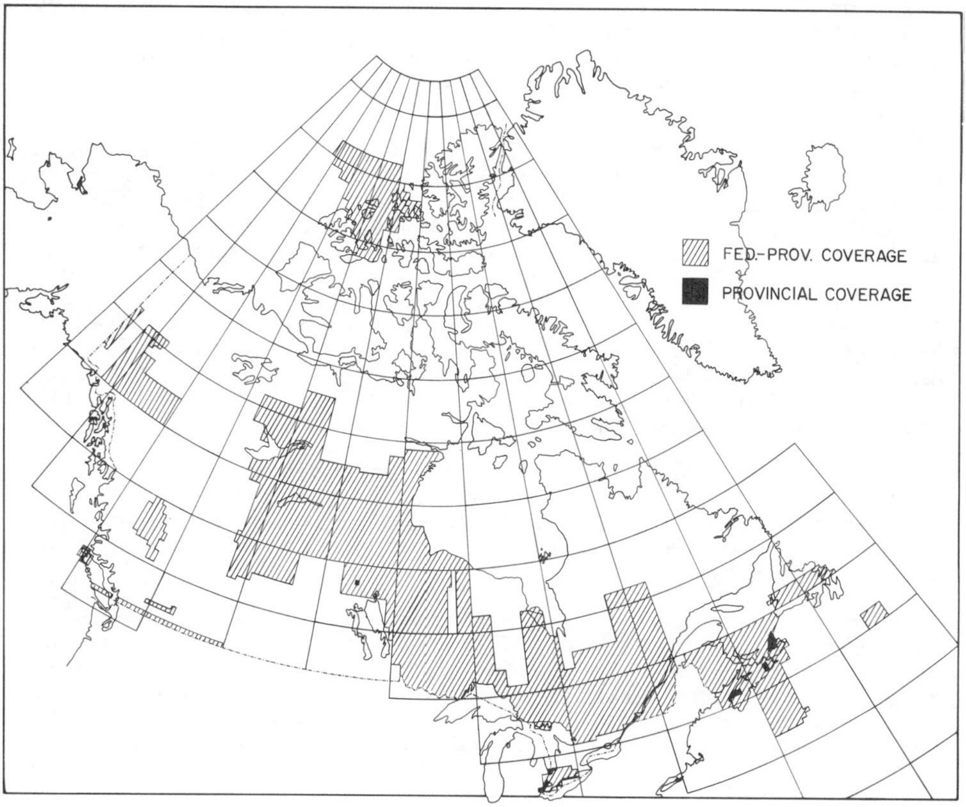


Figure 2. Detailed total-intensity magnetic survey coverage of Canada to December 1966. Spacing of survey lines is generally 1/2 mile, and altitude of observations 1000 feet above terrain.

have been developed at the Dominion Observatory, involving the matching of the statistical properties of observed profiles with models made up of random arrangements of sources. Surprisingly intense magnetization at great depths in the crust is indicated. This statistical approach to magnetic interpretation is being developed further at several universities.

In favourable situations where extended regular patterns of magnetic anomalies exist, as in the case of the anomalies associated with ocean ridges, or the edge of the continental shelf, valuable indications of crustal structure can often be obtained from magnetic profiles 100 miles or more apart. Examples of such interpretations can be found in reports of the National Aeronautical Establishment - Geological Survey project, and in the reports of many marine magnetic surveys.

At the present rate of publication of low-level total intensity aeromagnetic maps, it will be understood that detailed interpretation of such maps is lagging far behind. A useful approach to this problem has been developed by the Geological Survey. Hundreds of map sheets are contoured at coarse intervals (200 gammas), reduced in scale by a factor of 35, and combined to form a composite map covering a large region. Many large-scale features of the geomagnetic field, some extending for hundreds of miles, which were not apparent in the detailed maps, are thus made clear. These features are undoubtably of great interest in studies of the upper mantle.

Of great importance is the development of automatic methods of fitting models to the observed magnetic field, making use of high speed computers. In a method devised at the Geological Survey of Canada, detailed aeromagnetic total intensity charts are digitized on a uniform grid, and the field is expressed as a double Fourier series, which permits easy filtering to remove anomalies due to shallow sources, and a straightforward way of correcting for variations in survey altitude. Selected anomalies are then fitted by rectangular prismatic bodies of the finite depth. The depth to the top and bottom of the bodies, and the intensity and direction of their magnetization are determined in a computer program. The development of techniques such as this should greatly speed the interpretation of the thousands of aeromagnetic charts now becoming available.

## C. Induction Studies

Natural variations in the geomagnetic field considered as a function of time induce electric currents in rocks composing the earth. Because the rocks have a finite electrical resistance, potential differences are produced which can be recorded by placing a pair of electrodes in the ground and connecting a recording voltmeter between them. Alternatively, the induced currents can be studied by observing the magnetic field produced by them, at least in favourable circumstances, where the original magnetic field due to induced underground currents can be separated. Both electrical and magnetic measurements are often combined in a single experiment.

Theoretical models of various underground distributions of electrical conductivity are tested in an attempt to explain the observed magnetic and electric fields. Since electrical conductivity depends on the composition, structure, and temperature of the rocks, such experiments provide a method of studying the properties of the crust and mantle at great depths.

Three prominent anomalies of magnetic induction in Canada have been studied in considerable detail. The first of these is at Alert on Ellesmere Island where the magnetograms display an abnormally high level of irregular magnetic activity and a persistent tendency for the horizontal variation vector to be confined to a single direction. The main features of the anomaly have been explained by postulating the presence of a highly conducting body in the lower part of the crust. The existence of such a conductor seems to imply an upheaval of about 100 km of the 1400°C isotherm to within 25-30 km of the surface.

The second anomaly is located at Mould Bay on Prince Patrick Island. Here the outstanding feature of the magnetograms is the absence of shorter period fluctuations in the vertical component. The presence of a large subterranean conducting body is again postulated to explain the effect. A discussion is given (Whitham, 1965) of all available geophysical data which can be related to structural changes at depth.

In southern British Columbia a series of field observations by the University of British Columbia and the Dominion Observatory have shown that along an east-west profile across the Cordillera from Victoria, British Columbia, to Lethbridge, Alberta, the vertical force variations are consistently smaller at stations west of longitude 118° than they are at stations to the east of this meridian. Similar effects have been observed on east-west profiles farther to the south and it has been found that the western Cordillera region may be generally characterized by small vertical force variations and low seismic Pn velocities while the eastern Cordillera and plains are characterized by higher values of these parameters. The observations suggest that the physical properties of the upper mantle under the eastern and western Cordillera are not the same, and that two broad structural regions may be separated by a narrow transition zone.

## D. Palaeomagnetism

Almost all rocks are magnetic, in the sense that the intensity and direction of magnetization of small specimens can be measured. This fact is important in upper mantle studies, not simply because the magnetic properties of a rock depend on its composition and crystalline structure, but more importantly because the magnetization can reveal much about the history of the particular sample. Many rocks acquire a strong magnetization when they cool from high temperatures, the direction of magnetization indicating the direction of the geomagnetic field which existed at the time when the temperature passed through the Curie point. Sedimentary rocks become magnetized in the direction of the earth's field because the individual particles tend to align their magnetic moments parallel to the field as they are deposited.

Since many rocks acquire their magnetization at the time they were formed, and the direction of the geomagnetic field at a particular location will have gone through great changes during geological time, palaeomagnetic measurements provide a useful technique for dating rocks. Great care must be exercised in drawing conclusions, because there are many ways in which rocks can acquire additional magnetization, often completely masking the original magnetization, at later stages in their history. Methods have been developed for separating such secondary magnetizations from the original, by subjecting the rock samples to high temperatures and artificial magnetic fields, and observing the change in magnetization. In this way, the secondary magnetizations provide a method of studying the history of rocks since their formation, as for example when they have subsequently been heated to temperatures below the Curie point.

Practical applications of palaeomagnetic methods to dating formations in Canada have been very widely made, and can not be listed here. Another application of palaeomagnetism to geological interpretation is the study of deformations of structure which have taken place since the rocks acquired their original magnetization. Such movements may take place about a horizontal axis, changing the dip of a formation, or about a vertical axis, as in the case of the possible rotation of the island of Newfoundland relative to the North American continent. Palaeomagnetic studies have provided the most convincing evidence for the hypothesis of continental drift, and theories of spreading of the ocean floor. Palaeomagnetism is of course a world-wide study, and many of the Canadian measurements are planned as a contribution to international knowledge rather than for the investigation of local problems.

Many studies have been carried out at Canadian universities on the mechanisms of rock magnetism. Details are given in Part III.

## II. SUMMARY OF CURRENT PROBLEMS AND THE DIRECTION OF FUTURE RESEARCH

### A. Magnetic Surveys

The high-level three-component airborne magnetic surveys now cover Canada fairly well, except for British Columbia. A survey of western Alberta, British Columbia and the Pacific continental shelf is planned for the near future, with east-west lines extending several hundred miles over the Pacific Ocean. Because of the great difficulty of determining secular change reliably, large regions of the country will have to be resurveyed, or at least sampled, at intervals of 10 to 15 years.

More interesting for upper mantle studies are plans to conduct three-component surveys with a somewhat closer line-spacing. In 1965, Norway, Sweden, Finland, Denmark and Iceland were surveyed at a 20-mile line-spacing, and preliminary results indicate that this spacing is close enough to delineate large crustal features, with the use of three-component information. It is likely that surveys with line spacing of the order of 10 to 20 miles will be carried out over regions of particular interest in Canada, in the next few years.

The low-level detailed total-intensity surveys will continue until the country is completely covered. The program of the federal and provincial governments does not include areas which have been, or are likely to be, flown commercially, since the aim is to encourage commercial exploration, and not to duplicate it or make it unnecessary. Attention is being given to increasing the quality of data, through the use of temporary stations on the ground recording time variations of the field, and strict control of navigation, particularly over water areas, using Doppler and Decca navigation techniques. There is still great difficulty in carrying out surveys with the necessary accuracy in mountainous regions, in spite of the development of special techniques by the Geological Survey of Canada.

Detailed aeromagnetic surveys will be carried out over Hudson Bay and the continental shelves, including the Arctic, whenever Decca control of navigation can be arranged. Surveys by ship-towed magnetometer will be conducted as a part of most oceanographic studies. The Bedford Institute of Oceanography is developing a technique of using ship-based helicopters to bridge the gap between ship surveys and land surveys, and to permit the more convenient investigation of local features at sea.

Considerable work is being done in the direct measurement of magnetic gradients, by carrying two magnetometers in a single aircraft. The method permits better use of the high sensitivity obtainable with optical-pumping magnetometers, because of the effective cancellation of time variations in the geomagnetic field.

An aeromagnetic surveying technique of great promise has been developed by the Geological Survey of Canada. A proton processing magnetometer is carried by a light aircraft or helicopter, and the proton precession frequency is telemetered to a fixed ground station by frequency modulation radio. The cycling of a second proton magnetometer at the ground station is synchronized with the operation of the airborne instrument, and the difference between the proton precession frequencies is recorded on the ground. The effect of time variations in the geomagnetic field is thus automatically removed from the record. This is of considerable importance in the vicinity of the auroral zone, where magnetic disturbances are large and sudden. There is also a subsidiary advantage in that the magnetometer operator is moved from the aircraft to the ground station, effectively increasing the aircraft performance particularly in mountainous terrain.

## B. Interpretation of Anomalies

It is obvious that at the present rate of acquisition of magnetic survey data in Canada, a breakthrough in methods of interpretation is necessary. Millions of miles of magnetic profiles are available, and within a few years 10,000 map sheets will have been published. The only hope is more effective use of modern high-speed digital computers.

The first step is to have the magnetic data in a form which can be read by computers. Magnetic charts can be, and are being, systematically digitized, with the help of suitable apparatus, but this is obviously a laborious and expensive process, and it inevitably results in some degradation of the data. Digital recording of data in the field is probably the answer, either in the survey vehicle, or at a base station, using telemetry by radio. Digital recording on magnetic tape is already in use by the Dominion Observatory and the National Aeronautical Establishment in their airborne surveys. The Bedford Institute of Oceanography has recorded geophysical data on punched paper tape in their oceanographic surveys for several years.

The first operation in the analysis of magnetic data is usually the removal of a regional magnetic field. This is easily accomplished by computer if the regional field can be expressed as a mathematical function of latitude and longitude. The form of representation used by most Canadian agencies, is a non-orthogonal polynomial of degree not higher than 3, fitted by least squares either to the data under analysis, or to independent survey results. There are strong arguments for the international adoption of a standard reference field, and this may be one of the by-products of the present World Magnetic Survey. The standard field would be defined by an agreed set of spherical harmonic coefficients. Anomaly maps produced by different agencies would then be compatible, and would fit at national boundaries. There are two serious objections to this proposal. One is that the geomagnetic field is not constant, but changes from year to year. Accurate knowledge of the secular change inevitably lags several years behind the accumulation of survey data, and unless secular change is accurately introduced, residual maps for surveys conducted in different years will not fit together in spite of the common reference field. The other objection is that although recent spherical harmonic analyses show remarkably close agreement in the coefficients deduced by different agencies, it has been shown that fields calculated from these coefficients reveal alarming discrepancies over limited regions of the earth's surface. If the adopted reference field has local errors of this type, there is a danger that these will be unquestioningly accepted as anomalies with physical significance. If different groups choose their own reference fields, and the results do not agree, then the possibility of error in interpretation due to the particular choice will be kept in mind.

Assuming that the question of a suitable reference field has been solved, the computer may be programmed to plot the residual or anomaly field in some graphical form. Automatic contouring of data is possible, but has been little used for magnetic maps. It is usually preferred to present the data in a form which allows rapid contouring by an experienced interpreter. Profiles of magnetic residuals can be plotted automatically on maps; this approach is particularly useful where lines are widely separated, as in marine surveys. From the results of three-component airborne surveys, vector diagrams can be plotted automatically, showing the direction and magnitude of the residual field at closely spaced points along the flight lines. Such diagrams are extremely suggestive in the interpretation of anomalies. They are also valuable in drawing attention to errors and inconsistencies in the data.

The most important use of the computer is of course in fitting hypothetical models of magnetized bodies to the observed anomaly field. In general, there is no unique solution to this type of problem, and the success of the procedure depends on the judgement and experience of the man who devises the models. Once the observational data are in the computer, a great variety of models, each with many adjustable parameters, may be tried in a relatively short time. The interpreter is thus given enormously increased power by the computer, but he must decide which of the various models satisfying the observations is the most reasonable, on geological and physical grounds. Here, additional evidence from rock magnetism, gravity, seismic, and electromagnetic induction measurements can be of great assistance.

Increasing attention is being paid in Canada to the study of large-scale features in the magnetic anomaly field. Distinct patterns of highs and lows in the residual field have been found extending for hundreds of miles through the Canadian Shield and out into Hudson Bay. Hudson Bay itself appears as a great circular feature, 500 miles in diameter, with the vertical component depressed by some 70 gammas below the expected value. Similar large-scale circular and linear features have been found in Scandinavia.

Obviously, the source of these anomalies must be sought in the crust. They are still too small in extent to be explained by electric currents flowing at the surface of the liquid core, 2,000 miles deep. They must be due to variations in the magnetization of rocks in the upper 10 to 15 miles of the crust, above the level at which temperatures reach the Curie point.

Models consisting of broad flat bodies of magnetic material, of a horizontal extent much greater than the vertical thickness, tend to predict rather weak anomalies. In order to explain the observed intensity of large-scale features, one must postulate intensities of magnetization one, two, or three orders of magnitude greater than are commonly found in rocks collected at the surface. Moderate increases in intensity of magnetization with increasing temperature have been observed in the laboratory, but it is unlikely that temperature could account for as much as a factor of two. Pressure is quite unlikely to furnish an explanation. It appears possible that accepted ideas about the composition of the crust at depths of 5 to 15 miles beneath the continents will have to be revised as more large-scale magnetic features are studied.

## C. Induction Studies

There has been no difficulty in finding regions of anomalous electromagnetic induction in Canada; two striking anomalies have turned up underneath magnetic observatories. The problem is in producing an explanation in terms of a reasonable model. If one believes Maxwell's equations, such explanations must exist. The experience in Canada has usually been that after the first field season of preliminary observations in the vicinity of an anomaly, possible explanations appear fairly obvious. Then when further magnetic and electric measurements are carried out, the preliminary hypotheses prove untenable, and the more data are collected, the more impossible it becomes to explain the observed facts. A most distressing feature is that, almost invariably, measurements of other geophysical quantities such as heat flow, gravity, seismic velocities, and static magnetic fields fail to reveal the anomalies predicted by the models developed to account for the induction observations. These difficulties are not peculiar to Canada. The Japanese induction anomaly remains unexplained after 10 years of intensive investigation.

It is possible to accept induction anomalies as a fact of nature, without asking why, and to search for correlations with seismic velocities, continental margins, mountain ranges and ocean ridges. This approach is gaining some success, and it may eventually lead to a better understanding of the causes of induction anomalies.

Induction studies in Canada present some special problems. Even on the southern border of the country, it cannot be assumed that the sources of disturbances are a great distance away. Close to the auroral zone, interpretation is greatly complicated by the proximity of strong ionospheric current systems. Inside the polar cap, inducing fields are more uniform, but the pattern of ionospheric currents is not well understood.

Until now, most induction experiments have been conducted with observing stations spread out along a line, perpendicular to the strike of the suspected anomaly, or to its boundary.

If the observing stations could be arranged in a two-dimensional array, a much more powerful approach to interpretation would be possible, particularly where there is a difficulty from non-uniform inducing fields. Such an experiment would require a great many three-component recording magnetometers operating simultaneously, and practical considerations require that the instruments be inexpensive and capable of operating unattended for several weeks at a time.

One program of instrument development to meet this need was begun at the Southwest Center of Advanced Studies in Dallas, Texas, and is being continued at the University of Alberta. It is hoped to have in a year or two 40 three-component photographic variometers which will record unattended for a month on 35 mm film. They are shaped so that they can be buried in post holes to reduce diurnal temperature changes. A method of digitizing the film records is being developed.

Another technique used in Arctic studies is to record the output of three-component fluxgate magnetometers on simple magnetic tape recorders of wide dynamic range. With transistor circuits requiring little power, operation on batteries for several weeks is possible. It is believed that problems of temperature compensation have been overcome.

The interpretation of induction observations requires sophisticated techniques of spectral analysis. Even more elaborate computer programs will have to be developed to carry out analyses over a surface rather than along a profile, and to take into account the complicated source configurations which occur near the auroral zone.

## D. Palaeomagnetism

While palaeomagnetism has always had its share of careful and cautious workers, its reputation as a discipline perhaps suffered in the 1950's, when many enthusiasts maintained that they did not have to worry about the mechanism of rock magnetism, or the various additional magnetizations rocks might have acquired since their formation. If one collected and measured enough samples, the effect of these uncertainties would average out, and unwarranted conclusions could be avoided through the use of elementary statistics. This optimistic approach was valuable, since it provided much evidence for periodic reversals of the geomagnetic field, for polar wandering, and for continental drift, but it is now realized that many of the results and conclusions published during this period were, if not wrong, at least misleading.

The preceding paragraph of course overstates the case, but it is certain that the tendency in palaeomagnetic studies over the last 10 years has been towards greater rigour. Palaeomagnetic measurements which do not include some test of the stability of magnetization are unlikely to be accepted for publication by scientific journals. The statistical treatment of results has

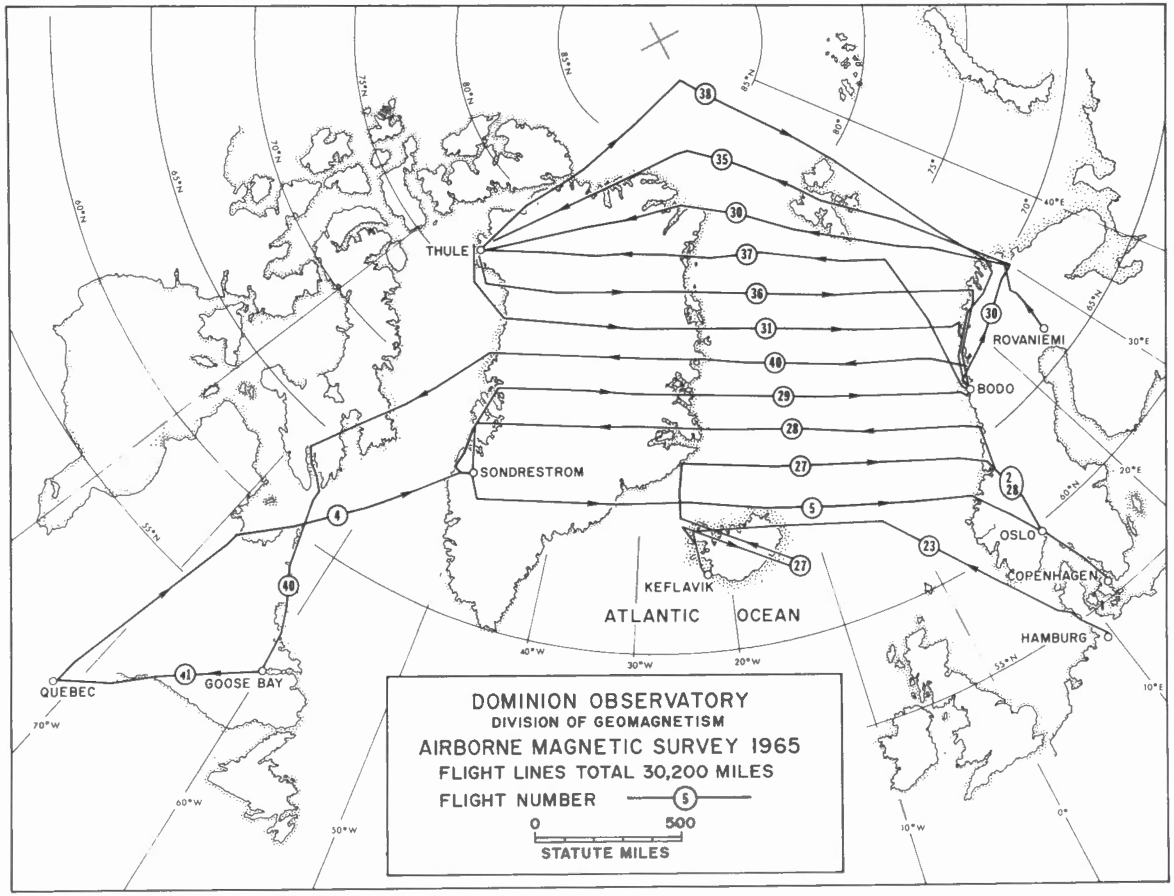


Figure 3. Three-component airborne magnetic survey, 1965, Greenland and North Atlantic Ocean.

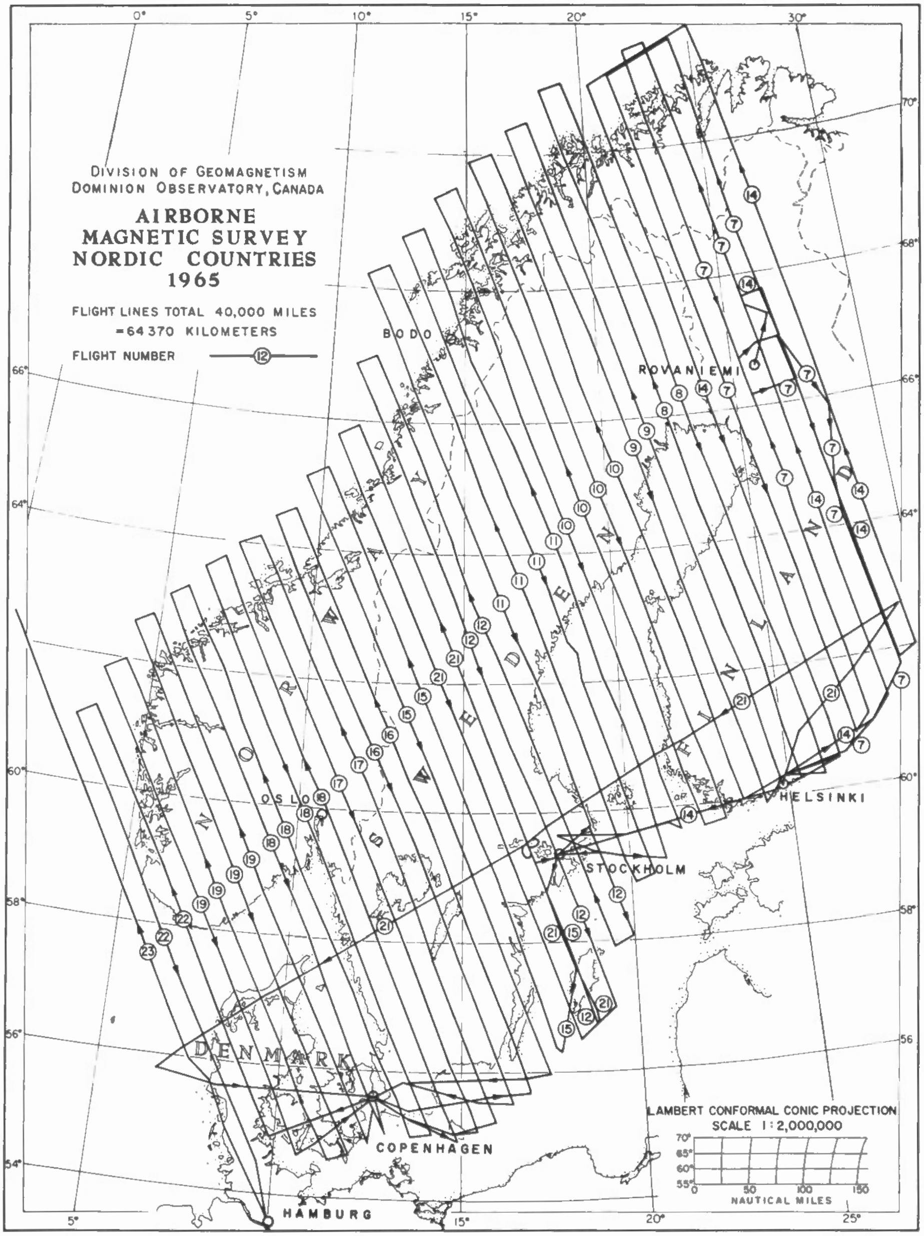


Figure 4. Three-component airborne magnetic survey, 1965, Nordic Countries.

been greatly refined, and techniques are being developed further. There is still much to be learned about the physics and chemistry of rock magnetism, but considerable progress has been made.

In the future, palaeomagnetism will undoubtably continue to make important contributions to such interdisciplinary problems as the spreading of the ocean floors, continental drift, the formation of continents, the bending in plan of such features as mountain ranges, and the rotation of large sections of the continents or ocean floor. The recent astonishingly successful correlation of world-wide reversals of the geomagnetic field as identified by palaeomagnetic measurements of lava flows, with the direction of magnetization of deep sea sediments, and again with the symmetrical pattern of static magnetic anomalies associated with ocean ridges, will be extended backwards in time. There is already evidence that such patterns of reversed and normal magnetization will be found in continents, as in the Canadian Shield. On a still broader time scale, there is evidence that geomagnetic reversals have occurred much more frequently at some intervals of geological history than at others, and that these times of frequent reversal can be correlated with times of activity in continental drift, the rotation of blocks, and mountain building. There is no lack of applications for the sophisticated techniques which are being developed in palaeomagnetism.

## III. SUMMARY OF PROJECTS UNDERWAY IN CANADA

### A. Magnetometer Surveys

(1) The Dominion Observatory in its program of charting the secular variations has selected 103 repeat stations uniformly distributed over Canada for systematic re-occupation at least once every five years. In addition, auxiliary sites which can be occupied if the original station becomes inaccessible will be tied in with each repeat station. During the field seasons 1963 to 1966, observations were obtained at eighty-seven stations and eight auxiliary stations were established.

In 1965, as part of a cooperative program with the Geomagnetic Division of the U.S. Coast and Geodetic Survey, two stations were occupied in Alaska and a comparison of instruments was made at College Magnetic Observatory.

The Observatory's three-component airborne magnetometer survey of November 1963 is shown in Figure 6. Approximately 38,000 line miles were flown over the Canadian Arctic, mostly at an observational altitude of 10,000 feet.

In 1965, the newly rebuilt three-component magnetometer proved very successful during an 84,000 line mile survey of Norway, Sweden, Finland, Denmark, Greenland, the Norwegian Sea, and the Greenland Sea (see Figures 3 and 4). This operation was a joint Canadian-Scandinavian project and included a survey

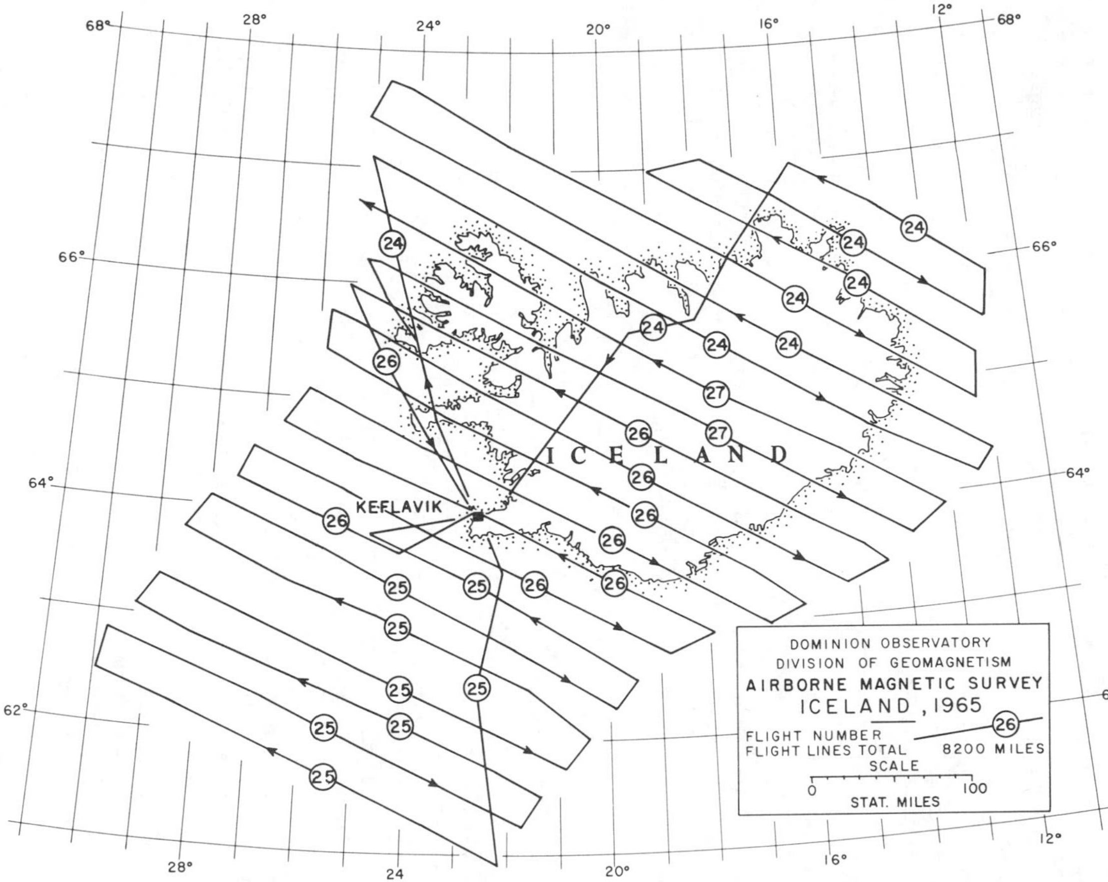


Figure 5. Three-component airborne magnetic survey, 1965, Iceland and Mid-Atlantic Ridge.

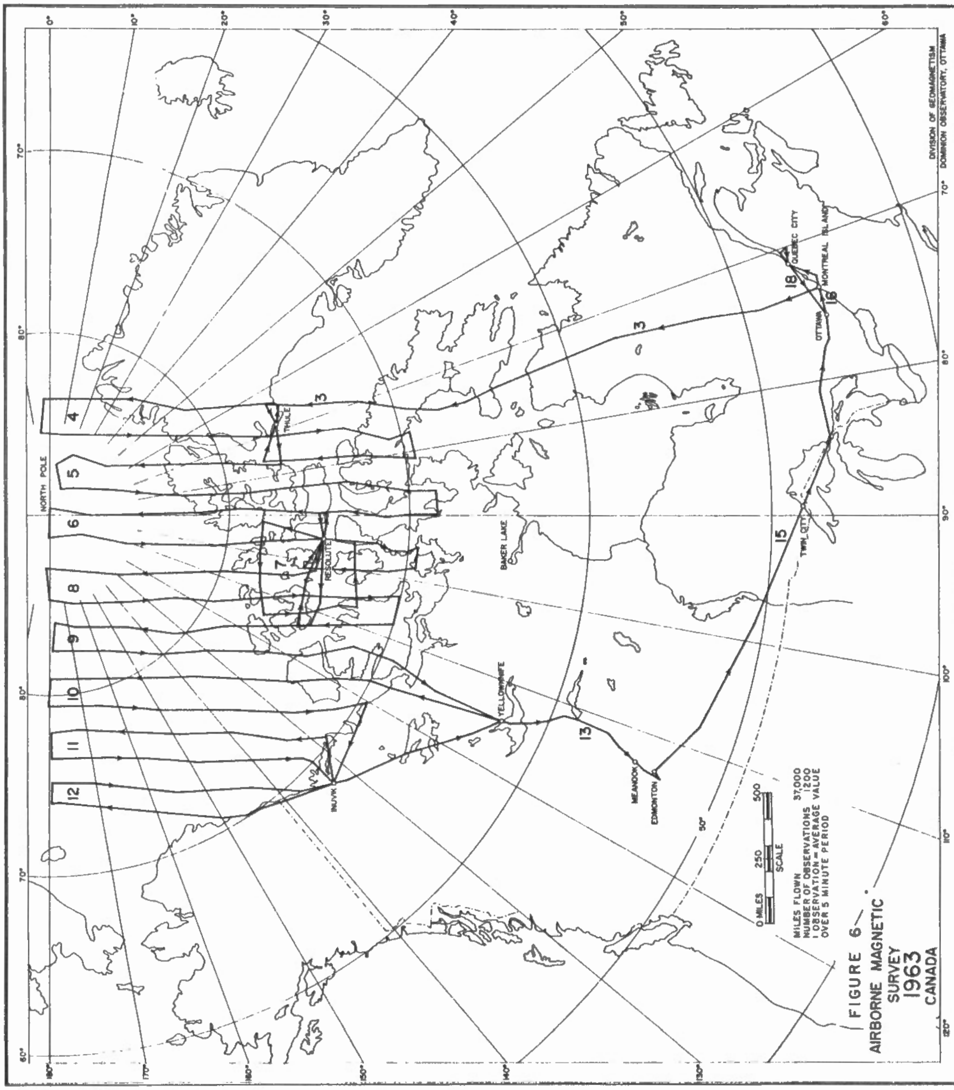


FIGURE 6 — AIRBORNE MAGNETIC SURVEY 1963 CANADA

of Iceland and the Mid-Atlantic Ridge (Figure 5) which extended south to approximately latitude 61°N, joining the northern limits of a similar survey by U.S. Project Magnet. The Observatory published magnetic charts of Canada for the elements D, I, H, Z, F and their isopors for epoch 1965 on a scale of 100 miles to the inch. A magnetic chart of the Canadian Arctic showing the mean daily range of magnetic variation and the areal limitations of the magnetic compass was also published.

A preliminary computer listing has been produced of average values for each 5-minute segment of profile from the Scandinavian and North Atlantic three-component aeromagnetic survey. A computer program has been developed for fitting sections of the survey (Iceland, Scandinavia) to the Taylor expansion of the earth's magnetic field and automatically plotting the residuals along the flight lines.

(2) The Geological Survey of Canada continued its low-level total intensity surveys. The areas now surveyed, including the joint Federal-Provincial projects are shown in Figure 2. 501,900 line-miles have been flown on these surveys in 1965 and 1966.

High sensitivity total intensity reconnaissance surveys were carried out in a cooperative program between the National Aeronautical Establishment of the National Research Council and the Geological Survey of Canada. In 1964 and 1966 areas of the Labrador Sea, Southern Baffin Bay and Davis Strait were covered by a series of flight lines. A survey of central Hudson Bay was carried out in 1965. The area is bounded by the following coordinates 58° 20'N, 89°W; 58° 47'N, 89°W; 58° 58'N, 86°W; and 59° 45'N, 86°W. In 1966 several tracks were flown across the North Atlantic and four lines across the Denmark Strait. Profiles across many of the producing oil fields in Alberta have been obtained.

The Geological Survey is continuing development work on the Overhauser spin-precession magnetometer, including the establishment of a liquid proton sample for use in the coil system which has more permanent atomic properties.

(3) During the period 1964 to 1966 the Bedford Institute of Oceanography surveyed over 74,000 nautical miles. The 1964 work consisted of surveys off the coast of Nova Scotia and in Lancaster Sound. The following year, measurements were obtained over Hudson Bay and its approaches, the Atlantic between 44°N and 47°N, and the Labrador Sea, Davis Strait, Baffin Bay regions. In 1966 the three main areas surveyed were the Grand Banks, the Labrador Sea, including a detailed survey of Ungava Bay, and a section of the Mid-Atlantic Ridge between longitudes 27° 40'W and 27° 20'W and latitudes 48°N and 46°N.

(4) The Institute of Oceanography of Dalhousie University, in 1963, obtained profiles over the southern edge of the Grand Banks, the Labrador Sea and Nares Strait regions. The Marine Science

Branch surveyed the Sheet Harbour - Liscomb area and the Tail of the Banks section of the Grand Banks.

(5) The National Aeronautical Establishment has outfitted a North Star aircraft with two rubidium vapour magnetometers, one is a bird towed some 300 feet from the aircraft and the other is a long tail boom. The output from the magnetometers is recorded in both analogue and digital form. The first vertical derivative of the earth's magnetic field is thus measured directly.

The three component airborne magnetometer of the Dominion Observatory was completely rebuilt. In the new version three component fluxgates are servo driven in azimuth to produce D information while H and Z are nulled within a pair of Fanselau coils. The detector-coil assembly is mechanically linked to a new smaller stabilized platform using the improved Honeywell MIG gyros. The data output is recorded on digital magnetic tape.

## B. Interpretation of Anomalies

The general problem of determining the depth of near-surface magnetic sources which contribute to the magnetic anomaly spectrum has been analysed at the Dominion Observatory in terms of crossings per unit interval. Assuming random distribution of either magnetic poles or magnetic dipoles aligned in any of three orthogonal directions, explicit functions have been derived expressing the crossing per unit interval directly in terms of either the depth to a thin layer or depth to the top of a thick layer.

The double Fourier series expression of aeromagnetic data over an area has been evaluated by the Geological Survey and found to be very accurate and convenient for determing the derivatives of the total magnetic field, components of the total field, and upward and downward continuation of the field. The method was tested for various theoretical models and was used to study individual isolated anomalies.

New methods utilizing the characteristics of the independent components of the total field caused by uniformly magnetized rectangular prisms with arbitrary polarization have been developed by the Geological Survey for calculating dimensions, depths to top and bottom, and intensity and direction of polarization of the bodies. This method was applied to a large surveyed area in Northern Ontario in order to calculate these parameters for deep crustal anomalies. The total field data had first to be stripped of the near-surface, high amplitude components by special filtering techniques. The results were surprisingly consistent, yielding roughly westerly dipping polarization vectors.

The possibility of using power spectral information for determining the dimensions of the bodies causing magnetic anomalies had been studied by the Geological Survey.

Theoretical investigations were carried out of the first vertical derivatives of the magnetic anomalies associated with various theoretical models.

Research is also in progress to develop new methods for calculating amplitude and phase spectrum of two dimensional aeromagnetic anomalies.

An aeromagnetic-geological study of the Churchill-Superior boundary was carried out. This study suggests a relocation of the boundary to an eastward trend north of 56°N latitude.

In a multi-disciplined field project on the Moose River magnetic anomaly, gravity, magnetic susceptibility and remanent magnetic measurements were made. It is considered that a major zone of dislocation occurs along the anomaly.

Over 1,200 one-mile aeromagnetic maps surrounding Hudson Bay were contoured at 200 gamma intervals and interpreted on a scale of 35 miles to the inch. This work forms part of the Centennial Volume on Hudson Bay. The area of interpretation is being extended to eastern Alberta and to the northwest of Great Slave Lake. Its value is in tectonic analysis using both geological and aeromagnetic data over a broad area.

Quantitative interpretation of the available aeromagnetic data over the Canadian Arctic Archipelago will be finished by the end of this year. A residual total field map and two maps continued downward to depths of one-half and one mile respectively from the level of the flight elevation have been prepared. With the help of these maps it has been possible to calculate the depth to the basement, the Curie-point geotherm and the polarization vectors associated with the causative bodies. These maps have also proved to be very effective in delineating regional and local geological structures.

The cooperative program of the Geological Survey of Canada and the National Aeronautical Establishment of the National Research Council has published interpretations of the surveys carried out over the Labrador Sea, Ungava Bay and Hudson Bay. The advantages of vertical gradient measurements have also been studied and reported. The preliminary interpretation of the recent work over the North Atlantic and Alberta has been completed.

A study of the crustal magnetic anomalies in the western portion of the Superior province of the Canadian Shield is being carried out by the University of Manitoba. The magnetic susceptibility and remanence of surface specimens have been measured and various methods of interpretation applied to the aeromagnetic maps.

The Bedford Institute of Oceanography has published the interpretation of the magnetic survey of Lancaster Sound. Interpretations of the magnetics over areas of Hudson Bay, Ungava

Bay, Baffin Bay and the Grand Banks were included in more comprehensive oceanographic papers and reports of the Institute. Analyses of the results from the North Atlantic an in particular a section of the Mid-Atlantic Ridge have been completed.

C. Induction Studies

The Dominion Observatory has published several papers on the magnetic variation anomaly at Alert, N.W.T. These papers describe the results of the field programs, discuss the theoretical limitations, and comment on the geophysical significance of the anomaly. The magneto-telluric results, though confirming the exceptionally high electrical conductivity, conflict in other areas of interpretation. Additional field work to determine the areal extent and tectonic implications of the anomaly is in progress.

The suppression of shorter period magnetic variations at Mould Bay, N.W.T. has been studied both theoretically and by several field programs. The induction of an arbitrary magnetic source over a low dipping inclined plane has been examined and applied to the experimental data. Results indicate the presence of a thin (5 to 10km) highly conductive layer at shallow depths (20-30km) in the Mould Bay vicinity, whereas at Resolute Bay, 700km distant, the layer is four or five times as deep. Parkinson induction vectors have been computed to provide information on the location and nature of the boundaries of the anomaly. Magneto-telluric measurements have been made at Meanook Observatory and at Leduc, Alberta and Penticton, B.C. The method of Price for treating non-uniform inducing fields has been used in the analysis and the theory extended to enable the computation of master curves for any number of horizontal layers.

During the summer of 1964 magneto-telluric experiments were conducted at Oka and Richmond, Quebec, where fairly large positive gravity anomalies are known to exist. Preliminary examination of the records indicates that no appreciable magnetic variation anomaly exists.

Magneto-telluric measurements have been made on either side of the Gloucester fault near Ottawa, at a distance of about 8 miles from the feature. At both stations the electric field shows a strong tendancy for polarization, while the effect is less marked in the magnetic field. Further field work and analysis are in progress.

Six locations were occupied during the 1966 summer field program in a line from St. John's, Newfoundland to Goose Bay, Labrador. The data are being analysed to see if there is prominent 'ocean effect' associated with the proposed magnetic observatory site at St. John's. The effect of the different crustal structures between the Grenville region and younger tectonic areas is also being investigated.

Work is continuing on the interpretation of the Victoria short period anomaly. The effects of coastlines have been ruled out as an explanation for the anomalously high Z fluctuations at very short periods. Parkinson plots are being compared with other geophysical and geological information in order to establish possible correlation in strike direction.

A joint project of the Dominion Observatory and the Department of Geophysics, University of British Columbia is in progress to investigate the correlation of the inland geomagnetic variation anomalies in Western North America with seismic low Pn velocities.

Some problems in electromagnetic induction have been investigated theoretically at the Pacific Naval Laboratory in an attempt to determine the effect of geological environment on the micropulsation measurements taken by the P.N.L. group. The effect of coastline was studied considering the earth as a flat semi-infinite conductor divided into two regions of different conductivities by a plane normal to its surface. The theoretical results agreed well with measurements obtained at Victoria, B.C., and Dartmouth, N.S., on the coast, Ralston, Alberta 750km inland, and Sable Island 170km out to sea.

The theory of electromagnetic induction in a two layered earth has been developed for a general inducing field varying periodically in time. Particular attention has been given to the solutions for the magnetic field components in the top layer, in order to determine the shielding effects of sea-water on external geomagnetic variations.

Five component magneto-telluric data were recorded by a University of Alberta field party at eight locations, 30km spacing, along a N-S line crossing the north German conductivity anomaly. Analysis indicated that a considerable portion of the anomaly may be due to a basin of unusually conductive sediments.

Magneto-telluric data have been obtained from ten stations in a traverse about 200km long in southern Alberta in conjunction with a seismic survey.

Similar data obtained in southern Alberta were analysed and at two stations, Brooks and Beiseker, the data showed a very resistive crust and upper mantle with a decrease in resistivity of about two orders of magnitude near 80km. At the third station, Vulcan, which is closest to the Rocky Mountains the decrease in resistivity occurs at a depth of only 35km.

Recordings have also been obtained at the University's observatory site, approximately 30 miles south of Edmonton. These were taken simultaneously with the field data, and a comparison of the data from these stations provided information on the extent and morphology of the sources.

Theoretical studies of conductivity analysis are being carried out and specific results on the solution for a continuously variable conductivity distribution have been obtained.

A cooperative program with the Southwest Centre of Advances Studies, Dallas, Texas is in progress. A three component portable variometer has been designed and tested along an east-west line across Colorado. A northward continuation of the anomaly discovered by Schmucker in New Mexico has been located near Solida, just west of the Rock Mountain Front.

At the University of British Columbia a new method has been developed to determine the electrical conductivity of the sub-surface regions of the earth using natural telluric and magnetic disturbances. The method is free of the assumptions in other methods that an inducing field is uniform in space (the magneto-telluric method) or is derivable from a scalar potential function (the magnetic method).

Recordings of the geomagnetic components have been made for several field seasons along two east-west profiles. One profile runs through New Mexico and across the Texas panhandle into Oklahoma, at latitude 35°N. The second profile crosses British Columbia and the Rocky Mountains at latitude 51°N. Both profiles intersect the transition zone between the region of normal amplitude variations in the vertical component and the region of attenuated vertical component variations. Considered in conjunction with earlier profiles of Schmucker and Hyndman, at latitude 32.5°N and 49.5°N respectively, the project showed that the attenuated vertical component regions are indeed part of a large scale structure covering western North America.

The University of Toronto extended the line of temporary magnetic variation recording stations into Southern Quebec. No anomalous effects were observed in the profile between London, Ontario and Sherbrooke, Quebec.

The program of magnetic variation measurements in Iceland, started in 1964, was extended during the summer of 1965. Measurements were made at six stations on a line across the island. These observations together with observatory records for the north Atlantic area, have been digitized and spectral analyses and correlation studies made. There is no reversal of sign of any component across the central rift area and in fact, consistent variation in amplitude must be very small.

In order to facilitate the correction for coastline effect, measurements have been made on a scale model of Iceland, surrounded by a conducting ocean and underlain by a conducting mantle. The variations in each component of the field, for different source configurations and frequencies, have been contoured over the island. It appears from these results that the coastline effect will not seriously disturb the measurements at stations in the interior of Iceland.

At the University of Victoria the effect of geological structure on micropulsations for a plane wave field was investigated using both mathematical and analog methods. The mathematical model assuming homogeneous conducting layers was extended to describe to a good approximation inhomogeneous layers with the conductivity varying as a function of depth. The results indicate that amplitudes and phases of the varying electromagnetic field components are strongly affected by inhomogeneity of the conducting medium.

A plane-wave analog model for studying the effect various geological structures have on natural electromagnetic variations observed at the surface of the earth has been constructed. Measurements of both horizontal and vertical field components have been made for sloping model earth-sea boundaries, vertical faults and dykes, seamounts, cylindrical and ring structures, and sloping and horizontal conducting layers.

The University of McGill has obtained magneto-telluric measurements over the ultrabasic rocks of Thetford Mines, Quebec. Natural telluric signals in the range 0.5 to 0.005/sec are being studied, including the vertical component. Man-made micropulsations have been investigated using telluric as well as magnetic data.

Single frequency, 8 c/s magneto-telluric measurements are currently being carried out by the Geological Survey of Canada in collaboration with McGill University. These measurements are dedicated to the mapping of near surface geological features. Preliminary measurements in the Ottawa area and in Bartouille Township, Quebec, have been quite successful.

At the Bedford Institute of Oceanography, impedance relations for non-uniform conductors with plane and spherical boundaries have been derived and show the similarity between the magnetic scalar potential method and the magneto-telluric method. The impedance relations for plane layers are presented in such a form that they can be used for any number of different conductivity layers inside the earth. A method of interpretation of magneto-telluric data, when the source field is considered has been suggested in which the vertical magnetic component is included with the horizontal ones.

## D. Palaeomagnetism

The Geological Survey of Canada has studied a collection of samples from the Muskox layered intrusion to determine the age relationship between the various intrusions and their cooling history. Results from Precambrian to Mesozoic rocks from Newfoundland and the adjacent coast of Labrador and from New Brunswick, Prince Edward Island and Gaspé have been published. Pole positions for samples of Cretacious age from Ellef Ringnes

Island have been determined. A collection of later Triassic to Quaternary rocks from the Yukon have yielded additional pole positions for that period. A Precambrian group from Victoria Island, N.W.T. has been studied. Remanent magnetism measurements were made on some 500 diabase dyke oriented samples and the data indicate that some dyke swarms may be identified on the basis of their palaeomagnetism. Detailed studies have been completed on additional samples of the dykes from the Noranda-Val D'Or and Sudbury regions. A well substantiated pole position has been obtained from the Triassic rocks of the Manicouagan area. Another Triassic pole was derived from a 100 km long diabase dyke in southern Nova Scotia. Samples of weakly magnetized sedimentary rocks from southern Ontario were measured and so far found inadequate for palaeomagnetic studies. An investigation of the magnetic properties of sulphides is in progress. A study of the magnetization of potsherds from southwestern Ontario has shown that the earth's field intensity varied in this area, during the past 5,000 years, in approximately the same manner as in Europe and in Japan. A detailed magnetic and geological survey of the Kapiko Iron range was undertaken. Vertical force magnetic measurements on a close grid and in situ susceptibility results were obtained as well as samples for remanent measurements. The results of these surveys were compared with detailed geological mapping.

Results from upper Palaeozoic red sandstones from Prince Edward Island have been published by the Dominion Observatory. Samples of weakly magnetized Ordovician limestone from southeastern Ontario have been measured. In cooperation with the Lamont Geological Observatory a study has been made of the palaeomagnetism of Silurian strata in the Appalachians. Rocks from the supposed meteorite crater at Manicouagan have yielded early Mesozoic magnetization directions. A study of the magnetic properties of Carboniferous and Permian rocks from the Maritimes and the Gaspé has been published. Additional work on Carboniferous and Devonian rock from the Maritimes is in progress.

The University of Western Ontario has studied basaltic intrusive formations from the Superior and Grenville provinces of Ontario. Several radiometric dates have been obtained from these units. Oriented samples from the Triassic North Mountain basalt of Nova Scotia give a high precision palaeomagnetic pole which differs slightly but significantly from other late Triassic poles of North America. This volcanic section is thin and probably represents less time than the period of secular variation. Lava flows and sills of basaltic composition from the Lake Superior Region have been studied. All of these units are believed to be in the age range of $1.1 \pm 0.1 \times 10^9$ years. The presence of reversals of magnetic polarity in the sequences of Keweenawan lavas will be an aid in correlating these units from one area to another. A suite of varvites from the Huronian sequence near Iron Bridge, Ontario are being studied to test if Precambrian glaciations were confined to near-polar regions: A collection of Jurassic, Cretaceous and Tertiary rocks were obtained on a research trip to Chile and Peru.

The positive aeromagnetic anomaly associated with the Port Caldwell syenite intrusive at Marathon, Ontario has been studied using remanent magnetic data from oriented samples, vertical and horizontal ground magnetometer traverses, and aeromagnetic data measured at several heights. Computer calculated anomalies were compared with measured ratios to select a probable source.

A study of the composition of magnetite-ulvospinel exsolved and unexsolved crystals from Indian Basalts has been made using X-ray, Curie temperature and electron probe methods. It has been shown that in exsolved systems the various methods may give discordant results.

A study of the correlation between palaeomagnetic field intervals and rapid changes in the number of biological species has been made.

At the University of Toronto a dual astatic magnetometer system and a non-magnetic press have been built in order to study the effects of stress on rock magnetizations. Provision has been made for the addition of a furnace so that the acquisition of thermal remanent magnetism under pressure can also be studied. A careful study of the Neel theory for mono-grains has been completed, with the object of making quantitative comparisons between its predictions and the properties of ultra-fine-grained samples. A method of deducing the samples grain distribution function from experimental data has been devised and applied to the experimental work published by Everitt.

Magnetic susceptibility and remanent magnetization over two areas, Texada Island, B.C. and three townships near Vermillion Bay, Ontario were measured by the research group at the University of Manitoba. Contour maps of the physical properties were prepared and interpreted in relation to the aeromagnetic field and associated petrographic and geochemical studies. A study of the regional distribution of magnetization in the Archaean province of the Canadian Shield from the magnetic properties of the rocks and magnetic anomalies has been completed. The area lies between latitude 48° 45' and 50° 00'N and longitudes 93° 30' and 95° 00'W. There are three greenstone belts separated by areas of granite and gneiss in the area. Similar work has extended the area to the north and west.

The Memorial University of Newfoundland has studied oriented samples collected from lower Palaeozoic formations on the island of Newfoundland and in southeastern Labrador. Similar samples were obtained on a reconnaissance scale, in Mayo and Donegal counties of Ireland to test the palaeomagnetic correlation, if any, between rock formations in Ireland and Newfoundland. Some rock samples have been obtained from two shoals in the Virgin Rocks area of the Grand Banks 130 miles southeast of St. John's. The rock samples were oriented <u>in situ</u> and recovered by divers.

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# GRAVITY, GEODESY, TIDES AND RECENT MOVEMENTS OF THE EARTH'S CRUST

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This report summarizes the results of Canadian investigations of the earth's gravitational field which have aided geologists and geophysicists in their study of the upper mantle and lower crust. Part I below is a brief resumé of past achievements and future goals while Parts II to V give brief descriptions of current studies at Canadian institutions.

## I. PRESENT KNOWLEDGE AND DIRECTION OF FUTURE RESEARCH

### A. Measurements

Much of the Canadian effort to date has been concerned with outlining the general gravity field over Canada and its coastal waters using gravimeters and pendulums. The Dominion Observatory has been responsible for most of this regional study but universities and provincial agencies have made specific contributions in particular areas.

Prior to 1945 measurements were restricted to road surveys and pendulum measurements at isolated points. From 1945 to the late 1950's aircraft were used to map much of the Precambrian Shield at a density of one station every 20 to 30 miles. In 1958 a comprehensive gravity mapping program was initiated by the Observatory to investigate specific anomalies in greater detail. During the past eight years helicopter-supported parties have been sent to the field yearly. Progress with the regional gravity mapping (Figure 1) has been excellent and an area of approximately two million square miles, in which the observations are located at intervals of about eight miles, has been covered. The Observatory, university groups and provincial research organizations have also conducted numerous detailed gravity investigations of geological structures.

Underwater and surface gravity measurements have been made in the last five years off the Atlantic and Pacific coasts by the Bedford Institute of Oceanography and the Dominion Observatory. Measurements on the Arctic ice pack have been part of the Observatory's program since 1960.

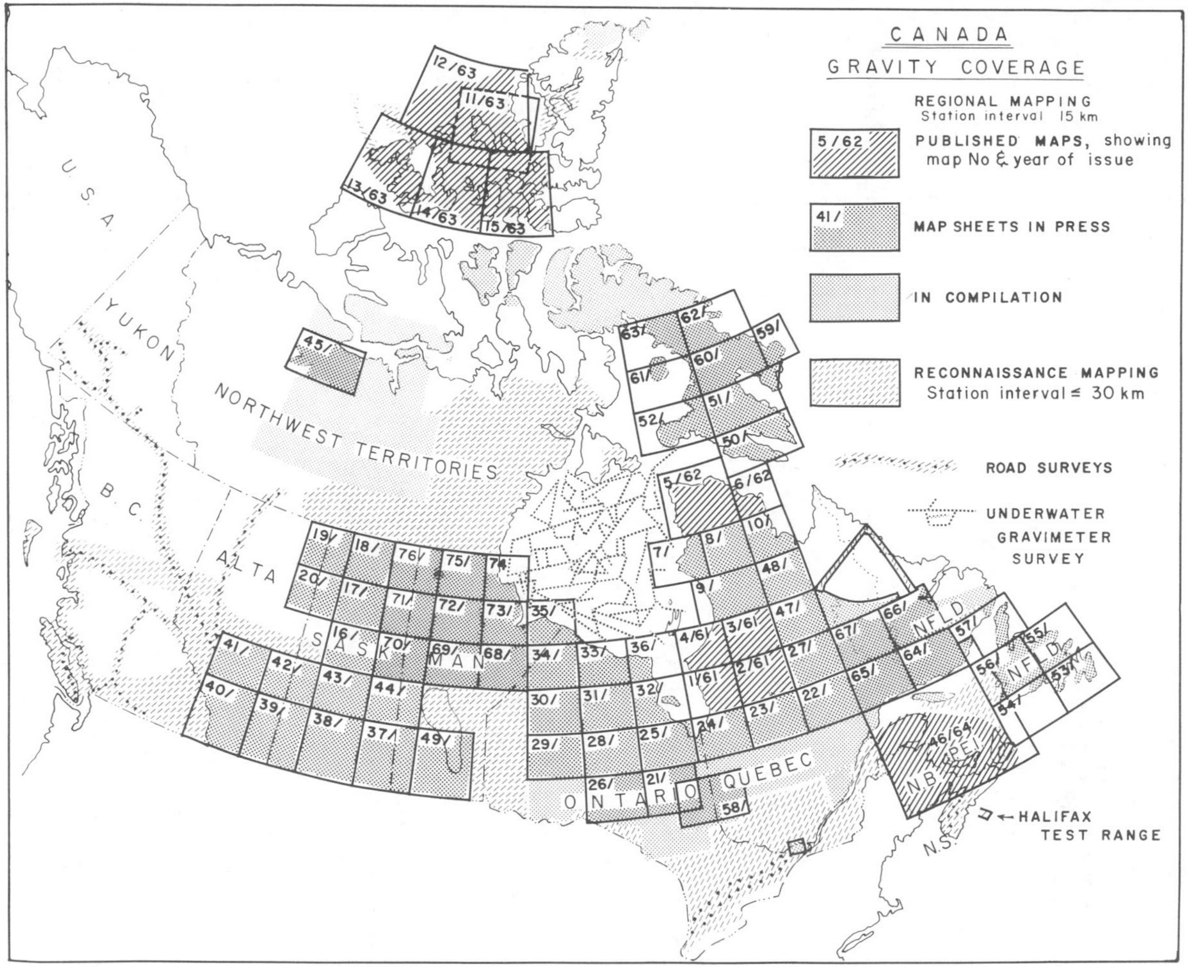


Figure 1. Summary of the regional gravity mapping program of the Dominion Observatory.

Precise relative gravity measurements have been made in the vicinity of several dam sites. These observations, which have been made at bench marks and other relocatable points, will be repeated at five to ten year intervals and will be used to study the long term behaviour of the earth's crust due to crustal loading.

Approximately five or ten years work will be necessary to complete the regional mapping program. This basic coverage is essential to guide future, more detailed investigations with gravimeters and will also be important for locating experiments using instruments other than gravimeters. Much of the remaining regional work is in the Cordillera and other areas of mountainous terrain. Detailed elevation information must be collected in order to calculate terrain corrections for the gravity stations in these areas and special procedures are now being developed.

Recently the Dominion Observatory, Dalhousie University and the University of British Columbia have acquired instrumentation to measure earth tides. It is hoped that these measurements, when conducted at several locations across the country, will aid in the study of the deformation of the crust due to loading by ocean tides, moving atmospheric masses, and tectonic stresses.

## B. Computers

Since 1960 much of the reduction and analysis of gravity data has been done using computers. At the Dominion Observatory an extensive library of computer programs has been developed for many aspects of gravity work. At present these programs, as well as the observed data, are being incorporated into a magnetic tape library with which the computer will carry out many of the steps necessary to process and interpret the data without the necessity of intermediate output. The preparation of maps, including contouring, will be done on a plotter. Several programs for handling data and for the interpretation of gravity anomalies have also been developed by the universities. These programs have greatly reduced the time required for quantitative interpretation of the data.

## C. Interpretations

Crustal studies using gravity were begun in Canada at the Dominion Observatory in the late 1940's. Early work was concentrated on the preparation of cross sections along road traverses in eastern Canada, northern Ontario and British Columbia. Isostatic studies made over these profiles suggest that the southern portions of the Canadian Shield are overcompensated while the Canadian Cordillera is close to isostatic equilibrium. The earlier workers discovered several major gravity anomalies which they interpreted in terms of deep crustal structure, for example, the Kapuskasing high in Ontario, the

Nelson River high in Manitoba, and the New Ross low in Nova Scotia. Geological mapping and additional geophysical studies have added greatly to the knowledge of the structures causing these anomalies.

The regional mapping program of the Dominion Observatory has revealed other anomalies of interest to scientists studying the upper mantle. Publication of gravity maps and interpretation of the new gravity data in terms of geological and crustal structure are proceeding. Perhaps the most important problem in interpreting the data is the explanation of regional variations of the gravitational field which are important in the study of crustal and upper mantle structure. For example, as mentioned above, the gravitational field over the Canadian Shield has a smaller magnitude than is predicted by the theory of isostasy. Although some explanations have been presented, no generally accepted hypothesis has been put forth. This problem has been complicated by the results of recent crustal seismic experiments which often indicate that the crust is abnormally thick in areas of relatively positive Bouguer anomaly and thinner than average in areas of relatively negative anomaly. In the Hudson Bay region the seismic and gravity observations can only be reconciled by postulating lateral variations of density and/or velocity in the crust, and/or the upper mantle.

Detailed gravity studies conducted over many ultrabasic bodies in Canada support deep origins for some of the bodies (the Mount Albert Intrusion, the Monteregian Hills, Muskox Intrusion). Further work is required over many of these bodies and similar structures in the Shield.

Geodetic applications of gravity data were carried out intermittently during the 1950's and early 1960's. In the last few years the Observatory has begun a detailed study of geodetic problems. A series of computer programs has been developed to determine the geoid regionally in Canada from gravity field. Variation in the geoid can be important in determining mass variations in the mantle and the elastic properties of the crust and mantle.

## II. SUMMARY OF GRAVIMETRIC INVESTIGATIONS IN CANADA IN 1966

Specific investigations which may add to current knowledge of the lower crust or the upper mantle are described below.

### A. Measurements on Land

In 1966 the regional gravity coverage of Canada was extended over large areas of the Northwest Territories, the Cordillera region, some parts of the Arctic Islands and parts of Nova Scotia, Newfoundland, and New Brunswick. The Dominion Observatory had parties in the Arctic Islands, the Mackenzie

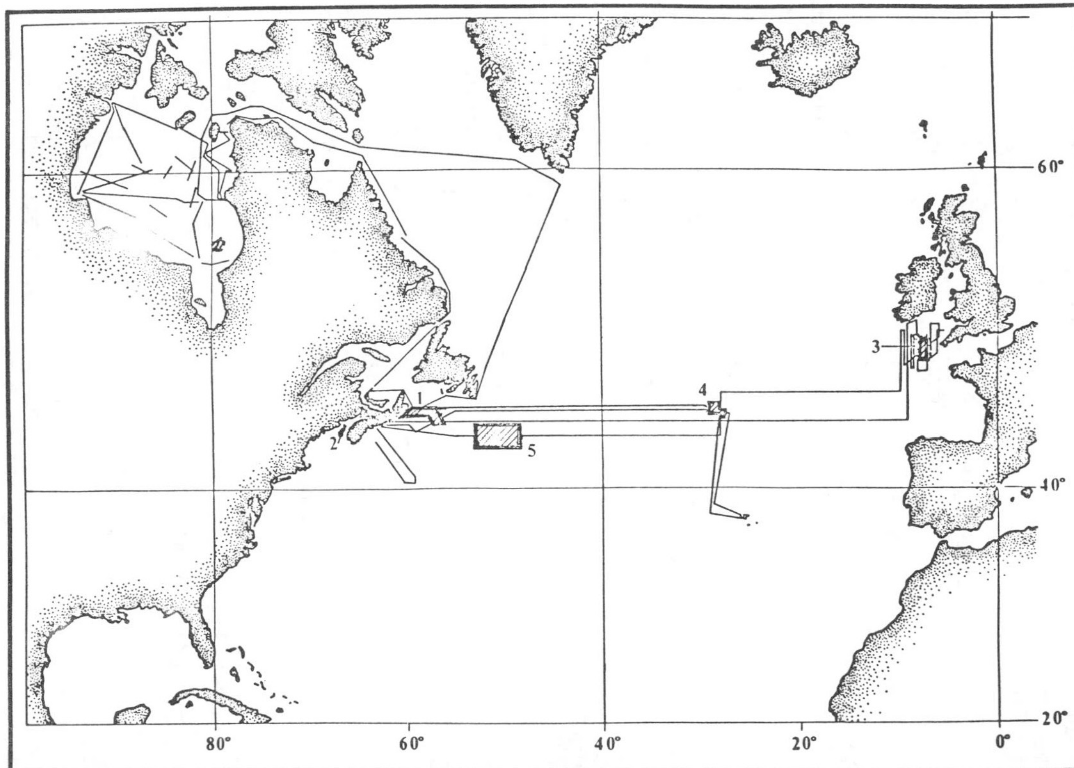


Figure 2. Surface gravimeter measurements taken by the Bedford Institute of Oceanography. Numbers represent areas of special interest.

District of the Northwest Territories and British Columbia. Over 6500 observations were added to the existing regional coverage. Figure 1 shows the progress made to the end of 1966. The work in the Atlantic Provinces was done by the Nova Scotia Research Foundation, Memorial University of Newfoundland and the University of New Brunswick. The Observatory hopes to produce a new Gravity Map of Canada at a scale of 1:2½ million by late 1967.

B. Measurements at Sea.

(1) Underwater gravity measurements (A.K. Goodacre, B.G. Brulé, and R.A. Stacey, Dominion Observatory, Ottawa, Ontario.) Regional measurements were made along both the eastern and western coastlines in 1966. In the east, 313 stations were established at intervals of 12 km in the region south and west of the Island of Newfoundland. This work will be used to study the relationship of anomalies previously outlined in the Gulf to those on the Island of Newfoundland and to determine the possible extension of Logan's Line. The analysis of the data will be done by A.K. Goodacre and B.G. Brulé.

The work on the west coast was carried out in conjunction with land traversing and will be used to complete the western end of three Cordilleran traverses to be interpreted by R.A. Stacey. A total of 234 underwater gravity measurements, spaced at intervals of 10-15 km, were made in the Dixon Entrance, Hecate Strait, Queen Charlotte Sound, the Strait of Georgia, and in several fiords.

(2) Shipborne gravimeter measurements (B.D. Loncarevic, C.S. Mason, D.H. Matthews, C.E. Keen and G.N. Ewing. Bedford Institute of Oceanography.) Three ships have at present fully equipped laboratories suitable for gravity measurements at sea: CSS HUDSON, CSS BAFFIN and CCGS LABRADOR. One Askania sea gravimeter has been in operation since 1963 and delivery of a second Askania sea gravimeter is expected before the end of 1966. The extent of gravity measurements to the end of 1966 is shown in Figure 2. The areas of special surveys are as follows:

1. Orpheus Anomaly, Scotian Shelf
2. Bay of Fundy Survey
3. Western Approaches
4. Mid-Atlantic Ridge
5. Grand Banks.

The interpretation of Orpheus Anomaly, Scotian Shelf (discovered in 1964) has been completed by Loncarevic and Ewing. The interpretation suggests that the anomaly is caused by a 3-5 km depression of the basement rock and deposition of low density sedimentary rock (2.21 g/cm$^3$).

The gravity study of the continental margin of the eastern seaboard was initiated in 1963. The purpose of this study is to systematically cover the continental margin from

Georges Bank (Gulf of Maine) to Hudson Strait at a line separation of approximately 30 miles. In 1966 work was done over the Grand Banks off Newfoundland.

Keen and Loncarevic have interpreted the results off Nova Scotia. They find that models fitting both seismic and gravity data require both horizontal and vertical density variations in the upper mantle down to 100 km.

Another major project at the Bedford Institute of Oceanography is a detailed investigation of an area of the mid-Atlantic Ridge near 45°N. by Loncarevic, Mason and Matthews.

Publications

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1966: Crustal structure on the eastern seaboard of Canada: studies on the continental margin; Can. J. Earth Sciences, Vol. 3, No. 1, pp. 65-76.

Loncarevic, B.D., Mason, C.S., and Matthews, D.H.
1966: Mid-Atlantic ridge near 45° north: I; the median valley; Can. J. Earth Sciences, Vol. 3, No. 3, pp. 327-329.

Loncarevic, B.D. and Ewing, G.N.
in press: Geophysical study of the Orpheus gravity anomaly; VII World Petroleum Congress.

## C. Gravity Investigations of the Canadian Shield

(1) Quebec and Labrador (J.G. Tanner, D.F. Weaver, R.K. McConnell, Dominion Observatory, Ottawa, Ontario.) With the exception of that area north of 55°N and east of 63°W, gravity mapping has been completed in Quebec and Labrador. A comprehensive investigation of the results is in progress with special emphasis being given to a study of the structural significance of the anomalies over the boundary of the Grenville and Superior provinces, over the Labrador Trough and over the Cape Smith fold belt. The study includes detailed gravity investigations of several anorthositic and ultrabasic bodies, as an aid in delineating their deep structure and possible connection with the mantle. A statistical analysis of the anomalies is also being carried out to provide information for isostatic studies.

(2) Grenville Front (F.S. Grant, University of Toronto, Toronto, Ontario) A traverse was made by canoe along the Mushilagan River in Central Quebec between Lake Mushilagan and Lake Atticoupi. About 100 gravity stations were occupied at about one mile spacing. A previous traverse was completed in 1964 about 100 miles to the east along the Rivière aux Pékans. Both traverses cross a large negative anomaly discovered in 1956 by the Dominion Observatory.

Preliminary interpretation of these two profiles suggests that the cause of the anomaly may be a large depression controlled by deep faulting along the Grenville Front, which is concealed by later metamorphism and filled with lighter-than-average material (possible unmetamorphosed sediments). Approximately 300 density determinations were made from outcrops along both rivers. On the basis of these observations it is inferred that the depth of the "fill" may be greater than 8 km.

(3) Grenville geological province (R.M. Ellis, University of British Columbia and E.C. Appleyard, Waterloo University.) A gravity survey covering 400 square miles has been carried out in the Madawaska Valley region of Ontario which is crossed by the Haliburton-Bancroft belt of nepheline-bearing alkaline gneisses. The purpose of this survey is to investigate whether there is structural evidence that these alkaline rocks may be derived from a parental magma of partially melted upper mantle rocks.

(4) Major positive gravity anomalies in northern Manitoba and northern Ontario (R.A. Gibb, Dominion Observatory, Ottawa, Ontario.) The Nelson River and Kapuskasing regions exhibit prominent positive anomalous areas in the gravity field of the Canadian Shield. The Nelson River high has been previously related to the deeply eroded roots of a former Precambrian mountain range, whereas the Kapuskasing high has been interpreted as the gravity expression of a deeply eroded counterpart of the present day rift valleys.

Although the interpreted structural histories of these areas are different, they have several features in common. Both are underlain in part by fault-bounded belts of Archaean granulite facies rocks, characteristically associated with gabbroic and anorthositic intrusive bodies. These belts cut across the regional geological trends in both areas. Intrusive rocks, peridotites in both areas and alkaline rocks in the Kapuskasing area, originating perhaps from the mantle, are present in both areas. The gravity variations are locally related to the surface geology but model studies indicate that the large scale regional highs can be interpreted in terms of uplifted denser parts of the lower crust.

(5) Gravity studies in Manitoba and northwestern Ontario (H.D.B. Wilson, W.C. Brisbin, and D.H. Hall, University of Manitoba, Winnipeg, Manitoba.) Both regional and detailed gravity studies at the University of Manitoba during 1966 have been centred on the extension of the English River gneissic belt and adjacent crustal blocks into Manitoba from northwestern Ontario.

In southeastern Manitoba approximately 150 stations were occupied in the area between the Ontario border and 96$^{o}$ east longitude (station spacing three to four miles). This area is one in which very little gravity coverage was previously available and in which crustal seismic studies are currently taking place. The data has been reduced and is being compiled with previously acquired data to the east. The objectives of the interpretation phase of both gravity and seismic data are to study the extension of the English River gneissic belt into Manitoba and its relationship to the crustal block to the south.

Detailed gravity studies took place during 1966 in the Rice Lake, Manitoba volcanic-sedimentary belt. This area is just north of the northern boundary of the English River gneissic belt and presents an opportunity to study the changes in composition and structure of the upper crust which take place across the north boundary of the gneissic belt. The gravity investigation is part of a detailed geological and geophysical study being done in the area by the Manitoba Mines Branch and the University of Manitoba. It is one of many geophysical techniques being used to interpret the three dimensional distribution of greenstone belts and granitic intrusions.

(6) Northern Saskatchewan (Saskatchewan Research Council, R. Agarwal, University of Alberta, Edmonton, Alberta, and R.K. McConnell, Dominion Observatory, Ottawa, Ontario.) The Saskatchewan Research Council conducted a conventional gravity survey in the Wappella area of Saskatchewan to provide more detailed gravity observations to assist in their interpretation of a seismic survey across the southerly continuation of the Nelson River gravity high. A preliminary review of these gravity results confirms the previous interpretation of the reconnaissance gravity data.

R. Agarwal of the University of Alberta and R.K. McConnell of the Dominion Observatory, are carrying out a gravity study in the Stony Rapids area, Saskatchewan. A basic intrusion which outcrops in the Precambrian Shield is associated with a positive residual anomaly of 35 milligals. The anomaly lies on a northeasterly trending gravity high which extends for several hundred miles in both directions from the area of study.

(7) Bear and Slave geological provinces (R.W. Hornal, Dominion Observatory, Ottawa, Ontario.) The results of a regional gravity survey from Great Slave Lake to Victoria Island and from Dubawnt Lake to Great Bear Lake show that the anomalies correlate well with the major structural trends and geological formations. A large positive gravity anomaly north of Coppermine is due to late Proterozoic flood basalts which underlie Palaeozoic cover rocks except in the areas of the Minto Arch and the Coppermine River where up to four kilometres of basalt are exposed. The basalt has its origin deep within the crust. A belt of positive anomaly parallels the rocks of the Snare group from Great Slave Lake to Great Bear Lake and may represent basic intrusions along the geosyncline. A gravity high over the east arm of Great Slave Lake may be related to basic sills and dykes intruding the rocks of the Great Slave and Et-then groups. A steep gravity gradient between massive granite of Archaean age and gneisses of Proterozoic age marks the boundary of the Churchill and Slave geological provinces between Artillery Lake and the Back River.

## D. Gravity Studies of the Interior Plains

(1) Structural implications of gravity data for Hudson Bay and vicinity. (A.K. Goodacre, M.J.S. Innes, A. Argun-Weston, J.R. Weber, and R.K. McConnell, Dominion Observatory, Ottawa, Ontario.) The analysis of underwater gravity measurements of a reconnaissance nature in Hudson Bay, and of regional gravity surveys over adjoining regions of the Canadian Shield and Hudson Bay Lowlands shows that (a) the main variations of the Bouguer anomaly field in Hudson Bay cannot be easily reconciled with depths of the crust-mantle boundary as determined seismically, but find a satisfactory explanation in terms of structures within the crust. (b) Palaeozoic and recent sediments within the Bay have little effect on the total anomaly field. (c) The source of a large positive anomaly belt trending southwest across the northern part of Hudson Bay may reflect high density metamorphic gneiss related to the orogenic event that deformed the Cape Smith-Wakeham Bay volcanic-sedimentary belt. An equally plausible explanation is that the anomalies stem from basic volcanic rocks underlying the veneer of Palaeozoic sediments. (d) A north-south trending series of positive anomalies between the Belcher Islands and a point 100 km west of the Ottawa Islands is interpreted as reflecting a zone of crustal rifting. This may be the northerly extension through James Bay of the postulated crustal rifting related to the Kapuskasing gravity high. (e) Although other interpretations are possible, the negative gravity field in the circular area outlined by the Nastapoka Island arc and its western extension may be due to crustal deformation resulting from meteoritic impact. (f) Mean free air anomalies evaluated over concentric zones show a systematic decrease toward Hudson Bay confirming results suggested by earlier work. The negative gravity anomaly of 25 mgal may reflect incomplete isostatic adjustment of the crust following deglaciation of this broad area of the Canadian Shield.

### Publications

Innes, M.J.S., Goodacre, A.K., Argun-Weston, A, and Weber, J.R. in press: Gravity and isostasy in the Hudson Bay region; Hudson Bay Centennial Volume.

Innes, M.J.S., Goodacre, A.K., Weber, J.R. and McConnell, R.K. in press: Structural implications of the gravity field in Hudson Bay and vicinity; Can. J. Earth Sciences.

(2) Alberta (R.R. Kanasewich, University of Alberta, Edmonton, Alberta.) Approximately 400 gravity and ground magnetometer measurements have been made to provide geophysical information on the trends of the deep crustal structures being studied in detail by seismic methods. The east-west trends present in the Churchill geological province of southern Alberta are continuous from the Saskatchewan boundary to as far west as the main range of the Rocky Mountains. The seismic and gravity data correlate well in the area studied to date with Bouguer anomalies ranging

from -115 to -80 milligals.

## E. Gravity studies of the Canadian Cordillera

(1) Southern Cordillera (R.R. Kanasewich, University of Alberta, Edmonton, Alberta.) An interpretation has been made of the combined gravity and seismic data along a line across the plains and Rocky Mountains (Kanasewich, 1966). The Airy hypothesis of isostatic compensation is incompatible with the data and density variations in the upper mantle are used to obtain a fit with the observed gravity field.

### Publication

Kanasewich, R.R.
1966: Deep crustal structure under the plains and Rocky Mountains; Can. J. Earth Sciences, Vol. 3, No. 7, pp. 937-945.

(2) Central Cordillera (R.A. Stacey, Dominion Observatory, Ottawa, Ontario.) Gravity has been measured along three profiles running at right angles to the trend of the Cordillera between latitudes 52° and 55°N and extending from the top of the continental slope to the interior plains. The results are being used to investigate the isostatic condition in the Cordillera and to construct crustal sections.

(3) Vancouver Island (R.I. Walcott, University of British Columbia, Vancouver, B.C.) A gravity survey of Vancouver Island south of Kelsey Bay, Georgia Strait and the adjacent mainland is in progress. Already 300 stations have been occupied at 3 to 5 mile spacings. A total of 600 new stations is planned. The observations will be used together with 200 Oregon State Survey and 200 other previous measurements to compile a Bouguer anomaly map of the region. Terrain corrections will be applied to the data.

## F. Appalachian Region

(1) Bouguer anomaly field of Newfoundland (D.F. Weaver, Dominion Observatory, Ottawa, Ontario.) Analysis of gravity data reveals a major gravity gradient across a line that trends northeasterly over the southern part of the Great Northern Peninsula. This line may mark the boundary between the Grenville and Appalachian geological provinces. The anomalies north of this line average about 30 mgal less than the anomalies in the southern area. Seismic work suggests a thinner crust of lower density in the north where the anomalies are negative, and a thicker, higher density crust in the south where the anomalies are generally positive. Calculations show that the results are compatible with the gravity data if density variations in the upper mantle contribute to the gravity field. There does not appear to be any dependence of Bouguer anomaly on elevation in either area.

A correlation of the local Bouguer anomalies with the surface geology suggests that granite is the prime cause of the negative anomalies of Newfoundland. The sediments, most of which are metamorphosed, appear to have very little effect on the gravity field. Most of the positive anomalies of Newfoundland correlate with large bodies of diorite or with gabbroic and ultrabasic intrusions. It is suggested that many of the longer wave-length regional variations in the gravity field are produced by changes in the crustal parameters at depth.

Publications

Weaver, D.F.
in press: Preliminary results of the gravity surveys of the Island of Newfoundland (with maps); Grav. Map. Series, Nos. 53-57, Dom.Obs.

Weaver, D.F.
in press: A geological interpretation of Bouguer anomaly field of Newfoundland; Dom. Obs. Pub. Vol. 35, No. 5.

(2) Structural implications of gravity measurements in Appalachia. (M.J.S. Innes, and A. Argun-Weston, Dominion Observatory, Ottawa, Ontario.) Analysis of gravity data indicates that the marked positive gravity anomaly over the Sutton-Green Mountain anticlinorium, and an adjacent negative gravity anomaly to the west and northwest cannot be explained entirely by the surface geology, and deep-seated sources at the base of the crust or in the upper mantle are necessary. These major gravity field trends, which mark the boundary between Applachia and the Shield, are persistent and extend south to Alabama, and northeast to Newfoundland. Statistical analyses show that Bouguer and free air anomalies are 30 milligals greater over the Appalachians than over the adjoining Precambrian Shield. The Appalachian region is under-compensated by 20 milligals while the Shield is over-compensated by about 10 milligals. These gravity results are inconsistent with the crustal thicknesses determined seismically, but consistent with the higher seismic velocities indicating a denser crust underlying Appalachia.

Publication

Innes, M.J.S., and Argun-Weston, A.
1966: Gravity measurements in Appalachia and their structural implications; Proc. Roy. Soc. Can., Sym. on Appalachian Tectonics.

(3) St. Lawrence River (P.S. Kumarapeli, and V.A. Saull, McGill University, Montreal, Quebec.) Mr. Kumarapeli, a graduate student in the Department of Geological Sciences, has gravity observations along 10 profiles across the geologically-inferred location of Logan's Line. Seven profiles lie between Lake Champlain and Drummondville and three between Drummondville and Quebec City.

Mr. Kumarapeli and Dr. Saull have proposed a rift system extending through the St. Lawrence and Ottawa River valleys to the Great Lakes and beyond to the Midcontinental Gravity High.

Publication

Kumarapeli, P.S. and Saull, V.S.
1966: The St. Lawrence valley system: a North American equivalent of the East African Rift valley system; Can. J. Earth Sciences, vol. 3, No. 5, pp.639-659.

## III. THEORETICAL STUDIES

The major problem of physical geodesy is to find the potential of the earth, such that its normal derivative takes on prescribed values at the surface. This is the second boundary value problem of potential theory, also known as the Neumann problem. In the practical case the normal derivative, the gravity value, is not known all over the earth's surface, which introduces errors into the solution.

At the Dominion Observatory a computer method is being developed to determine the geoid over Canada. The geoid is an equipotential surface at mean sea level and is simply the potential divided by the theoretical gravity value. The input data for the computations are the gravity values which may be obtained either from direct measurements or from analysis of satellite orbits. The important part of the program is a provision for error analysis.

A program for terrain corrections has been developed and is currently being applied to data collected from the Canadian Cordillera. Error analyses are providing estimates of the accuracy of the derived corrections.

Publications

Nagy, D.
1966: Terrain corrections by digital computer; Pure and Applied Geophysics, Vol. 63, pp. 194-202

Nagy, D.
1966: The gravitational attraction of a right rectangular prism; Geophys. Vol. 31, No.2, pp.362-371 (Contr. Dom. Obs. Vol. 6, No. 12).

Nagy, D.
1965: The evaluation of Heumann's Lambda function and its application to calculate the gravitational effect of a right circular cylinder; Pure and Applied Geophysics, Vol. 62, pp.5-12.

## IV. EARTH TIDE STUDIES

D.R. Bower, Dominion Observatory, Ottawa, Ontario.
J.E. Blanchard and T. Lambert, Nova Scotia Research Foundation, Halifax, Nova Scotia,
University of British Columbia, Vancouver, B.C.

An earth tide observatory is being established near Ottawa. The purposes of the studies are: (i) to extend the existing coverage of continuous, systematic observations of the earth tide; (ii) to investigate the reliability of micro-gravimetric instruments and the techniques of site selection and installation; (iii) to investigate the utility of these measurements in regional studies of the earth's crust.

The site of the station is an abandoned asbestos mine located about 30 miles north of Ottawa. Two horizontal pendulums of the Verbaandert-Melchior type are being installed in a niche cut in the rock face at the end of an 800 foot adit. A mirror mounted on each pendulum reflects the image of a light source on to a servo-driven photocell located 14 feet away. Proportional voltages are generated and carried outside the mine to a small hut where they are filtered and then recorded, together with time, on magnetic tape in a computer-compatible format.

A LaCoste and Romberg earth-tide gravimeter will also be installed at the site shortly and extensometers are being considered for future installation.

Horizontal pendulums have been purchased by Dalhousie University and the University of British Columbia. A site has been selected in Nova Scotia and is being prepared.

## V. ISOSTASY AND VERTICAL AND HORIZONTAL MOVEMENTS OF THE CRUST

Reference was made in the Canadian Progress Report, December 1964 to vertical movements of the crust as indicated by repeated precise levellings by the Geodetic Survey of Canada in Quebec, Manitoba and British Columbia. Further work has been done in the Lake St. John area of Quebec and the results have been published.

A very small network was established near Quebec City in 1926 to investigate possible horizontal movements. The net was re-surveyed in 1964 and no appreciable movement could be detected.

In 1965 a network was established extending from Cap Tourmente (30 miles northeast of Quebec City) to Tadoussac, incorporating points on both sides of the St. Lawrence River. This was intended as the basis for a further survey in 10 or 15 years to check the possibility of horizontal movement. Since several points of a survey carried out 50 years ago were included in the new network an attempt was made to detect movement over this 50 year period. Results were not conclusive but there is a slight indication that the two shores of the river have moved past each other by 2 or 3 feet in the 50 year period.

In 1966 a survey was made in the vicinity of Campbell River, British Columbia, incorporating points on Vancouver Island and on the British Columbia mainland. It is the intention to repeat this survey in 10 or 15 years to check on possible horizontal movement. It is hoped to re-survey in 1967 a quadrilateral, connecting Vancouver city with Vancouver Island, which was part of the triangulation carried out 50 years ago.

Plans are underway for a survey in 1967 to establish the relationship between points on northern Ellesmere Island and in Greenland; here again, it is the intention to repeat the survey in 10 or 15 years time.

The first phase of a long term program to determine the possible vertical movements of the crust due to loading by water at the Saskatchewan River dam site was begun in 1966 by the Dominion Observatory. About 45 observations were made in the vicinity of Elbow, Saskatchewan.

The cooperative program between the Observatory and the Geodetic Survey of Canada to provide gravity values at bench marks in the Eastern Townships, Quebec, by P.J. Winter. Dr. Stacey measured gravity at 250 bench marks in central British Columbia. These and previous observations will be examined in conjuntion with precise levelling data for evidence of recent crustal movements.

D. M. Barnett of the Geographical Branch has reviewed the tide gauge data from Churchill Manitoba. He suggests that the water level is decreasing at a rate of about two feet per century.

C.F.M. Lewis of the Geological Survey of Canada studied post-glacial lacustrine and littoral features around the Lake Huron basin. An instrumental survey of an interesting sequence of shore features along the edge of the Precambrian highlands between Sault Ste. Marie and Gros Cap, Ontario was completed jointly with Dr. W. M. Tovell of the Royal Ontario Museum. Instrumental surveys of possible outlets and radiocarbon dating of lacustrine sediments from abandoned drainage channels were carried out with the help of Dr. J. Terasmae.

D. R. Grant of the Geological Survey of Canada examined the Nova Scotia coast in order to document the age, sequence, extent and causes of recent changes of level responsible for regional submergence. Rates of submergence of 1.4 to 2.0 feet per century have been reported.

## VI. PUBLICATIONS

Barnett, D.M.
1966: A re-examination and re-interpretation of tide gauge data for Churchill, Manitoba; Can. J. Earth Sciences, Vol. 3, No. 1, pp.77-89.

Dick, W., Fyles, J.G., and Blake, W.J.
1965: Geological Survey of Canada radiocarbon dates IV; Radiocarbon, Vol. 7, pp. 24-46.

Dick W., Lowdon, J., Fyles, J.R., and Blake, W.J.
1966: Geological Survey of Canada radiocarbon dates V; Radiocarbon, Vol. 8, pp. 96-127.

Frost, N.H., and Lilly, J.E.
1966: Crustal movements in the Lake St. John area, Quebec; The Canadian Surveyor, Vol. 20, No. 4,pp.292-300.

Grant, D.R.
1967: Reconnaissance of submergence phenomena, Nova Scotia; Geol. Surv. Can. Paper 67-1, pp173-174.

Innes, M.J.S., and Argun-Weston, A.
1966: Crustal uplift of the Canadian Shield and its relation to gravity field; 2nd Int. Symposium on Recent Crustal Movements, Aulanko, Finland, Annales Academie Scientiarum Fennicae, Helsinki, Finland, Vol. A III 90, pp. 168-176. (Contr. Dom. Obs. Vol. 7, No.5.)

Lewis, C.F.M.
1967: Post-glacial uplift studies in northern Lake Huron basin; Geol. Surv. Can. Paper 67-1, pp.150-151.

Lilly, J.E.
1965: Crustal movements in Canada; 2nd Int. Symposium on Recent Crustal Movements, Aulanko, Finland, 1965. Annales Academie Scientiarum Fennicae, Helsinki, Finland, Vol. A III, 90, pp.248-250.

# HEAT FLOW STUDIES

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## I. SUMMARY OF PRESENT CANADIAN KNOWLEDGE

The two most active groups, at the Dominion Observatory and the University of Western Ontario, have a large number of results which will be published shortly. New groups have been formed at the University of Toronto and the University of Calgary, and the group at McGill University is again active.

A major project was initiated several years ago to establish a widely spaced grid of boreholes across Canada for heat-flow studies. The emphasis on wide spacing has now been abandoned in favour of clusters of closely spaced groups for the examination of specific geophysical features. The first group of holes has been drilled in the Stikine Plateau of British Columbia in an attempt to detect thermal anomalies across a volcanic belt. A group of measurements have been made in the floor of the Arctic Ocean and the deep inter-island channels as part of a program to investigate the magnetic anomaly over Prince Patrick Island. In three other projects, holes drilled for commercial purposes have been used.

A large number of these boreholes have been made available by industry. Their use is particularly important in northern areas, where the cost of drilling special holes is prohibitive. In western Canada, where temperatures are measured during the normal logging runs in oil well holes, the data from several thousand boreholes has been collected and analysed. Although only a minute proportion of the holes yielded reliable data, there is sufficient to plot isogeotherms and isogeograds on a regional scale and to correlate these with regional structure. On a smaller scale several holes in southwestern Ontario and eastern Michigan are being used for a similar purpose, although in this case the temperatures are being measured with accurate equipment and cores collected for thermal conductivity measurements. Similar work on a much more detailed scale is being carried out in a large number of holes near Noranda, Quebec.

TABLE I

SUMMARY OF HEAT FLOW DATA FOR CANADA

All heat flow values are given to the nearest 0.05 $\mu$ cal/cm$^2$sec. Unpublished results should be considered as preliminary. Values in brackets are unpublished corrected values.

| PROVINCE | NEAREST TOWN | HEAT FLOW | GROUP | DATE OF PUBLICATION |
|---|---|---|---|---|
| Nova Scotia | Halifax | 1.3 | Dom. Obs. | Unpubl. |
| | Oldham | 1.4 | Dom. Obs. | Unpubl. |
| Quebec | Calumet | 1.3 | Toronto | 1951 |
| | Lonan-Centien | 0.8(1.3) | McGill | 1961 |
| | Malartic | 0.7 | Toronto | 1951 |
| | Noranda | 0.6-1.0 (12 sites) | U.W.O.* | Unpubl. |
| | Ste. Rosalie | 0.8(1.3) | McGill | 1961 |
| | Thetford | 1.05 | Toronto | 1951 |
| | Valleyfield | 0.75 | McGill | 1961 |
| Ontario | Brent | 0.75 | U.W.O. | 1964 |
| | Elliot Lake | 1.3 (7 sites) | U.W.O. | Unpubl. |
| | Franktown | 1.3 | Dom. Obs. | Unpubl. |
| | Kirkland Lake | 1.0 | Toronto | 1951 |
| | Larder Lake | 0.9 | Toronto | 1951 |
| | London | 0.8 | U.W.O. | Unpubl. |
| | Ottawa | 0.85 | Dom. Obs. | Unpubl. |
| | Sudbury | 1.0 | Toronto | 1951 |
| | S.W. Ontario | 0.9-1.05 (35 sites) | U.W.O. | Unpubl. |
| | Timmins | 0.75 | Toronto | 1951 |
| | Toronto | 1.0 | Toronto | 1951 |
| Manitoba | Flin Flon | 0.9 | U.W.O. | 1962 |
| Alberta | Leduc | 1.6 | Alberta | 1962 |
| | Redwater | 1.45 | Alberta | 1962 |
| British Columbia | Penticton | 2.0 | Dom. Obs. | Unpubl. |
| North West Territories | Neilson Island | 0.8 | Dom. Obs. | Unpubl. |
| | Muskox intrusion | 1.3 | U.W.O. | 1966 |
| | Normal Wells | 2.0 | Alberta | 1962 |
| | Mould Bay (off shore) | 0.4-1.7 (15 sites) | Dom. Obs. | 1965-6 |

* U.W.O.: University of Western Ontario.

In the field of instrumentation the last four years have seen the development of three basic types of temperature-measuring equipment capable of measuring temperatures to ±0.01°C. One consists of an inexpensive very light-weight four-conductor cable using a standard Wheatstone bridge having automatic compensation for series resistance, shunt resistance, and their variation with temperature. With very reliable cable only three conductors are necessary. Another consists of a three-conductor cable with two relays in a probe providing essentially four circuits so that very good compensation for the cable characteristics is obtained. The third basic type consists of an oscillator probe which requires only two conductors. All groups now appear to have, or are building, an oscillator probe in addition to their regular equipment. A very sensitive gradiometer to log temperature gradients directly has been tested but not fully developed. Further development in this field will probably consist of relatively minor refinements to existing equipment.

Laboratory measurements of thermal conductivities are usually made on a divided bar type of apparatus using either brass or fused silica as the comparison material. Temperatures at the ends of the bar are maintained by either thermostatically controlled baths or solid state heat pumps, the latter leading to a considerable saving in space and weight. Conductivity values are obtained by the usual temperature measurements along the bars with thermistors or thermocouples, or by a direct readout of thermal conductivity with the calibrated meter. Line source transient methods have also been used.

Perhaps the most interesting advances in conductivity measurements are the *in situ* methods of measuring conductivity in a borehole. A probe used in measuring the conductivity in uncased boreholes has been modified for use in cased boreholes; these probes measure the conductivity in a direction that is radial to the hole. A method is being developed for detecting any significant conductivity anisotropy in the direction radial and parallel to the borehole. A model experiment using thermally induced convection under a strong central force has been initiated to study the possible influence of convection currents on upper mantle phenomena.

A number of theoretical studies, covering topics ranging from the effect of the thermal properties of rocks on mine climates to the thermal history of the earth, have also been carried out.

## II. CURRENT PROBLEMS AND THE DIRECTION OF FUTURE RESEARCH

There are two main philosophical problems of heat flow:

1. How to make a meaningful measurement and determine the area over which it is representative;

2. How should these measurements be interpreted, and what features are reflected in the results?

The preliminary results from the Noranda area are difficult to explain. Over 200 conductivity measurements have been made in 12 of the 82 holes in which temperature measurements were made. The heat flow values from these 12 holes, in an area of 5 sq km, vary from 0.6 to 1.0 $\mu$ cal/cm$^2$ sec. Corrections for topography, geological structure and possible oxidation of ore are not great enough to explain these differences. The most probable explanation is a very slow movement of underground water but, unfortunately, there is no other evidence that this is occurring. More detailed rock sampling with associated conductivity measurements is required. It is obvious that in some regions a single heat flow measurement may be very unreliable.

The heat flow data from the Quirke Lake syncline near Elliot Lake, where uranium, thorium, and potassium gamma ray emission measurements have been made on surface samples, suggest that there is a higher than normal concentration of radioactivity in the crust below the syncline. It therefore appears to be important to make gamma ray measurements in addition to heat flow measurements, so as to determine the radioactive content of rocks from various depths and to estimate the heat production of the various rock units.

Although it is known that the heat flow from Shield areas is lower than that from non-Shield areas, the nature of the transition is not established. It would therefore be useful to make heat flow measurements along a line of holes from Port Arthur, Ontario, to Calgary, Alberta. It also seems reasonable to suppose that there may be variations of heat flow in the various geological provinces of the Precambrian Shield. Since the more recent areas have a high heat flow it might be argued that the older the Precambrian province the lower the heat flow. Heat flow determinations in groups of well selected holes in each of the Precambrian provinces would be useful in determining whether there is in fact any difference between the oldest and the youngest.

One of the main problems in the interpretation of Canadian heat flow data is the unknown effect of the Pleistocene glaciation. Most Canadian results are uncorrected for this effect which could explain the low values attributed to Shield areas. I.K. Craig of McGill University has studied the effects of palaeoclimate on the thermal gradient. His results suggest that in the Grenville province of the Precambrian Shield the flow values are artificially low because of the lack of correction for glaciation and, if corrected, they would probably be near the world average.

In southwestern Ontario and eastern Michigan the temperature gradients in different sedimentary formations, and the conductivities of samples from these formations, seem to be

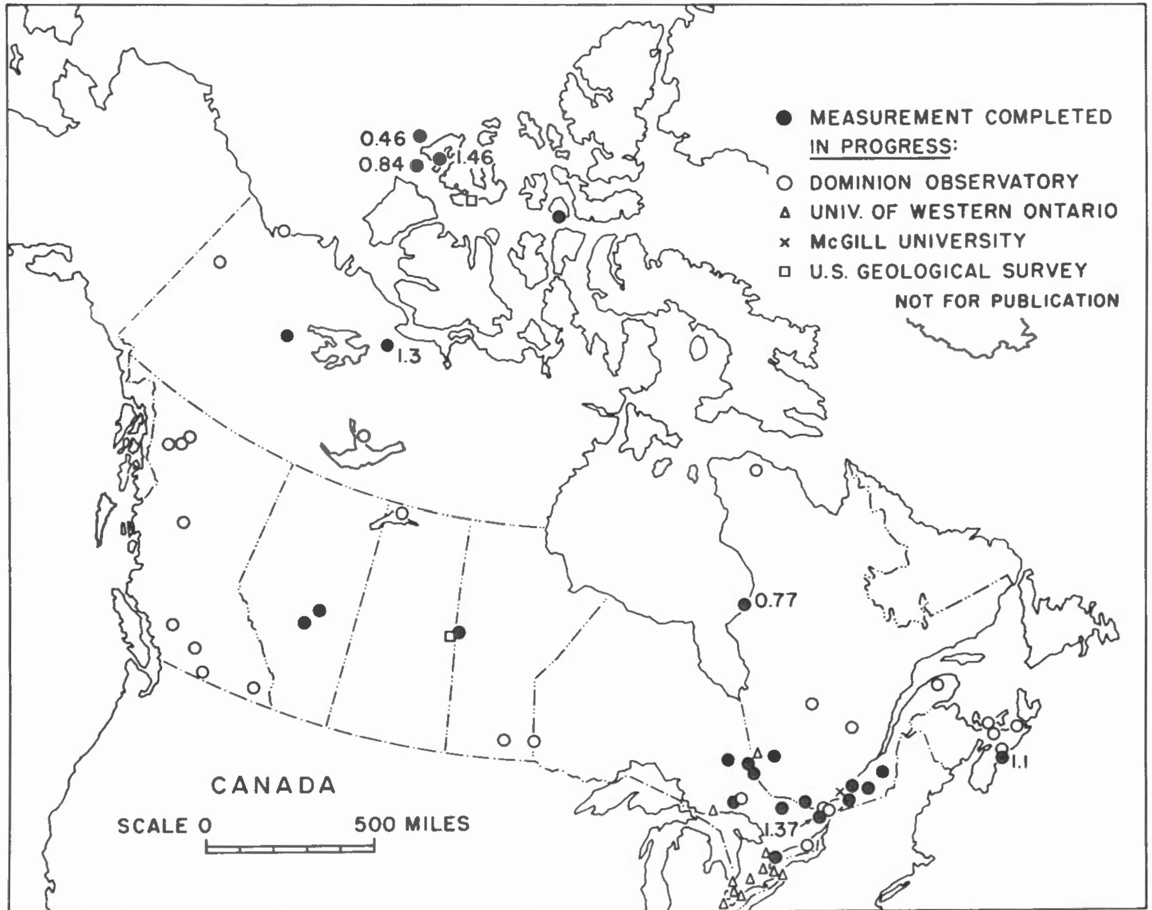


Figure 1. Sites of heat flow measurements in Canada, April 1967.

remarkably uniform for a particular formation over a long distance. This leads to a remarkably uniform heat flow over the whole area, with no significant change with depth. These results are rather surprising since one would expect the probability of underground water flow to be greater in sedimentary areas than in hard rock areas such as Noranda. It may be that the presence of the Algonquin Arch is responsible for the slightly low value of heat flow at London, compared with the surrounding area.

The Stikine Plateau drilling project in British Columbia was designed to look for remanent heat in an area of recent volcanism, as contrasted with the non-volcanic surrounding areas. The lateral extent of the project is about 100 km, and the volcanic zone is of the order of 100 km by 40 km. No results are available yet.

The Polar Continental Shelf Project has been trying to use heat flow measurements to outline a possible temperature anomaly suggested by magnetotelluric studies on Prince Patrick Island. Measurements have been made over an area of 150 km, and variations in heat flow have been found. Unfortunately the original hypothesis has not yet been proved or disproved.

Work now in the final stages at the Dominion Observatory suggests that different parts of the Shield might have a different heat flow for geochemical reasons. It is difficult to be at all definite in this kind of distinction, as geochemical analyses are incomplete for surface rocks, and non-existent for great depths in the crust.

All of these investigations involve areas 100 km or more in extent, and it seems that this may be the best size of feature for investigation by heat flow techniques. This does not prove that heat flow measurement cannot be used to examine much smaller features, and the Noranda work may shed some light on this possibility, but it does mean that major features such as the Grenville Front or the Nelson River gravity high offer the best opportunities for future heat flow research.

At the present time heat flow measurements are so expensive in time and money that it is most likely that they can be used to the same extent that gravity and magnetic methods are now used. However, if some way of determining heat flow cheaply and easily were developed, this situation might be changed. To this end, the Dominion Observatory will shortly be starting a program of investigation into the possibility of measuring heat flow in lakes.

## III. CANADIAN PROJECTS UNDERWAY OR COMPLETED DURING PERIOD COVERED BY REPORT

The following list indicates work by Canadian institutions, with the names of people who have participated. The material is essentially that submitted by the institutions.

Dominion Observatory (A.M.Jessop, T. Lewis, L. Law, W.S.B. Patterson, K. Whitham)

Ten bore-holes have now been drilled specifically for the measurement of heat flow. The locations and depths are:

| | |
|---|---|
| Ottawa, Ontario | 600 m |
| Halifax, N.S. | 370 m |
| Penticton, B.C. | 600 m |
| London, Ontario | 600 m |
| St. Jerome, P.Q. | 770 m |
| Roberval, P.Q. | 600 m |
| Winnipeg, Manitoba | 600 m |
| Dease Lake, B.C. | 300 m |
| Hotailuh Range, B.C. | 430 m |
| Buckley Lake, B.C. | 430 m |

The plan to drill holes at widely spaced sites has been abandoned in favour of the investigation of specific geophysical features by means of groups of holes. The first such group consists of the last three holes listed above; one is in a volcanic belt, while the other two are outside it, the total spread being about 100 km. The original idea of a nation-wide heat flow survey has not been forgotten, but is being implemented where possible by means of holes drilled for other purposes.

Underground temperature measurements are being made whenever suitable holes can be found. Mining companies, drilling companies, and Provincial government departments have been very helpful in the search for holes. Altogether work has been done or is in progress at thirteen holes and two mines, in addition to the ten special heat flow holes. Another six holes and one mine are under consideration for 1967.

The relay-operated thermistor probe is used wherever possible for temperature measurements, but an oscillator probe is being developed. New divided bars have been built, which have glass reference bars instead of metal. This enables the bar to be much shorter, thus reducing side losses.

Heat flow results from the Arctic Ocean and deep inter-island channels are being obtained using the ocean probe technique. Direction for this study, part of the Polar Continental Shelf Project, has recently been transferred to the Heat Flow Section of the Seismology Division, Dominion Observatory, where the project will be continued and extended in scope. A large variation (1.5 to 0.5 $\mu$ cal/cm$^2$ sec) has been found from the channels to the shelf. It is planned to continue this line across the continental shelf and into the ocean basin.

The Observatory is cooperating with A. Lachenbruch of the U.S.G.S. in the measurement and analysis of a very deep hole at Flin Flon, Manitoba. It is hoped that positive evidence of the effect of Pleistocene glaciation will be found.

McGill University (V.A. Saull, I.K. Crain)

A theoretical study of the influence of climatic changes on thermal gradients has been made. Periodic fluctuations have been considered at the boundary of homogeneous and layered media. Some of the problems involved in determining paleoclimates were examined with particular reference to palynological methods and post-Wisconsin time. Results have been applied to some typical data from wells near Montreal. The results may indicate that the temperature of the base of the ice sheet during the latter part of the Wisconsin glaciation was between -4°C and -8°C.

University of British Columbia (K.O. Westphal)

Theoretical work on heat conduction and phase changes has been continued. Using Stefan-Bolzmann's law at the fixed surface a solution for the position of the moving interface has been obtained applying the concept of the heat-balance integral. Examining the propagation of heat pulses through a finite slab of material, an expression for the temperature distribution inside the slab has been obtained under the assumption of Newton's law of cooling on one side and constant temperature on the other. Preparations have been made to carry out a Fourier analysis of the temperature fluctuations measured at different levels in an ice sheet in order to determine the diffusivity of the material from the amplitude attenuation.

University of Calgary (P. Gretener)

This group has been newly organized. It is planned to concentrate on routine heat flow measurements and studies of convection patterns in non-stable wells.

University of Toronto (G.D. Garland, J. Weaver, J. Wright)

Two transistorized temperature sensitive oscillators have been used to obtain bore-hole temperatures. A temperature detectability of better than 0.01°C was obtained for the thermistor twin-T bridge oscillator and the voltage controlled oscillator gave a detectability of 0.02°C. Temperature information was telemetered from a depth of 130 m in the Roberval borehole. This method of telemetry appeared to be ideal for monitoring lake bottom temperatures over extended periods. In each circuit, zener compensated voltage regulators lessen frequency instability due to supply voltage variations. Standard resistors in a relay bridge give a measure of inherent frequency drift due to the aging of components and capacitance effects. The bridge oscillator has an average frequency change of 175 Hz per degree centigrade at a frequency of 6 kHz and the voltage controlled oscillator has a linearity of better than 0.1% with 1 mv corresponding to 1 Hz. Printed circuit boards in the bridge oscillator and modular circuits in the voltage controlled oscillator are used to simplify maintenance and construction. Both instruments are encapsulated in silicone rubber sealants to minimize vibration effects and to maintain temperature uniformity throughout the electronic circuits. The cases are of 1.5 inch outside diameter, 0.035 inch thick brass tube. Bulkhead connectors with O-ring pressure seals are used to pass the instrument leads to the surface. Surface instrumentation consists of a high input impedance broad-band preamplifier capable of handling frequencies up to 15 kHz. A modular instrument counter is used to make frequency determinations either directly or after demodulation by an fm receiver. Sets of temperature logs for five boreholes have been obtained with the bridge oscillator and for two with the voltage controlled oscillator.

In situ methods for determining thermal conductivity are useful for coarse-grained rocks or in boreholes where no samples of core are available. Two types of probes have been used. One employs a line source of heat while the other has a point source. A long length of borehole (10 m) is heated by a cylindrical probe with a resistance wire source along its axis. The temperature rise, two centimeters radially from the source, is recorded. Knowing the geometry of the hole and probe and the thermal properties of the probe, the conductivity of the rock can be determined. Experiments of different duration and using the heating and cooling curves have been carried out to obtain the conductivity in the radial direction. Of more interest is the conductivity in the axial (vertical) direction. In bedded rocks the K (radial) may be significantly different from the K (axial). Measurements with the second probe are affected by two principal conductivities. A small immersion heater source is used in a 2 m plastic probe. Temperatures are recorded at distances 20 cm, 40 cm, and 60 cm, below the centre of the source. Convective loss of heat is limited by making a tight fit between the hole and the probe above the source. Using theoretical results and the radial conductivity calculated in the first test, a value of the axial conductivity can be determined. Several tests have been made at five Dominion Observatory boreholes in Quebec and the Maritimes.

University of Western Ontario (A.E. Beck, J.H. Sass, F.M. Anglin, A.S. Judge, E. Mustonen)

A number of in situ probes using different geometries and materials were developed and used in 1963 to measure the thermal conductivities of the rocks at a number of depths in uncased portion of the central borehole of the Brent Crater. Attention is now focused on the development of a probe for use in cased boreholes; this probe has given very good results in the laboratory borehole and is at present being tested in the University's 600 m borehole. Full scale field trials are planned for the summer of 1967.

Two modified divided bar apparatuses have been built, the first using solid state heaters and coolers in an attempt to eliminate the present cumbersome thermostatic bars; it is hoped that a further development of this apparatus will make it suitable for use in the field. The second apparatus was designed in such a way as to give a direct reading of the thermal conductivity, thus eliminating much of the work of reducing the data. Present development work consists mainly of trying to combine the two types of equipment so that the one instrument will give a direct reading using solid state heaters and coolers with the facility of interchanging stacks of different diameters (and in fact different cross sections) mounted on a press for applying axial pressures; use of the solid state heaters and coolers makes it possible to operate the equipment at a mean temperature that is below room temperature and at a later date it is hoped to operate it at sub-zero temperatures.

A number of sets of temperature measuring equipment have been built, all capable of measuring temperatures to within 0.01°C. The standard equipment is simple and cheap to build and weighs only 28 kg complete with two km of 3-lead cable, winch, casing mount and pulley, bridge and power supply; with only 1 km of cable the weight is 18 kg. A probe with latching relays and one containing a temperature sensitive oscillator are also used, with the same or different cables. The probes can readily be arranged to be interchangeable using the same cable.

As part of the effort to make use of a large number of oil wells from which only chips of rock are available, it was established that the chips could be imbedded in a matrix of known conductivity and the conductivity of the rock chips computed from the volume composition using the weighted geometric mean (or the Maxwell model); it was estimated that in nearly all practical cases the computed conductivities should be within 5% of the bulk conductivity. In those cases where only porous friable cores are available, a method using only one disc has been devised for eliminating the large contact resistance by saturating the rock in various fluids of known conductivity. In most cases it is now necessary to know the exact form of the contact resistance.

A 600 m drill hole has been drilled on the campus as part of the Dominion Observatory network of heat flow holes. During the drilling, input and output temperatures and waterflows were continuously recorded. In addition the drill was frequently stopped to make temperature and gradiometer runs down the drill stem; bottom hole temperatures were also measured at intervals up to 48 hours after cessation of drilling. The results suggest that bottom hole temperatures taken at various depths about 12 hours after the cessation of drilling give a temperature gradient that is almost as good as the gradient obtained after waiting several months for the borehole to return to thermal equilibrium.

The collection of underground temperature data from western Canada has been completed and analysed. On a regional scale the data indicate an increasing heat flow northward and are consistent with the heat flow values for Norman Wells, NWT and Leduc, Alta. There appears to be some correlation of the data with two basement intrusions (of different conductivity from the country rock) inferred by Garland and Burwash from gravity data; from the geothermal data a third similar basement intrusion is indicated to the north of the other two. In one small area where fairly detailed temperature data were available from three allegedly separate oil fields, an inversion of the temperature gradient in the reservoir datum of the fields suggested the presence of a counter-flow of water and hence that the fields are interconnected at depth.

Another survey on a slightly smaller scale is being undertaken in southwestern Ontario and nearby Michigan. However, in this case the temperatures are being measured by the personnel of the department, and to date about 35 holes of depths up to 1.8 km have been logged. A detailed study of the five major formations involving several hundred conductivity determinations is now nearly complete. Over a distance of 300 km the mean conductivity of a given formation varies randomly by about 10%; a similar variation in the temperature gradient in a given formation is also observed. The uncorrected heat flow values from all holes except the hole at London lie between 0.9 and 1.05; corrections for the effect of the Great Lakes will tend to raise the lower figures. Over 150 determinations of thermal conductivity have been made on cores from the University hole; when combined with the temperature data, these result in a mean heat flow of 0.82 ± 0.05. The difference between this and the other values is as yet unexplained, but since this is the only hole over the top of the Algonquin arch, the explanation may be a structural one.

A much more detailed survey is being made around Lake Default Mines, near Noranda, Quebec. More than 1000 temperature measurements have een obtained from over 80 boreholes up to 700 m deep within an area of 5 sq km. The temperature-depth curves showed an unusually deep (100 m average) inversion region; this may be due to a continental-wide change in climate or to a bush fire that is known to have occurred about 40 years ago; this latter removed most of the vegetation, thus exposing the surface and essentially causing a step change in the mean annual temperature of the surface layer. The extrapolated surface temperatures were generally higher (0.4°C) for the south facing slopes of a low (100 m) line of hills than for the north facing slopes. Isogeotherm and isogeograd surfaces, and anomaly maps at different depths, have been drawn. At the upper levels these maps reflect the influence of topography. At the lower levels an anomaly can be correlated with an ore body. About 200 thermal conductivities have been measured using core samples from 12 holes distributed through the area. The mean heat flow from these 12 holes is 0.72 $\mu$ cal/cm$^2$ sec., and the extreme, but nevertheless well determined, values are 0.58 and 0.97. Corrections for structure and topography do not significantly affect these results; nor is there clear evidence that temperatures have been disturbed by water flow or oxidation of sulphides. With new temperature measurements in the present and additional holes, and much more complete conductivity sampling, it is hoped that the discrepancies in heat flow values can be more readily explained.

Over 100 conductivities have been measured on rocks from two holes at the Muskox site near Coppermine, N.W.T. Temperatures measured in the Muskox south hole during the summer of 1965 have been corrected for the warming effect of a nearby lake, and when conbined with conductivity data give a heat flow value of 1.3 ± 0.1. Preliminary studies indicate a high degree of correlation between thermal conductivity and mineralogy for rocks from the Muskox holes. A repeat of the temperature measurements in Muskox south is planned to check whether the hole was stable at the time the earlier measurements were made; if the Muskox east hole is still open, temperature measurements will also be made in this hole.

Further work on the thermal history of the earth has been carried out by investigating the distribution of energy per gram available from the accretion process and from gravitational reorganization. This distribution is essentially nonuniform and it is found that the energy in the mantle greatly exceeds that available in the core; any thermal history of the earth should be able to account for what has happened to this energy. Using this data and some data given by Carllaw and Jaeger in an elementary way, it appears unlikely that the whole earth reached a molten stage on completion of the accretion process. It also appears quite possible that the earth has always had a solid inner core, that the present inner core contains some compressed primary material, and that the slowness of the melting of the original inner core could result in appreciable quantities of radioactive material being trapped in the inner and outer core. A more detailed analysis is under way in an attempt to take into account such things as radiation losses, energy transfer mechanisms, and changes of state.

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# ISOTOPE STUDIES

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## I. SUMMARY OF PRESENT CANADIAN KNOWLEDGE

### A. Radiometric Dating

A reconnaissance picture of the geologic provinces of Canada has emerged in the past decade using radiometric dating methods, particularly K/Ar on micas from granitic rocks. This work has been done mainly by the Geological Survey of Canada and at the Universities of Alberta, British Columbia and Toronto, though K/Ar laboratories are presently being set up at Queens, Carleton and McGill Universities. The new tectonic map of Canada will give these data, and Stockwell's (1965) tectonic map of the Canadian Shield outlines the progress that has been made. Burwash et. al. (1964), picture the Precambrian beneath the plains. Farquhar and Gertner (1966) have provided a valuable compilation of K/Ar ages for Canada and Greenland.

Gabrielse and Reesor dealt in some detail with the geochronology of the plutonic rocks of two areas of the Canadian Cordillera, using K/Ar methods, and conclude that broadly speaking, there was a succession of granitic intrusions from quartz diorite in early Mesozoic to miarolitic leucogranite in the early Tertiary in northern British Columbia and a parallel succession in southern British Columbia ... encompassed within a 200 m.y. plutonic cycle.

White, Ericson and Northcote (1965) studied the Guichon batholith of British Columbia, an important producer of copper and molybdenum, and concluded it was one of the early intrusives in the Cordillera with an average date of intrusion of about 200 m.y. Important prophyry type copper and molybdenum mineral deposits with the metallic elements probably of mantle origin appear to be related to the early granitic intrusives of the Canadian Cordillera. This should be a potentially potent prospecting tool, as has been confirmed by the discovery of economic deposits of molybdenum (Endako) and copper (Granisle) related to the Topley granite, which, with Guichon, were pointed out by Baadsgaard et. al. (1961), as the earliest major intrusives of the Canadian Cordillera. Leech (1962) pointed out the existence of Precambrian granitic intrusions in the Cordillera with dates of 675-970 m.y. near the great Pb-Zn mine of Kimberley, B.C. with its 1250 m.y. leads. This observation rules out the possibility that all of the Canadian Cordillera accreted to the continent of North America in post Precambrian time, and suggests that the general outline of the continent has not changed much in the course of geologic time.

Recent developments have made radiometric dating of basic igneous rocks possible, and a number of Canadian laboratories are studying simatic rocks (both intrusive and extrusive) using K/Ar and Rb/Sr techniques. In the Maritimes, Cormier and Kelly (1964) dated the early Mississippian Fisset Brook formation at 349 m.y. a very useful date for establishing the Devonian-Mississippian boundary, and a demonstration of a method that gives promise of being very useful in dating extensive mantle derived volcanic rock series in unfossiliferous sequences. Crockett and McNutt at McMaster University (personal communication) have applied the Rb/Sr dating method to the mantle derived ultramafic rocks of the Mt. Albert Pluton, Gaspé, Quebec, with promising results.

Fahrig (1965) and his colleagues at the Geological Survey of Canada have continued their study of diabase dykes and correlated radiometric dates (using K/Ar) with paleomagnetic data, showing that these dykes were intruded over a short period of time, and that they may yield valuable information on magnetic pole positions over 1200 m.y. of Precambrian time.

In a geochronometric study of the Superior Province near Red Lake, Ontario, Purdy and York (1966) were able, using Rb/Sr techniques, to demonstrate quite clearly that the gneisses and granites gave a consistent 2450 m.y. isochron, suggesting that the gneisses are either not from an ancient crust, or that they were completely equilibrated during the Kenoran orogeny.

Wanless and his associates of the Geological Survey of Canada in a parallel study have confirmed their well established potassium-argon date of 2500 m.y. for the Kenoran orogeny using rubidium strontium methods (Wanless et al., 1965).

The literature on Rb/Sr dating is plagued by the uncertainties in the Rb 87 decay constant. McMullen, Fritze and Tomlinson (1966) have measured this decay constant using highly purified samples of rubidium perchlorate in which radiogenic Sr 87 had been allowed to accumulate for 8 years. They arrived at a value for the Rb 87 half life of $4.72 \times 10^{-10}$ years. If this value is confirmed it will tend to lower many Rb/Sr dates in the literature by about 6%. The beauty of this outstanding experiment is that it will continue to offer further data refining the half life determination for an indefinite period. One might hope that a similar experiment with K 40 may be started.

At the University of British Columbia, Russell, Slawson and Ulrych (1963), have continued their interesting isotopic studies of lead, for which improved analytical techniques have been developed, and new interpretations suggesting a deep or mantle origin have been advanced. An interesting workshop on lead isotopes was held on the UBC Campus, August, 1966. Lead isotope techniques are being applied by Kanasewich and Cumming at the University of Alberta (Robertson, 1966) on galenas from the Yellowknife province of the Canadian Shield (2860 m.y. model age, with a suggestion of a possibly much older date of 4 b.y.).

An intriguing application of radiometric dating was made on the I.O.L. Steen River well beneath the plains of northwestern Alberta. Drilled on a seismic anomaly this well encountered what appears to be a volcanic breccia with an anomalously high geothermal gradient at a depth of 624' and continued in this material to total depth of 1995'. Volcanics intruding this stable section of the Peace River Basin were completely unexpected. (These samples were dated at the University of Alberta for Imperial Oil Limited, who have kindly released the data for publication). Biotite from a depth of 1261' returned a K/Ar date of 560 m.y., while the whole rock volcanic at a depth of 1490' returned a date of 95 m.y., and this was confirmed by a Rb/Sr whole rock plot on samples from 1490 and 1673' of 95 m.y. ± 60 m.y., suggesting a Cretaceous volcanic similar in date to the Crowsnest volcanics (Folinsbee, Ritchie and Stansberry, 1957). Carrigy (1966) has investigated the rocks of the Steen River well in some detail and has come to the rather startling conclusion that some of the breccias may be of impact origin, the result of meteorite impact, and that the whole structure may be an astrobleme.

The area is of particular interest at present as it is on the line of the fabulous Rainbow Oil fields, perhaps 2,000,000,000 barrels of Devonian oil and immense volumes of natural gas encountered in a belt of reefs that extend from Pine Point in the N.W.T. through Steen River, Zama Lake and Rainbow to Fort Nelson in British Columbia.

Gittins has undertaken a study of the alkaline rocks of the Canadian Shield and demonstrated the emplacement of alkaline rocks in the 2400 m.y. old Superior Province in two distinct episodes 1.1 and 1.75 b.y. ago (Hayatsu *et al.*, 1965). Similar alkaline intrusives at Big Spruce Lake on the edge of the Slave Province yield similar 1.7 b.y. dates (Lambert, personal communication).

B. Stable Isotopes

Stable isotopes of upper mantle interest include deuterium, oxygen, magnesium and sulphur, and of these sulphur is of perhaps the greatest current importance. In a study of metamorphic sulphur isotopes in the Grenville Province, Speelman and Schwarcz (1966), clearly demonstrated metamorphic homogenization of sulphur during high-grade metamorphism. Some such mechanism might be invoked to explain the relatively small distribution of sulphur isotope values in sulphide deposits such as those of Pine Point (Folinsbee et al., 1966).

Fritz at the University of Alberta has commenced the study of the stable isotopes oxygen and carbon in carbonates associated with the Pine Point deposit, in an attempt to throw light on the temperature at which the hydrothermal dolomite of this area, and of the more deeply buried Presqu'ile reefs formed. Source of the wave of magnesian solutions that produced this dolomitization is still a matter of controversy ... it is likely that the source lies in the connate brines of the basin, but a deeper hydrothermal source is not impossible.

## II. CURRENT PROBLEMS AND THE DIRECTION OF FUTURE RESEARCH IN ISOTOPE GEOLOGY

In practically all the installations for isotopic studies in Canada one senses a trend towards the application of these studies towards the solution of practical problems.

Many laboratories are using stable isotopes to interpret problems of genesis (Harrison and Whitmore, 1967). These may relate to the origin of oil in particular pools using the tagged sulphur, since it is becoming abundantly clear that sulphur isotope studies can give us a great deal of information about the nature of, and conditions in, a sedimentary basin at the time certain deposits were laid down (Thode and Monster, 1965).

Or it may relate to the solution of the problem of genesis of sulphur (and the associated metals, Cu, Pb and Zn) in stratiform ore deposits such as those at Bathurst ([Tupper, 1960], Kimberley, B.C. [Leech et al., 1962] and Pine Point [Folinsbee et al., 1966]). The great body of data on sulphides tends to indicate a hydrothermal origin from homogenized deeply buried crustal sources for the sulphur in most of these deposits, and deposition in some instances in a submarine volcanic exhalative or perhaps a geyser type environment (Stanton et al., 1966).

Now that a reconnaissance picture of the radiometric dates to be expected in Canada has been completed, the method is finding increasing application in local problems. One of the major breakthroughs in the method has been the application of radiometric methods to the dating of basic rocks. The methods will undoubtedly find wide application in the dating of cores recovered from the Pacific, Atlantic, and Arctic Oceans in an attempt to test the hypothesis of ocean floor spreading as advanced by Vine (1966). Many of the volcanic sequences of British Columbia may lend themselves to a study by a combination of radiometric and paleomagnetic methods, as have the diabase dykes of the Canadian Shield (Fahrig and Larochelle, 1965). Hayatsu at Toronto has undertaken the challenging problem of dating the earth's mantle by measuring strontium and rubidium ratios in olivines.

Cores that may become available from the Grand Banks may be very interesting. Radiometric methods are useful in checking suspected astroblemes ... if the dates are random they would tend to support the meteor impact hypothesis, if related to other major tectonic and orogenic events the argument for terrestrial origin of the features would be strengthened. Cores from many of the Canadian craters are now available and should be studied in an attempt to settle the controversy that rages over the origin of these features.

Isotopic studies of most of the Canadian meteorites have been done abroad, rather than at home. Since we have a reporting network set up which has been demonstrated to be effective in recovering meteorites, the latest of which is Vilna (Feb. 5, 1967), it is likely that we should be devoting more time to a study of these interesting objects, using all the scientific tools at hand. This study has scarcely begun, and yet these objects are probably the closest mantle analogue that man may have for some years, and their study will pave the way to a better understanding of moon materials that may soon be available to the scientific community ... we have been attempting to set up a little international goodwill in this respect by making Canadian meteorites freely available to scientists all over the world.

Magnesium is one of the prime elements of the mantle, and though the isotopes of this element do not easily fractionate, it is possible that with improved instrumental techniques some of the pioneering work of Wanless in this field might yet bear fruit (sialic or simatic).

Tellurium is another of the elements that occurs in significant concentrations in some ore bodies. Krouse has been investigating this element isotopically and some suggestions of fractionation have appeared in the results (personal communication).

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# VOLCANOLOGY

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## I SUMMARY OF PRESENT CANADIAN KNOWLEDGE

### A. Calcic-Alkalic Cycles

The geological record of volcanism and intrusion from early Precambrian to Recent time contains many features which may be interpreted by theories of magma genesis in the upper mantle. Research on the chemical nature and field distribution of the volcanic rocks of Canada is indicating cyclic changes from a calcic or calc-alkaline type of volcanism towards an alkalic type.

(1) Precambrian Cycle. A major volcanic cycle is found in the Archean core of the shield. This cycle shows the change from calcic to alkaline chemical character through 1.5 b.y. Systematic sampling is showing that belt after belt of the Archean volcanic rocks contain calcic and calc-alkaline sequences ranging from basalt through andesite and dacite to rhyolite. Archean alkalic volcanic rocks first appear, in very small amounts, in the latest sequences in the Timiskaming volcanics in the Kirkland Lake area. Even in these small areas, the earliest suite consists of calc-alkaline andesites, trachytes, and quartz trachytes that are transitional to the calcic series of the underlying Keewatin. These calc-alkaline lavas were followed by alkaline trachytes, and potassic mafic and leucitic trachytes, tephrites, and phonolites, which appear to be unique in the Precambrian of the Canadian Shield.

Archean calcic and calc-alkaline granitic intrusions, which do not have basic portions, rose through the crust near the close of the early Archean volcanism. These granitic intrusions now occupy about one-half of the Archean core. Volcanic rocks related to the granites have not been identified, but numerous, related prophyry dikes occur, and may have been feeders of dacitic flows which are now completely removed by erosion. The source of the granitic magmas has not been identified but belts of ancient pyroxene and hornblende granulite paragneiss occur and may be the remnants of the source of an anatectic granitic magma. The continental core was henceforth relatively stable after the granitic magmatism subsided.

Tensional or torsional forces fractured the Archean core several times during the Archean and Proterozoic eras. Fracture direction was controlled mainly by Archean structural lineaments. Tholeiitic quartz-diabase and olivine-diabase rose along the fractures and produced several ages of flood basalts beginning as early as 2500 m.y. ago and ending as late as 1200 m.y. ago. More than sixty alkalic and alkaline ring complexes, probably great volcanic necks, have also pierced the Archean core. Very few of these complexes have been dated, but available dates range form 2600 to 1000 m.y. in age and thus appear to have been the last episode of the cycle in the core of the continent, which has since been stable for 1000 m.y. The impression is thus one of a single great irreversible cycle. Also, it is the same cycle as occurred in the Australian and Rhodesian Archean shields where the geological history is similar.

(2) Late Paleozoic to Recent Cycles in the Canadian Cordillera. The main episodes of volcanism have been established in the broad framework of tectonism in the Cordillera of western Canada. The distribution of volcanic deposits related to each episode within this framework is fairly well known.

Basalt, andesite, and dacite were erupted from many centres within a marine basin of deposition that covered most of the western Cordillera during middle and late Permian time. The Tahltanian orogeny, which affected the entire western Canadian Cordillera during early Triassic time, was accompanied during the eugeosynclinal phase, by the eruption of enormous volumes of andesitic fragmental rocks in central British Columbia and by basaltic pillow lavas and subaerial flows in western British Columbia. Volcanic activity persisted in many places into the early Jurassic period. As a group these late-tectonic rocks are more alkaline than the eugeosynclinal rocks and, locally, they include undersaturated, analcite-bearing flows. Volcanic activity during the late Jurassic-early Cretaceous, Columbian orogeny, was minor despite the extensive emplacement of granitic rocks in the Coast Crystalline Belt during this time. The early Tertiary, however, was a time of widespread explosive volcanism, accompanied by high-level granitic intrusion along both eastern and western margins of the Coast Crystalline Belt. Pyroclastics, including extensive sheets of ignimbrite, formed the predominant deposits during this episode in north-central British Columbia, whereas lavas are more common than in south-central British Columbia. Both rhyolitic ash-flows and basaltic lavas are abundant in the Queen Charlotte Islands. The early Tertiary volcanics, like the late-tectonic Jurassic lavas, are alkaline. Little volcanic activity occurred from mid-Miocene when the great sheets of flood basalt that covered much of the interior plateau of British Columbia were poured out. They are mainly thin, flat-lying flows, but the western edge of the pile has been tilted eastward by subsequent uplift of the Coast-Range Crystalline Belt. Periodic eruptions from central vents continued throughout the Pleistocene, during which time at least fifty small cinder cones and three large composite volcanoes were formed. One of the latter, Mount Edziza, is known to have been active as recently as 630 A.D., and a number of small cinder cones are less than one thousand years old.

The meager chemical and petrographic data now available show that the volcanic rocks which erupted in the Cordillera during every orogenic cycle are relatively poor in alkalies during the early stages and relatively rich in alkalies during the late stages of that cycle. It is also apparent that during any given episode of volcanism, rocks erupted west of the Coast Crystalline Belt are relatively rich in soda, whereas those erupted east of the Coast Crystalline Belt are relatively rich in potash.

(3) Comparison with Tertiary and Recent Volcanic Piles. Recent work in Hawaii has established the same progression from calc-alkaline to alkalic volcanism in single volcanic piles. Thus, we seem to have the general rule that in both short and long term volcanic cycles we have this noticeable progression from calcic to alkaline.

## B. Mafic-Felsic Cycles in the Archean Calc-Alkaline Belts

Individual Archean volcanic piles commonly contain generalized mafic-to-felsic stratigraphic sequences. The lower part of the sequence is tholeiitic basalt with higher members showing small but significant increases in salic constituents, culminating in the eruption of the acidic layer. The eruption of the acidic layer marks the termination of a cycle and is commonly followed by sedimentation resulting in the deposition of volcanic wackes and arenites.

Individual mafic-to-felsic sequences range from 15,000 to 25,000 feet thick and some piles contain two or more mafic-to-felsic sequences. Tholeiitic basalt is the dominant volcanic component. Andesite, dacite, rhyodacite, and rhyolite are generally present in that order of decreasing abundance.

Part of one of the Noranda sequences is exceptional in having no systematic increase of acidity of flows with stratigraphic height. However, the trend of alumina content increases markedly upward in the upper 15,000 feet with the development of high-alumina basalt-andesites. Potash also increases slightly in the high-alumina part of the section.

The basaltic and andesitic portions of the sequences in the Shield are dominantly subaqueous as shown by the predominance of pillow lavas. Felsic sequences on the other hand commonly contain mudflows and ignimbrites and thick non-bedded angular formations typical of subaerial volcanism. Fine layering characteristic of subaqueous deposition of ash and tuff is often lacking, but cobble conglomerates characteristic of upland erosion occur. In other acid sequences evidence of subaqueous deposition is prominent.

## C. Acknowledgements

This report has been prepared from contributions from J.G. Souther, A.M. Goodwin, W.R.A. Baragar, and W.W.

Moorhouse as well as the author. Some data have also been obtained from the recent publications and reports in preparation.

## II SUMMARY OF CURRENT PROBLEMS AND FUTURE RESEARCH

### A. Evolution of Chemical Composition of Magma.

When sufficient chemical data have been accumulated they can be correlated with ages of the various lava sequences. Accurate dating in only beginning in Precambrian volcanic rocks of the Shield, so the dating, chemical, and petrographic work must proceed together. All these data must then be correlated with the tectonic information being provided by the regional geological and geophysical research that is progressing so rapidly.

The correct interpretation of the nature of volcanic rocks is of fundamental importance. Canadian geologists in general have not been familiar with the criteria indicating different environments. Particularly in regard to Precambrian rocks, geologists have not recognized the nature of the volcanic products and they have held the general belief that deformation destroyed diagnostic characteristics. A metamorphic overprint is certainly present but many of the most important characteristics of origin and environment have not been destroyed, even on a microscopic scale. Future geologists will require training to recognize and map these volcanic features.

### B. Relationship of Volcanism to Tectonics.

The collection of quantitative chemical and petrographic data from volcanic rocks of all ages in the Canadian Shield, Cordillera, and Atlantic Provinces are of prime importance in order to establish evolutionary trends of magma associated with multiple orogenic and volcanic cycles. The apparent increase in alkali content of lavas and intrusions throughout a given cycle may provide many clues to tectonic history. The alkali-lime index of individual cycles has a wide range in the Archean Shield and may give a clue to the sequence of its development. Increase of alkali content also provides a possible means of determining the number of cycles that have affected different parts of the Cordillera.

### C. Origin of Increasing Alkali Content.

The cause of increasing alkali content with time is still speculative. Contamination of tholeiitic magmas by crustal material is usually suggested, but this hardly explains the abundant alkalic and alkaline ring complexes in the late non-orogenic stage. Many of these pierce the granitic crust where it is only twelve to fifteen kilometers thick, e.g. in the Kenora region. These rings show all the evidences of violent, rapid intrusion, such as vertical, circular walls, and abundant breccias. It seems that these alkalic rocks must originate in the mantle or intermediate layer. The great abundance and wide distribution of these complexes has only been recognized recently with the advent of wide aeromagnetic coverage. The alkalic complexes need mapping, dating, and petrographic and chemical work. Future lines of research should include geophysical studies to determine the depth and shape of late non-orogenic alkalic ring intrusions and calc-alkaline orogenic granitic rocks. Depth determinations might support the idea of partial melting of mantle or crustal material to produce the range of crustal rocks.

D. Variation of Composition of Lavas with Depth of Origin.

The systematic variation of recent Japanese lavas with respect to distance from the continental margin has been related to their depth of origin. This hypothesis should be tested in the Canadian Cordillera by systematic collection and analysis of samples from all recent cones and flows in British Columbia.

This type of research may possibly provide information concerning the position of the continental margin during several different episodes of volcanism. The apparent change from potash-rich rocks in the eastern Cordillera to soda-rich rocks in the west may also be significant in this respect.

E. Relationship of Volcanism to Plutonism.

A rough correspondence between periods of volcanic activity and periods of intrusion occurs throughout the history of the Cordillera. A genetic relationship can be assumed but detailed studies have not been made of the transition zone between volcanic and plutonic environments, nor has a comparative study been made of coeval volcanic and plutonic rocks in the Cordillera. The Precambrian, too, offers opportunity for such studies with its long succession of orogenies and intrusions at widely distributed time intervals. Studies of this type are needed to provide data on the origin and movement of magma and the processes of differentiation that are operative at different depths. The critical transition zone between volcanic and plutonic environments is exposed to many regions of high local relief in British Columbia.

F. Prediction of Future Eruptions in the Canadian Cordillera.

Periodic volcanic eruptions separated by periods of quiescence have occurred regularly in British Columbia since the last glaciation. The last large eruption occurred less than a thousand years ago and nothing suggests that this is the last of the volcanism. Plans have been proposed for industrial development in north-central British Columbia near these active volcanoes. Thus, an effort should be made to determine the probability of future eruptions. One continuously recording seismometer would be desirable in the region of recent volcanic activity in northern British Columbia. Evidence of liquid magma at depth under existing volcanoes might also be provided by other geophysical research.

## III WORK IN PROGRESS AND CONTINUING STUDIES

### A. The Western Cordillera, British Columbia

(1) Mt. Edziza. (Detailed study of a large Quaternary composite volcano in north-central British Columbia. Geological Survey of Canada: J.G. Souther.) Primary mapping of the central part of the Mt. Edziza volcanic complex was completed in 1966 at a scale of 1:25,000. Detailed stratigraphic sections showing the alternation of basalt with rhyolite and trachyte have been prepared. Pulses of volcanic activity have been related to successive stages of subsidence of a graben-like structure that bounds the volcanic complex on the west. Chemical and petrographic studies are in progress.

(2) Residual heat in the vicinity of a recently active volcano. (Dominion Observatory and Geological Survey of Canada. A. Jessop and J.G. Souther.) The Dominion Observatory and the Geological Survey of Canada are collaborating on a heat flow program. Three deep holes were drilled at varying distances from Mt. Edziza volcano. Thermal profiles will be measured during the summer of 1967 and heat flow calculated to determine its variation with respect to distance from the volcano.

(3) Chemical variation of recent lavas in B.C. (Geological Survey of Canada: J.G. Souther.) Specimens have been collected from seventeen recent cones distributed across the western Cordillera of British Columbia. Chemical analyses of these are expected to give a preliminary indication of the nature of chemical variation with distance from the continental margin. This data will be compared with that from Japan and other regions on the circum-Pacific belt of volcanoes.

(4) Chemistry and petrology of Tertiary lavas of central B.C. (Geological Survey of Canada: H.W. Tipper and J.G. Souther) Chemical analyses of 176 lavas from the early Tertiary volcanics and the late Tertiary Plateau basalts have been made in the analytical chemistry laboratories of the Geological Survey. This data along with a description of the distribution, stratigraphy and petrology of these rocks are being compiled for publication. Preliminary plots of total alkalies vs. silica and total Fe vs. silica indicate entirely different trends for the two groups of volcanics.

(5) Remnant magnetism of Tertiary and Recent Basalts in Northern B.C. (Geological Survey of Canada: D. Symons and J.G. Souther.) A detailed study of paleo-remnant magnetism in rocks of the Mt. Edziza complex will be made in 1967. An array of stratigraphic

sections has been measured in detail and preliminary work is underway on the determination of magnetic stability and scatter in the various rock types.

(6) Structure and Petrology of the rocks of White Lake Basin, B.C. (University of British Columbia: N.B. Church.) The stratigraphy, structural relationships and petrology of the Early Tertiary volcanics of the White Lake Basin are described in detail. This work has defined the type stratigraphy for rocks of this age in southern British Columbia. A mechanism of central collapse, and gravity sliding is proposed to explain the origin of the White Lake Basin breccias. The thesis, which includes a detailed map, will be completed in the spring of 1967.

(7) Early Tertiary Rocks of the Greenwood Area, B.C. (Geological Survey of Canada: J.W.H. Monger, Geological Survey Bulletin in preparation.) This study presents the stratigraphy of Daly's Midway Group and a revision of the nomenclature assigned to these rocks. It demonstrates the similarity of the volcanic stratigraphy over an area of more than 1500 square miles. The basal rocks are alkali-rich, silica-deficient, whereas those in the upper part of the section contain free quartz. The study also demonstrates the relationship of the volcanic rocks to associated plutons and to normal faults.

(8) Takomkane volcano. (University of Toronto: P.A. Peach.) Takomkane volcano in eastern British Columbia 300 miles north of the United States border is probably of late Pleistocene or Recent age because some of the lava is lying on a glaciated surface and the loose ash is unglaciated. The lava is alkaline olivine basalt or trachybasalt containing some leucite and abundant peridotite inclusions, together with inclusions of granodiorite-quartz monzonite in various stages of digestion. Tectonically the volcano is one of a group of five such structures related to a strong linear. This is almost certainly part of a fault system subparallel to the Rocky Mountain Trench.

B. The Precambrian Shield

(1) Yellowknife Volcanic Rocks. (Geological Survey of Canada: W.R.A. Baragar.) The volcanic belt has been measured and sampled at regular stratigraphic intervals. The section at Yellowknife is 45,000 feet thick, that at Cameron River 7,000 feet thick. The rocks in both sections are predominantly metabasalts and were mainly submarine because pillows are found intermittently throughout. Acidic layers occur near the center and the top of the Yellowknife section, and in the upper quarter of the Cameron River section.

The chemical data indicate that the acidic layers mark the termination of volcanic cycles. The modal composition of Yellowknife Group volcanic rocks is close to Nockold's average tholeiitic basalt.

(2) Noranda Volcanic Belt. (Geological Survey of Canada: W.R.A. Baragar.) The rocks studied are part of the Blake River Group of Archean age. The section south of Lake Duparquet is about 40,000 feet thick with neither top nor base defined, that in Aiguebelle Township is 12,000 feet thick. Both sections are predominantly basic to intermediate volcanic rocks and like the Yellowknife assemblage the presence of pillows throughout indicates eruption in a largely submarine environment. Acidic members are not present in either section although acidic rocks are prominent at several levels in equivalent rocks a few miles east of the main section.

Preliminary study of chemical data indicates that unlike the Yellowknife assemblage, systematic increase of acidity of flows with stratigraphic height is not evident. However, there is a marked trend of increasing alumina content upward and lavas in the upper 15,000 feet of the section are distinctly high alumina basalt-andesites.

(3) Coppermine Volcanic Belt. (Geological Survey of Canada: W.R.A. Baragar.) The Coppermine River flows of Middle Proterozoic age are gently dipping plateau basalts, 7,000 to 8,000 feet thick. Detailed mapping of five sections reveals only minor differences in the appearance of the flows throughout the stratigraphic column. Chemical work is in process.

(4) Archean volcanic belts. (Geological Survey of Canada: A.M. Goodwin.) Eight Archean volcanic-rich "greenstone" segments distributed across the southern part of the Superior province have been studied. Some 2,500 sequentially arranged, chemically analyzed volcanic components with supporting stratigraphic information, provide substantial insight into the form, pattern and composition of Archean volcanic rocks.

Individual Archean volcanic-rich piles or accumulations commonly contain generalized mafic-to-felsic sequences in which predominant lower tholeiitic basalt is overlain by increasingly felsic components. Individual mafic-to-felsic sequences range from 15,000 to 25,000 feet thick. One complete mafic-to-felsic sequence together with a mafic capping commonly constitutes a volcanic pile. However, some piles contain two or more superimposed mafic-to-felsic sequences. The total stratigraphic sequence of a pile is commonly 20,000 to 40,000 feet thick. Tholeiitic basalt is the dominant volcanic component. Andesite, dacite, rhyodacite and rhyolite, the other common volcanic components, are generally present in that order of decreasing abundance. With rare exceptions, these volcanic components belong to the calc-alkaline suite typical of active orogenic belts at continental margins. In exception, minor alkalic volcanic components are present locally in the southernmost Archean volcanic-rich belts of the Superior province. These are restricted as far as known to narrow zones at the top of normal calc-alkaline volcanic assemblages.

(5) Rice Lake Volcanic Belt, Manitoba. (Manitoba Mines Branch and University of Manitoba: R.F.J. Scoates and H.D.B. Wilson.) The Rice Lake Belt is being mapped and sampled in detail to determine the origin of individual volcanic formations in this Archean series.

(6) Comparison of composition of volcanic rocks in the Canadian and Australian Archean. (University of Manitoba: H.D.B. Wilson.) Chemical analyses of eighty specimens from Archean volcanic formations in Australia are typical of the calc-alkaline basalt-andesite-dacite-rhyolite suite. Compositions are in the same range as the volcanic rocks of the Canadian Archean. The structures and rock compositions of the two Archean shields appear identical.

(7) Cape Smith-Wakeham Bay volcanic belt, Quebec. (University of Manitoba: H.D.B. Wilson.) An elongate trough of low grade metamorphic lavas and associated sediments overlies the boundary of the Superior and Churchill province gneisses in northern Quebec. The lava samples thus far are high magnesia basalts averaging about 20% magnesia. The belt appears notably lacking in intermediate and acid varieties. The belt is intruded by numerous gabbroic and ultrabasic sills. Chemical analyses and petrography indicate that the ore-bearing ultrabasic sill had a liquid composition similar to that of the basalts but carried large amounts of olivine in suspension in its central portion, and copper-nickel-iron sulphide liquid in a suspension concentrated in the lower portion. The overall composition of the sill is approximately 33% MgO.

(8) Timiskaming volcanics and associated sediments of the Kirkland Lake area. (University of Toronto: D.L. Cooke.) The Timiskaming volcanics of the Kirkland Lake area may be grouped into three suites on the basis of petrography and chemistry. The earliest suite consists of calc-alkaline andesites, trachytes, and quartz trachytes that are transitional to the calcic series of the underlying Keewatin. The calc-alkaline lavas were followed by alkaline trachytes and potassic, mafic, and leucitic trachytes, tephrites, and phonolites, which are unique in the Canadian Shield.

Augite, biotite, plagioclase, and pseudoleucite are the common minerals, while potash, feldspar and hornblende occur in subsidiary amounts. Aegirine-augite and melanite are only rarely encountered. The chemical composition of the volcanic complex is characterized by high alkalies and alumina, and low $SiO_2$, $P_2O_5$, and $TiO_2$.

(9) Textures of Archean volcanics. (University of Toronto: W.W. Moorhouse.) Undeformed Archean volcanics preserve their original textures extremely well, and can therefore provide approximate clues to their composition in their original, unaltered condition. An atlas of typical, well-characterized Archean rocks

and of Mesozoic, Tertiary and Recent lavas of comparable texture is now in preparation.

C. Atlantic Provinces

Spilites and alkalic lavas. Memorial University of Newfoundland: V.S. Papezik.

One hundred and five published analyses of spilitic rocks were used to establish a definition of spilite. It is suggested that spilite be defined qualitatively as "a basic rock of volcanic origin consisting predominantly of minerals characteristic of the greenschist facies". It is further suggested that spilite be defined quantitatively by setting an upper and lower limit for each element. The limits are taken as the average of the 105 analyses plus one standard deviation, and the average minus one standard deviation for each value. The proposed limits are $SiO_2$, 45.18 to 54.62; $TiO_2$, 0.66 - 2.46; $Al_2O_3$, 13.63 - 18.31; $Fe_2O_3$, 1.22 - 6.38; FeO (+MnO), 3.62 - 9.38; MgO, 2.86 - 7.18; CaO, 3.45 - 9.47; $Na_2O$, 3.15 - 5.49; $K_2O$, 0.17 - 2.31; $P_2O_5$, 0.13 - 0.66; $CO_2$, 0.0 - 4.74; $H_2O$, 1.85 - 4.09; Ca/alk, 0.42 - 2.03; Normative An, 15.2 - 40.4 (Barth-Niggli).

The Ca/alk ratio is an important part of the definition.

D. Graphical Methods of Portraying Chemical Data.

Geological Survey of Canada: T.N. Irvine.

Projections have been developed to predict the order of mineral crystallization for a given basalt at low pressures, or for analyzing the chemical variations in a series of lavas in terms of a fractional crystallization model. The projections may be used to relate the compositions of lavas to the more important high pressure minerals, and one projection is potentially useful in the experimental melting of peridotitic rocks of various compositions under various conditions of pressure, water partial pressure, and oxygen fugacity. The projections may also be used for classifying lavas in terms of their chemical composition.

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# METEORITE STUDIES

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## I. INTRODUCTION

The average composition of meteoritic material provides us with the best estimate of the relative abundances of the non-volatile elements in the solar system. Meteorites, however, vary widely in composition from those composed mostly of nickel-iron to the chondrites, composed essentially of olivine and pyroxene. The latter form the most abundant group and are somewhat like basic terrestrial rocks. Although meteorites may not form a direct counterpart of the interior composition of the earth, nevertheless certain physical and chemical properties of meteorites seem to correspond to those inferred for the different layers of the earth's interior. Thus, complete description of available meteorites is considered as part of the Upper Mantle Project.

## II. SUMMARY OF PRESENT CANADIAN KNOWLEDGE

The number of meteorites recovered in Canada is 35 (Fig. 1), less than 2% of the world total. Twenty-five have been finds (16 irons, 2 stony irons and 7 stones). The 10 meteorites recorded as falls have all been stones as might be expected since stones are known to fall more frequently than irons throughout the world*.

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*In discussing meteorites a distinction is made between falls and finds. A fall is a meteorite which was picked up after it was seen to fall; a find is a meteorite which was not seen to fall but was recognized by its diagnostic features.

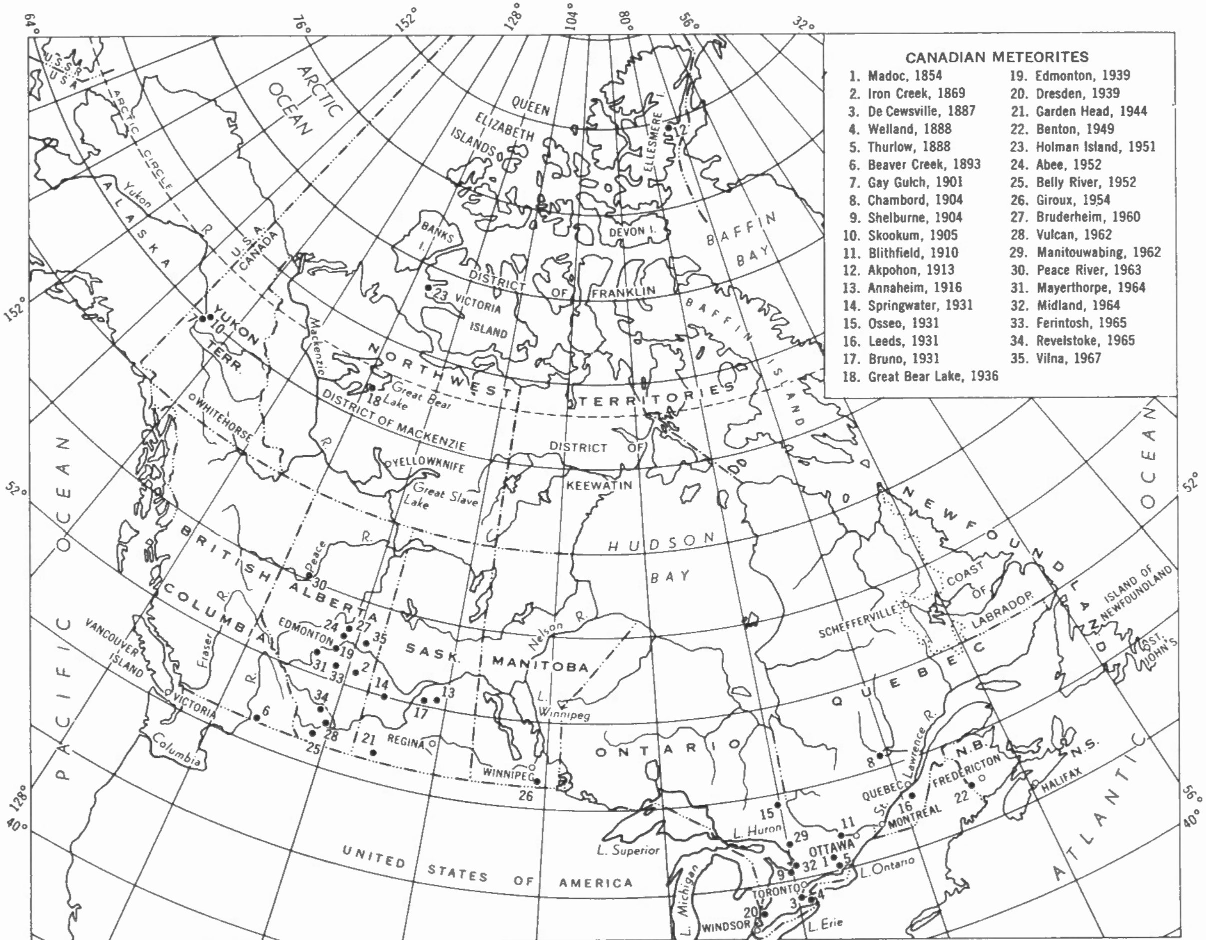


Figure 1. Distribution of meteorite falls in Canada.

Ten of the meteorites have been recovered since 1960, mainly as a result of planned searches and of efforts made by the National Research Council Associate Committee on Meteorites to inform the public about these objects and the phenomena accompanying their fall. Four falls have been recovered in Western Canada. Bruderheim (an olivine hypersthene chondrite) fell in 1960 near the city of Edmonton and nearly 300 kgs were collected. Peace River (also an olivine hypersthene chondrite) fell in 1963 and was recovered as a result of a planned search based on visual observations. Samples of both meteorites were widely distributed for investigation in various disciplines and they are among the most studied chondrites in the world. In 1965, small amounts of Revelstoke, (carbonaceous chondrite) were recovered, the first recovery of this perishable meteorite class in Canada. The most recent fall is Vilna, a grey chondrite.

In the same period the following meteorites were recovered as finds: Manitouwabing (iron, 1963), Garden Head (iron, 1964), Midland (iron, 1964), Vulcan (stone, 1964), Mayerthorpe (iron, 1965), Ferintosh (stone, 1965).

As has been shown by the recent falls in Canada, the documentation of bright fireballs may lead to the recovery of meteorites. In the past six years such investigations have been coordinated through Meteor Centre, National Research Council and by regional representatives of the Associate Committee on Meteorites. Some recent examples of this procedure has been the investigation of three fireballs in Eastern Canada during 1966. (McIntosh and Douglas, 1967).

The Revelstoke bolide of March 31, 1965 is unique in Canada (and with the exception of Tunguska, USSR, for the world) in that its statospheric detonations were clearly recorded on the network of seismic stations set up in Canada for crustal studies. It is possible to locate the "hypocentre" of the principal air blast with reasonable accuracy from the seismic records, for the centre as calculated lies almost immediately above the area where small meteorites from the fall were recovered.

Interest in meteorites in relation to geochronology in Canada dates back to some early K/Ar determinations on these objects (Folinsbee et al., 1956). Other isotopic investigations in Canada have included a study of gamma ray emissions in the Peace River meteorite (Taylor, 1964), isotopic composition of stable krypton (Clarke and Thode, 1964) and of sulphur (Thode et al., 1961).

Recent chemical analyses of five Canadian stony meteorites have been made at the Geological Survey of Canada (J.A. Maxwell). Abundances of palladium, thorium and platinum group metals have been determined in 5 iron and 3 stony meteorites (Sen Gupta, 1967).

The meteorite collections in Canada are small in comparison with the larger collections in various other countries. The principal Canadian collection (the Canadian National Meteorite Collection) is maintained by the Geological Survey of Canada. At present it contains samples of 287 meteorites ranging in weight from a fraction of a gram to over 150 kgs. Other collections in Canada are kept by the Redpath Museum of McGill University, the Royal Ontario Museum and the Department of Geology, University of Alberta. An unknown number of university departments hold a few specimens. Insofar as the Canadian National Meteorite Collection is concerned, samples requested for valid research are supplied where sufficient material exists, in exchange for pieces of other meteorites.

## III. CURRENT PROBLEMS AND THE DIRECTION OF FUTURE RESEARCH

The main task facing those studying meteorites is to ascertain the conditions under which these were formed and their subsequent history. A complete and accurate bulk chemical analysis is needed for an accurate description and classification of a meteorite and often for the interpretation of data obtained by other methods. Important conclusions about the compositional unity of meteorites and the earth have been drawn from chemical analyses while the study of the mineralogical composition of meteorites has shown their peculiarities.

At least one third of Canadian meteorites have not been adequately investigated in these basic disciplines of research and in the light of present knowledge and techniques. Work on these meteorites is in progress at the Geological Survey of Canada.

It has been estimated that 100 meteorites fall in Canada each year. The country is large and sparsely populated, and the recovery of meteorites and documentation of associated phenomena is difficult. Since the prairie provinces are best suited for observations in the fall and recovery of meteorites, the Dominion Observatory is establishing the first station of an all-sky camera network in Saskatchewan, which it is hoped will alleviate part of this problem.

Isotopic studies of Canadian meteorites are underway in Canada and abroad. For example, investigations at the University of Alberta of the sulphur isotope composition of troilite from Bruderheim and Mayerthorpe have been compared with sulphur from Cañon Diablo and the results are impressively concordant.

## IV. SUMMARY OF PROJECTS UNDERWAY

| | |
|---|---|
| Investigation of fireballs in Canada | - Meteor Centre, National Research Council Associate Committee on Meteorites. |
| Composition of Canadian Meteorites in the National Meteorite Collection | - J.A.V. Douglas and J.A. Maxwell Geological Survey of Canada. |
| Heating effects on the magnetic properties of two Canadian iron meteorites | - E.J. Schwarz and J.A.V. Douglas Geological Survey of Canada. |
| Isotopic studies on Canadian Meteorites | - R.E. Folinsbee, Dept. of Geology, University of Alberta. |
| Determination of precious metals in carbonaceous and enstatite chondrites by neutron activation analysis | - J.H. Crocket, Dept. of Geology, McMaster University. |

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# CRATER STUDIES

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The investigation of craters and circular structures in Canada was begun in 1950 and has been actively pursued by the Dominion Observatory since 1954. Structural, topographic, geophysical, and geological surveys, plus diamond drilling programs have been carried out at a number of these structures in an attempt to determine their origin. So far evidence in support of a meteorite impact origin has been discovered at twelve of the craters presently under active study (Fig. 1).

The diamond drilling program continued at Deep Bay, Saskatchewan, and West Hawk Lake, Manitoba, during the early months of 1966. One hole was put down through 376 feet of water at Deep Bay bringing to four the number of drill holes at this crater. After passing through 162 feet of drift and 792 feet of Upper Mesozoic shales, 216 feet of friable, moderately consolidated breccia was recovered before spring breakup forced cessation of drilling. At West Hawk Lake the number of drill holes was increased to four by the three new drill holes in 1966. Preliminary study of the core suggests that the West Hawk Lake crater is slightly smaller, and more deeply eroded, than previously believed.

Detailed geological mapping of three segments around the Deep Bay crater was carried out by P.B. Robertson in July 1966. M.R. Dence continued with the geological mapping of the Brent crater and the gravity survey of the Manicouagan crater also during July.

Intensive petrographic studies of quartz and feldspar in the shocked rocks from all twelve craters have led to the establishment of a progressive scheme of shock metamorphism effects in granitic gneisses, particularly detailed for rocks in the regions of low to moderate shock pressures. This scheme of shock metamorphism has been used to delineate zones of shock metamorphism decreasing in intensity downward below the Brent and East Clearwater Lake craters.

A comparison of the shock effects in rocks from Canadian impact craters with similar effects produced in nuclear explosion craters and in hypervelocity impact experiments reveals that the majority of shock features have been formed at pressures of from 50 to 250 kilobars. Hydrostatic pressures of this magnitude are encountered at from 150 to 170 kilometres below the earth's surface. Studies on the theoretical mechanics of crater formation have been continued by D.W. Sida of Carleton University.

Field investigation of two new crater sites plus geological mapping of other established craters is planned for 1967.

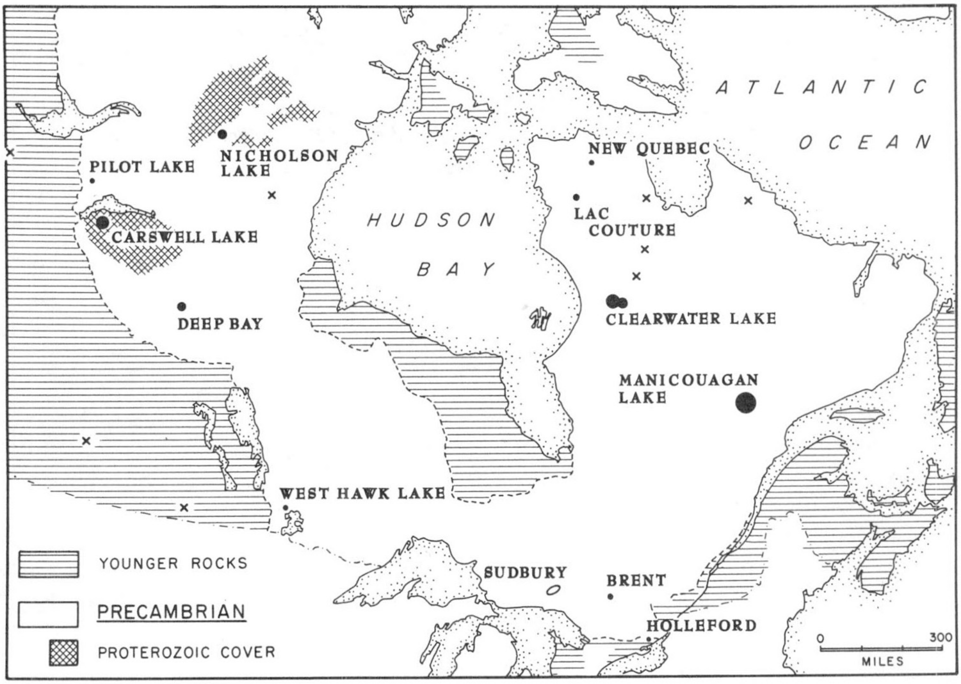


Figure 1. Location of possible meteor craters in Canada.

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# DRILLING FOR SCIENTIFIC PURPOSES

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> "It is difficult to place a price tag on a correct theory, or to assess the cost of an incorrect one except in particular instances. There is much to suggest that inadequate geophysical theories have had more costly consequences recently than in the past by many orders of magnitude, and that a program of verification has become a necessity rather than a luxury."
> - Panel on Solid Earth Problems of the U.S. National Academy of Science

Drilling provides the only direct means (except for mining) of testing the geological and geophysical theories developed from surface observations. Such theories often serve as basic guides to further geological studies, and expensive mineral exploration programs. Hence it is essential that they be fully tested.

Drilling is not commonly considered a glamourous occupation, and is regarded by many earth scientists with disinterest. Few would consider investing part of their own research budgets in a drilling project. True, the gamble is great, but so are the rewards. Consider that surface observations of the crust can only be extrapolated a few hundreds of feet in depth with confidence. Seismic, gravity, and magnetic data can be extrapolated to greater depths, but with less confidence. Interpretations of crustal structure and composition may differ, depending on whether they are made from seismic data or from gravity data. How long can the science continue to construct a 'house of cards' from restricted surface observations before subjecting it to the ultimate test of drilling?

The types of problems that can be evaluated by drilling are varied. Areas of the Canadian Shield represent some of the oldest crustal rocks identifiable. Their foundations can be explored by seismic probing tested by deep drilling. Heat flow studies, carried out in holes deep enough to allow measurements below the affect of Pleistocene glaciation, will provide more meaningful data than is now obtained in shallow holes. In this manner the earliest history of the continent can be explored. Its thermal history, and the influence of radioactivity on it, can be evaluated. The current migration of fluids and gases in the crust, and their metal contents, can be determined. In younger terrains, such as parts of the Cordilleran belt, the possible presence of shallow magma chambers related to potential volcanic centres can be ascertained. Major tectonic boundaries, such as exist between tectonic provinces of the Canadian Shield, or thrust structure in the Appalachians and Cordillera may be further tested. Type sections, drilled through sedimentary basins or volcanic piles, will provide a more meaningful base for studies in crustal geochemistry. These are but some of the types of problems that would be aided by drilling programs.

The obstacles to scientific drilling are obvious and considerable. The cost is high (from $100,000 to $1 million for a 10,000 foot hole depending on design and location to $127 million (+) for a mohole). Such costs cannot be met by research groups and will indeed depend upon governmental sponsorship. The International Upper Mantle Committee, meeting in Ottawa in September, 1965, recommended that

> "Drilling for increased fundamental knowledge of the deeper parts of the crust and the upper parts of the mantle should be considered by governments and government agencies as an integral part of scientific activities sponsored by them. They should make continuing budgetary provision for such work, which should be undertaken only on a basis of adequate geological and geophysical knowledge."

Herein arises a basic question of priority in the funding of earth science research. Should money be diverted to test fundamental tenets of geology or geophysics, rather than guided into the purchase of research facilities to perpetuate the present trends in research? There is a lack of agreement on this point.

A second obstacle to scientific drilling is the lack of equipment for deep penetration. Diamond drill holes in Canada have barely passed 8,000 feet, while rotary drilling for oil has penetrated to 16,540 feet. The design and testing of new equipment, the use of new materials, and other improvements in efficiency are being carried out at present to meet the needs of the exploration industry. This industry is, however, interested in relatively shallow depths of penetration and, if progress is to be achieved in the next generation, the scientific community will have to co-operate with industry in providing the guidance and support needed to develop the equipment required for deeper penetration.

Other limitations include the need to develop better logging tools for in-hole measurements, and the need to improve the technique of interpretation of geophysical logs (especially in crystalline terrains). Despite the obstacles the fact remains that those engaged in the growth of earth science knowledge in Canada must accept the need to encourage and conduct drilling programs on a greater scale, in order to test geologic and geophysical deductions. In the meantime, the careful definition of potential sites must continue, and the present co-operation between the mining industry and scientists in the use of existing holes for geophysical measurement must be nourished.

## SUMMARY OF CURRENT PROJECTS IN CANADA

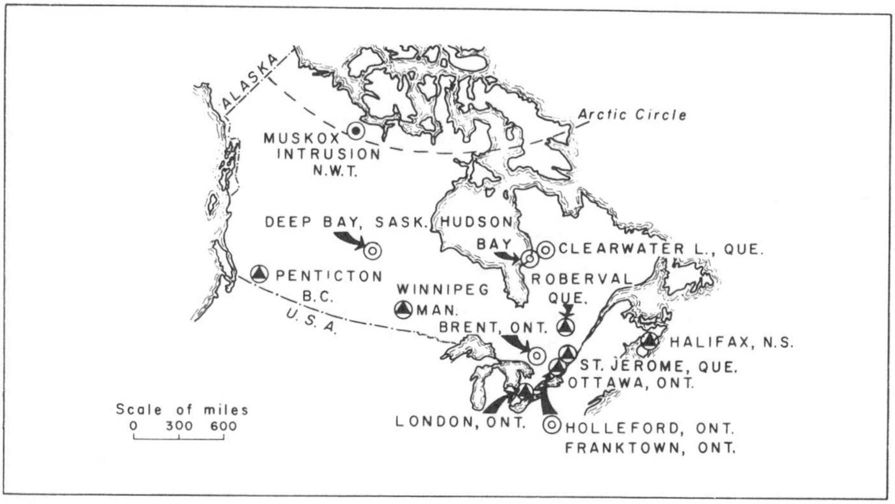
Since the inception of the Upper Mantle Project, a number of drilling projects have been designed and completed for basic scientific data. The nature of the project has been described in previous Canadian progress reports, and in the references following this report. Their locations are shown in Figure 1.

During the winter of 1965-66 a bore-hole was drilled to 10,060 feet in the Pre-Cambrian Renyard Lake granodiorite pluton near Creighton, Saskatchewan. Drilled with a heavy oil-well rig, this is the deepest hole known to date in Shield rocks in North America. Although it was not drilled primarily for scientific purposes, scientific studies carried out and currently in progress will yield valuable data on this fairly typical granitic Shield environment. Heat flow studies are being undertaken in co-operation with the U.S. Geological Survey. Petrographic, chemical and age determination studies are in progress on core and cutting material obtained from the bore-hole. Preliminary results indicate that the granitic intrusion penetrated is not homogeneous, but that a transition to more mafic rock types occurs with depth.

Ten bore-holes have now been drilled specifically for measurement of heat flow as part of the heat flow program of the Dominion Observatory. The locations and depths are:

| | | | |
|---|---|---|---|
| Ottawa, Ontario | 2000 ft. | Roberval, P.Q. | 2000 ft. |
| Halifax, N.S. | 1200 ft. | Winnipeg, Man. | 2000 ft. |
| Penticton, B.C. | 2000 ft. | Dease Lake, B.C. | 950 ft. |
| London, Ontario | 2000 ft. | Hotailuh Range, B.C. | 1400 ft. |
| St. Jerome, P.Q. | 2500 ft. | Buckley Lake, B.C. | 1400 ft. |

The original policy of drilling holes at widely spaced sites has been abandoned in favour of the investigation of specific geophysical features by means of groups of holes. The first such group consists of the last three holes listed above; one is in a volcanic belt, while the other two are outside it, the total spread being about 100 km. The original idea of a nation-wide heat flow survey has not been forgotten, but is being implemented where possible by means of holes drilled for other purposes.




| | *CRATER STUDIES* | *HEAT FLOW* | *ULTRAMAFIC ROCKS* |
|---|---|---|---|
| | ◎ | ▲ | ⦿ |
| YEAR BEGUN | 1954 | 1962 | 1963 |
| NUMBER OF HOLES | 24 | 7 | 3 |
| TOTAL FOOTAGE | 28,969' | 13,700' | 10,089' |
| RANGE IN HOLE DEPTHS | 202-3,491' | 1,200-2,500' | 2,496-4,000' |

Fig. 1. Summary of current and completed Canadian drilling projects.

A limited down-hole geophysical logging program carried out as a part of the Muskox Drilling Project in 1963 included self potential, resistivity, gamma ray, neutron, and geophone velocity surveys. The results of the program indicate that the neutron log is most useful log for igneous rocks such as the Muskox sequence. Features such as contacts between rock layers and changes in degree of serpentinization of ultramafic members are clearly indicated by the neutron record. Other surveys not included in the Muskox program would probably have contributed valuable ancillary data, notably continuous velocity or sonic as well as caliper logs. A tentative value for heat flow of 1.3 $\mu$ cals/cm$^2$/sec. has been obtained for the bottom part of one of the bore-holes.

Undersea Rock Drill (J. Brooke, R.L.G. Gilbert, Bedford Institute of Oceanography)

With the development of techniques for detailed investigation of the ocean bottom, marine geologists and geo-physicists have had a requirement for an economical tool that would extract rock samples from outcrops on the ocean floor. The hitherto employed techniques of dredging the ocean bottom with a bucket are too imprecise to satisfy modern scientists. Of special interest are oriented samples recovered from rock *in situ*.

A drilling rig is being developed at the Bedford Institute of Oceanography to enable small rock cores to be recovered from the sea-floor (see cover of this report). The first model was tested at sea in November 1965. Development has been continuous since that time; sea-trials were carried out in the summer of 1966, and more are planned for the summer of 1967. The trials so far have shown that the motive unit provided sufficient energy to drill a core about 3 cms. in diameter by 10 cms. long from hard calcareous sediment. Many problems remain to be solved, not the least being concerned with adequately placing the rig on a suitable sea-floor. It is anticipated that cores of the order of a metre long may be obtainable eventually. The sea-trials in 1967 are primarily to measure the energy available from the drill under normal working conditions.

The drilling rig is a self-contained unit weighing approximately 750 kg. in air. Its motive power is derived from the hydrostatic pressure which exists at depth in the sea; two versions have been built, suitable for use at depths between 400 m. and 1800 m., and 1000 m. and 3000 m. respectively. Either can be easily handled by oceanographic ships and untrained personnel. The core diameter is about 3 cms. Only standard parts have been used in the construction and the cost is comparable to the cost of a small undersea camera.

The full usefulness of this instrument will only be assessed after extensive trials at sea. Problems to be solved include station-keeping by ships, location of outcrops suitable for drilling and positioning of the drill. The design of the drill has been carried out by the Mechanical Design group at B.I.O. All the sea-trials so far have been made during cruises of the Geophysics group at the Bedford Institute of Oceanography.

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# GEOPHYSICAL THEORY AND COMPUTERS

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Much of the research which could suitably be reported under the present title is normally included in reports on the particular disciplines. This is particularly true of seismology, geomagnetism and gravity studies. Among these might be noted the application of time-term techniques, by G.F. West of the University of Toronto and others, to the interpretation of the recent Lake Superior seismic measurements. The studies of T. Watanabe at the University of British Columbia pertaining to geomagnetic micropulsations, represent another significant example of the development of geophysical theory. Attention is also directed to the research of D. Hall, University of Manitoba, into the importance of converted waves in crustal seismology and to the digital data link for geophysical data operated by E.R. Kanasewich and G.L. Cumming at the University of Alberta.

The processing, in half real time, of the data from the Yellowknife seismic array is the principal Canadian activity. A special purpose digital computer, with analog input and output, has been assembled at the Dominion Observatory, Ottawa, primarily to effect the routine processing of the Yellowknife data. E. Manchee, D.H. Weichert and K. Whitham are the scientists principally concerned with this program.

The joint program of the Arctic Institute of North America and the Dominion Observatory to study variations in short period records obtained from different Canadian Arctic seismograph stations and more recently from temporary stations in central Alberta is worthy of note. From the comparison of three hundred and five normalized spectral curves calculated from Arctic station records, it is found that some of the peaks and troughs of spectral curves are caused by source mechanism, and some of them by crustal layering beneath the station. Most of the differences in spectral amplitude among stations at the lowest frequency is explained by source mechanism. The large decrement of spectral amplitude with frequency at Resolute suggests increased absorption beneath this station.

Calculations have been made for many crustal and surface layer models using the Thomson-Haskell matrix method. Comparisons between the observed and the theoretical spectral ratio curves for Arctic stations indicate that the observed ratios are generally too small. Studies on the time domain of Alberta P wave coda show large transverse components and scattered phases. This, together with the facts mentioned previously, suggests that horizontal heterogeneity, and perhaps damping of waves in the crustal layers and mixing of waves with slower apparent velocity, are not negligible factors. Under these conditions, excellent agreement between the observed and the theoretical spectral ratios is difficult to obtain even if complicated crustal models are assumed. This project is being completed by R.M. Ellis and P.W. Basham at the University of British Columbia.

C.E. Keen of Dalhousie University has devised a method for the calculation of synthetic seismograms corresponding to head wave or refraction arrivals. Because they are observed as first arrivals in seismic refraction experiments and are not easily confused with other events, they have the potential of providing valuable information about the crust and mantle by means of a study of amplitudes and waveforms. The expression for the head wave arrivals has been derived for a point source disturbance situated in a liquid layer underlain by solid layers by finding a solution of the wave equation which satisfies the boundary conditions. Several waveforms have been calculated and compared with observed seismograms.

R. Ravindra (formerly Ravindra N. Gupta) has already published plane wave reflection coefficients for transition layers, with arbitrary variation of elastic parameters, between two homogeneous elastic half-spaces. The problem is being generalized to transient, point sources to study the dynamical characteristics of head waves from second-order discontinuities.

Other theoretical studies include (1) a comparison of the effects of inhomogeneity and anisotropy on the dispersion of Rayleigh waves, and (2) the relationship between the direction of particle movement and that of energy flow in these inhomogeneous elastic media in which the P and S wave potentials can be separated.

At the University of Western Ontario, C. Carmichael and E. Lilley have used the computer to calculate theoretical anomaly maps assuming induced dipole sources at various latitudes. Plotting routines were used to produce the maps as direct output. These maps allowed the optimum flight paths for detecting such anomalies to be determined. Theoretical anomaly profiles for three flight levels were computed for various source geometries appropriate to the Marathon, Ontario intrusive. The ratios of these profiles were compared with data from actual flight paths to indicate the most probable source geometry.

The theoretical temperature-time curves for a uniform cylindrical heat source with contact resistance, imbedded in an infinite medium, were computed by J.H. Sass. Various models of mineral assemblages in rocks have been studied to determine those most appropriate in explaining the thermal conductivities of the rocks.

R.F. Mereu has developed an iterative method of solving the time-term equations. The equations were modified in such a way that the method becomes applicable even though the seismic velocity was unknown. The method has the advantage over matrix inversion methods that it does not tax so severely the storage capacity of a computer. The computer was also used to determine apparent angles of emergence of the seismic waves arriving at Marathon, Ontario during the Lake Superior experiment of 1963. Miss A.E. Stevens applied the computer to the solution of force mechanism equations. It was shown how the forces operating at a focus of an earthquake can be determined objectively using the S data alone. In this work the polarization angles of the S waves were also determined by a least squares method. W.G. Milne, with the aid of the computer, showed how the extreme value theorem of statistics can be used to determine the return period of earth movements of a given magnitude in a given area. A seismic zoning map was drawn which shows the probability of earthquake damage in various areas of Canada. Mr. Dubey is using the computer to analyse elastic pulses which are generated by impacts. The analysis involves both experimental and theoretical work. A series of studies of thermal convection is being initiated by D.E. Smylie and C.P. McFadden.

H. Hasegawa of the University of British Columbia and J.C. Savage of the University of Toronto have completed a theoretical study of the attenuation of Rayleigh waves in the frequency range 100-500 kilocycles per second and in the strain range 4-40 micro strain. In all cases the internal friction, 1/Q, was observed to increase with frequency.

At the University of Toronto, A. Spector is endeavouring to apply the techniques of generalized harmonic analysis to the problem of extracting regional information from total-field aeromagnetic maps. He is working under the supervision of F.S. Grant.

D.H. Weichert and R.D. Russell, at the University of British Columbia, have developed a procedure for the computer reduction of mass spectra. The output from the mass spectrometer is recorded continuously on magnetic tape and the tape is fed into an IBM 7040 which applies direct filtering to substantially increase signal/noise ratio and which effects the required deconvolution of the lead trimethyl spectra. At the same university K.O. Westphal (Marine Science Branch, Department of Energy, Mines and Resources) has been working on heat conduction problems involving phase changes. In particular, he has extended the theory of ice formation under the influence of a linearized Stefan-Boltzmann radiation law.

M.A. Chinnery has computed the effect of large scale faulting using dislocation theory. A principal conclusion is that the vertical movements accompanying horizontal shear form a rather complex pattern of uplifts and depressions which may be 1-3% of the total horizontal movement. The scale of such effects may be very large for large (i.e. 1000 km) transcurrent faults.

At Memorial University an IBM 1620 computer was used by E.R. Deutsch to obtain estimates of the polar shift that should have resulted from specified crustal rearrangements due to continental drift. The Milankovitch model was adopted, with standard, tabular continental sections in perfect isostatic equilibrium with standard oceanic crust, and smoothed coastlines parallel to latitude circles or meridians. From the results it appears that polar wandering is restrained by (1) the diversity of mass distribution prior to drift, and (2) by partial compensation of torques contributed by the drifting crustal blocks. Another possibility is that the effective mass asymmetry is in the mantle.

Computer-oriented methods have been developed by B.K. Bhattacharyya of the Geological Survey of Canada for analysis and interpretation of all available aeromagnetic data in Canada. Research is being carried out at present to develop an accurate and reliable method for treating non uniformly spaced data. The objective of this study is to eliminate the random error associated with interpolation between flight lines otherwise necessary for digital manipulations. Some progress has also been made in the development of a method for calculating complex Fourier spectrum of two-dimensional data.

The Bedford Institute of Oceanography acquired two Digital Equipment Corporation PDP-S computers for shipboard use in 1966. They are identical and consist of the standard configuration with the addition of high speed reader and punch and 31" Calcomp incremental plotter. An extra teletype unit is taken to sea for off-line listing work. Each computer has been to sea for one extended cruise. One unit was at sea for 72 days during which it was operated for 407 hours. The other unit has been at sea for 81 days, with over 500 hours operation. No maintenance has been required in the total of 153 days at sea. However, it should be noted that the ship on which the computers were used, the HUDSON, is air-conditioned.

Geophysics programs were used to calculate magnetic and free-air gravity anomalies. Programs to plot the ship's track from DECCA navigation data, and from ranges and bearings on radar transponder buoys were used. An on-line geophysical data monitoring program was developed and run at sea.

The principal activity of the Working Group on Theory and Computers of the International Upper Mantle Committee has been the organization of annual symposia. It is expected that Canada will extend an invitation to hold the 1969 meeting in Halifax, Nova Scotia.

# LAKE SUPERIOR STUDY

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The "Lake Superior Project" was first conceived in 1962 by Dr. John Steinhart of the Carnegie Institution, Washington, as an intensive seismic refraction study of a Precambrian Shield area, to be made cooperatively by research groups from the U.S.A. and Canada. The field program which he developed was carried out in July 1963, and the results of the experiment were very surprising. A very complicated crustal structure was found instead of the simple, classical, crustal layering which had been expected. The difficulties that were encountered in interpreting the 1963 experiment data and the exceptionally large distances to which explosions in Lake Superior could be recorded, together with the long standing interest of geologists in the Lake Superior basin have lead to a continuing program of geophysical exploration of the region. Also, the cooperative nature of the initial seismic program has helped foster continued cooperation between research groups, both for Lake Superior region studies and for other seismic explosion studies carried out since 1963.

Because the program of work has been a joint American-Canadian venture and so much of the observational data has been exchanged for interpretational studies, it is very difficult to describe the scientific results in a purely national manner. We therefore apologize in advance for reporting some of the American work in the Canadian National Report, but hope that a general scientific review will be more useful to a reader than a listing of Canadian-made measurements.

## I. REVIEW OF STUDIES

### A. The 1963 Experiment

The first experiment consisted of a pattern of 78 one ton charges detonated on the bottom of Lake Superior during July, at a rate of about five per night. The blasts were recorded by 46 recording crews, in addition to a number of observatories and an AFTAC station. Nine of the crews were Canadian; three from the Dominion Observatory of Canada, two each from the Universities of Alberta and Toronto, and one each from the Universities of Western Ontario and Manitoba. They recorded at 12 sites. The

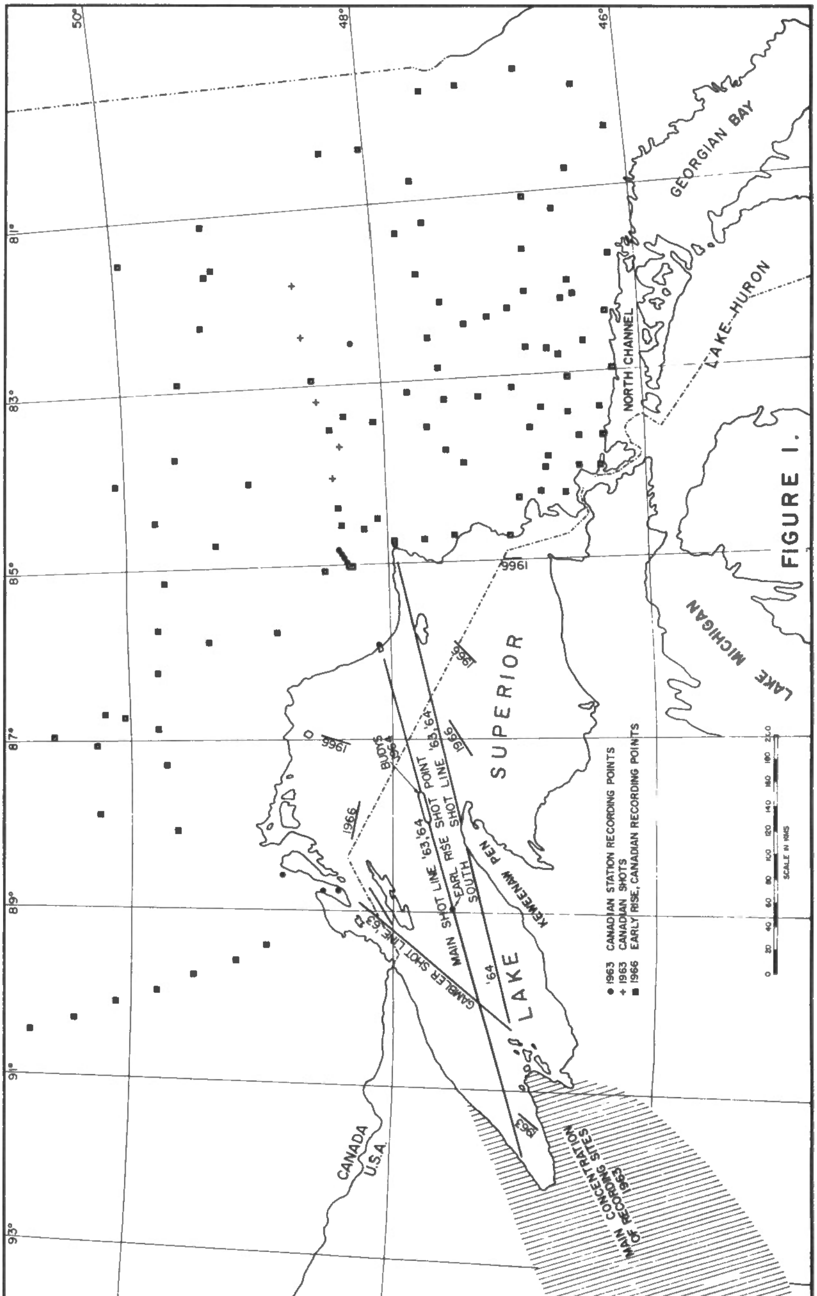
LAKE SUPERIOR
GEORGIAN BAY
NORTH CHANNEL
LAKE HURON
LAKE MICHIGAN
MAIN SHOT LINE '63,'64
SHOT POINT '63,'64
EARL RISE SHOT LINE
GAMBLER SHOT LINE '63
BUDYS
SOUTH
KEWEENAW PEN.
CANADA
U.S.A.
MAIN CONCENTRATION OF RECORDING SITES 1963
● 1963 CANADIAN STATION RECORDING POINTS
+ 1963 CANADIAN SHOTS
■ 1966 EARLY RISE, CANADIAN RECORDING POINTS
SCALE IN KMS

FIGURE I.

shooting was done by the Carnegie Institution from the USCG Cutter Woodrush. Shot locations were obtained by recording the water wave arrivals at eleven sites, three of which were manned by Canadian crews. A shooting crew from the Dominion Observatory detonated five shots in lakes to the east of Lake Superior in an attempt to reverse the eastern profile. These shots were not widely recorded, however, since the lakes used were shallow and the shots inefficient. The principal features of the shot and station location pattern are shown in Figure 1.

First arrival times of all recordings were submitted on punched cards to a compilation that was published by Steinhart (1964) together with a description of the experiment and the shot times and positions. The compilation contains some 3000 travel times and has constituted the basis of a number of interpretation studies made by various research groups.

### B. The July 1964 Experiment

In the summer of 1964, the University of Wisconsin detonated a series of shots in the Lake. The south line of the 1963 experiment was reshot and extended west of the Keweenaw Peninsula, with recordings made on land. The 1963 main line was then reshot with recordings at a buoy station in the Lake. Buoys were operated by the University of Wisconsin, and by the Southwest Center for Advanced Studies. The University of Western Ontario was the only Canadian group to participate in this experiment.

### C. The October 1964 Experiment

Because the shots of the 1963 Lake Superior Experiment had been extraordinarily well recorded at large distances (about 2000 km), the U.S. Geological Survey detonated a series of charges during October 1964, in a region near the west end of the Lake, the chief purpose of which was to enable them to record a profile running toward the Nevada nuclear test site. The shots were recorded by a number of other crews as well. The Dominion Observatory with two crews and the University of Toronto with one crew, recorded at several sites northeast of the Lake in an attempt to define the crustal thickness.

### D. The July 1966 "Early Rise" Experiment

The October 1964 experiment showed that a five ton charge detonated in Lake Superior could be well recorded at distances up to 2000 km, thus opening up the possibility of performing a refraction survey penetrating into the upper mantle, using only chemical explosives. The experiment, carried out in July 1966 under the name "Early-Rise", was sponsored by the U.S. ARPA under the Vela Uniform Program. Thirty-eight five ton charges were detonated at a fixed site in the Lake, at the rate of about two per night. Recording crews worked along radial lines from the shot point, as shown in Figure 2. Canadian crews from the Universities of Alberta, Manitoba, Toronto, and Western

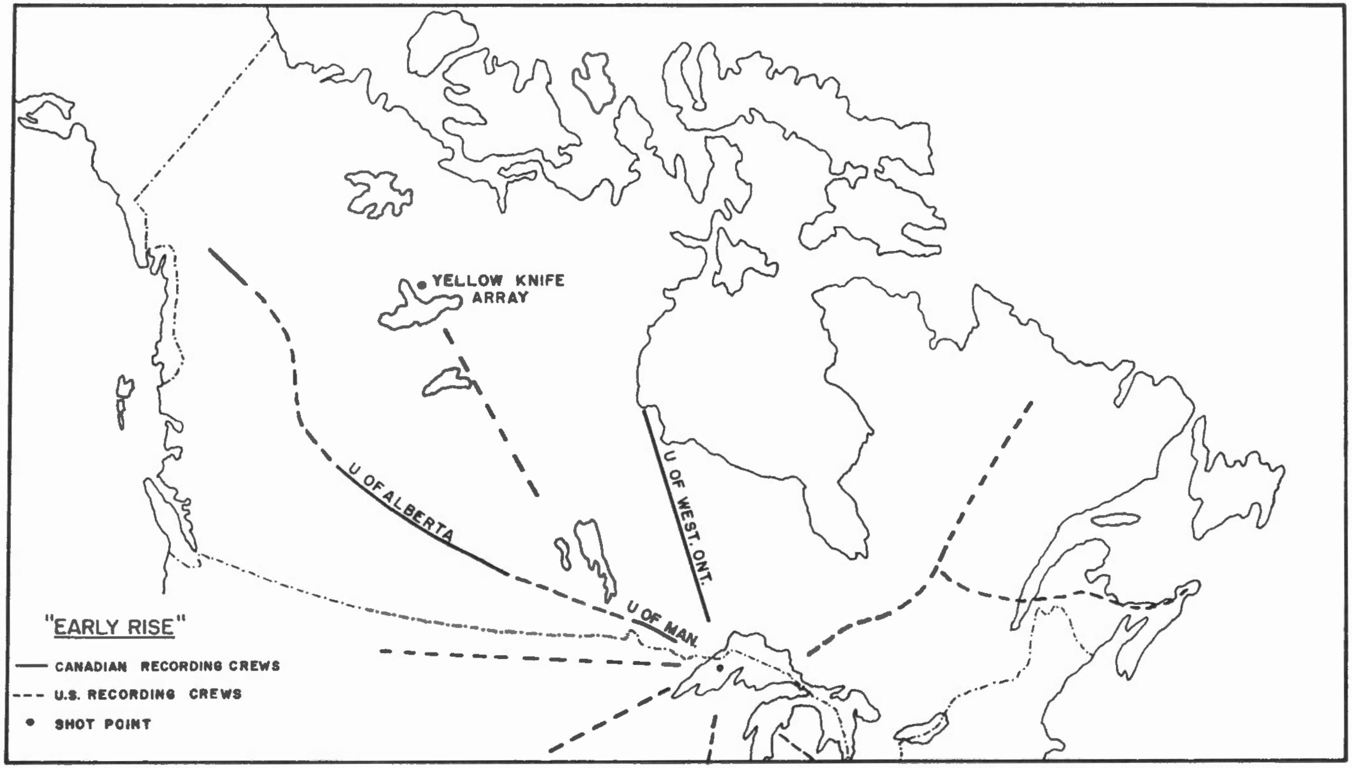


Figure 2. Recording profiles in Canada for the 1966 "Early Rise" experiment.

Ontario participated in the experiment. Some American crews also recorded in Canada. Although the principal aim of the experiment was to investigate sub-crustal conditions, the Universities of Manitoba and Toronto took advantage of the shots to investigate crustal structure by recording at moderate range over a network of sites. A compilation of all "Early Rise" observations is being made and will be available to all participants for interpretation studies. However, it was not available at the time of writing.

E. Shallow Seismic Studies

The buoy observations of the July 1964 experiment provided considerable information on the velocity structure of the upper few kilometers of the Lake Superior basin that was not available from the 1963 experiment. In August, 1966 the University of Toronto obtained a number of reconnaissance refraction profiles in the northern and east-central parts of the Lake. The University of Wisconsin has operated a sub-bottom profiler over parts of the western end. These seismic data, when combined with gravity and magnetic surveys, should provide a good picture of the geological structure down to depths of 10 km or more.

F. Gravity Studies

The Dominion Observatory made a reconnaissance underwater gravimeter survey of Lake Superior, the North Channel of Lake Huron, and Georgian Bay during September 1964. A Bouguer gravity map has been published which constitutes the only complete survey of the Lake area to date (Weber and Goodacre, 1966). Detailed underwater surveys of the western end are being carried out by the University of Wisconsin, but have not yet been published. The Dominion Observatory conducted a gravity survey around the Lake on a roughly eight mile grid during the summer of 1965. The results are not yet published. The University of Manitoba has also carried out surveys in the Chapleau, Kapuskasing region of Ontario.

American land coverage is very detailed in comparison with that in Canada. For example, very detailed surveys have been made over the mid-Continent Gravity High, which starts from the southwest end of the Lake and is caused by Keweenawan formations of the type which form the Lake Superior basin.

G. Magnetic Studies

Aeromagnetic surveys on ¼ mile lines at 1000 ft. terrain clearance have been conducted by the Geological Survey of Canada and the Province of Ontario throughout the Canadian part of the Lake Superior region. Maps at an inch to a mile and compilations at 1:250,000 were published in 1964 and earlier. More recent publications cover the Kapuskasing feature (Figure 3) which may be related to the Lake Superior structures. The surveys are

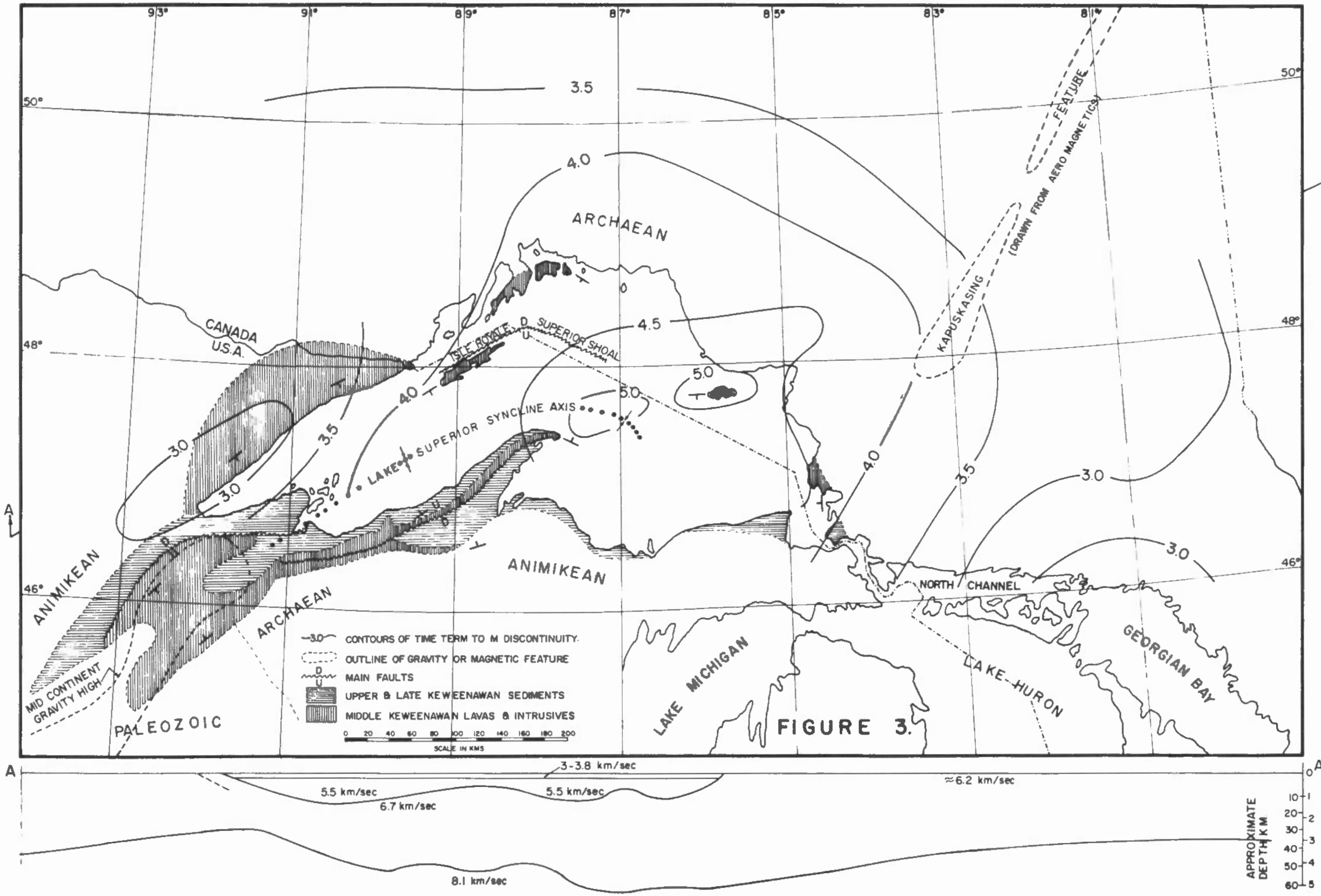
3.5
4.0
4.5
5.0
3.0
ARCHAEAN
ANIMIKEAN
PALEOZOIC
CANADA
U.S.A.
ISLE ROYALE
SUPERIOR SHOAL
LAKE SUPERIOR SYNCLINE AXIS
KAPUSKASING
(DRAWN FROM AERO MAGNETICS)
FEATURE
MID CONTINENT GRAVITY HIGH
NORTH CHANNEL
GEORGIAN BAY
LAKE HURON
LAKE MICHIGAN
CONTOURS OF TIME TERM TO M DISCONTINUITY.
OUTLINE OF GRAVITY OR MAGNETIC FEATURE
MAIN FAULTS
UPPER & LATE KEWEENAWAN SEDIMENTS
MIDDLE KEWEENAWAN LAVAS & INTRUSIVES
SCALE IN KMS
3-3.8 km/sec
≈6.2 km/sec
5.5 km/sec
6.7 km/sec
8.1 km/sec
APPROXIMATE DEPTH KM
TIME TERM, SEC
A
A'

FIGURE 3.

remarkably useful in tracing major geological structures in the Superior province, and where there is coverage, of the Keweenawan basin also.

Magnetic coverage of the American part is complete in a few regions, and very sparse in others. A relatively high altitude survey of the Lake and the immediately adjoining land areas has been published by the Universities of Wisconsin and Michigan. This map is very helpful in outlining the Keweenawan geological structures that underlie the Lake. A more detailed survey has been made in the Isle Royale area by the University of Toronto, using a ship-borne magnetometer.

Palaeomagnetic studies have been made of a number of formations in the Lake Superior region. The most comprehensive study was made by P.M. Dubois (1962) of the Geological Survey of Canada. Additional relevant studies have been made by the University of Western Ontario as well as by a number of American workers. Besides providing much useful structural information, it seems that a reasonably coherent picture of magnetic pole wandering can be determined for Keweenawan time.

## H. Age and Isotope Studies

The main geochronological studies of the Lake Superior region are those of Goldich *et al* (1961) and Silver and Green (1963). A few of the ages determined by the Geological Survey of Canada in their comprehensive program for the Precambrian Shield are relevant to the region. A study of alkaline intrusives in and near the Kapuskasing lineament has been made at the University of Toronto (McIntyre, 1966).

## I. Geological Studies

The Lake Superior region has been under active geological study for a century, chiefly due to the iron and native copper deposits found there. Geological mapping is still far from complete, especially in Canada. Access to many of the poorly mapped areas is still relatively difficult and it seems likely that it will be some time before substantial progress has been made. A review of the work to 1965 has been published by Halls (1966) of the University of Toronto.

To help correlate the geophysical and geological surveys, Halls has made a large collection of samples on which physical property measurements are being made (seismic p wave velocity to 2 kilobars, magnetic susceptibility and remanence, density).

## II. REVIEW OF SCIENTIFIC PROGRESS

Prior to 1963 the existence of a major synclinal axis running northeast through the western part of Lake Superior was well known. Geological mapping showed that the Lake was apparently underlain by a great thickness of Precambrian clastic rocks, which themselves were underlain by intermediate and basic volcanic rocks. The volcanics, at least where they outcrop on the shore, were known to have a very great thickness and had been dated at 1.1 billion years. At least in some regions these Keweenawan rocks were found to overlie Animikian formations dated at 1.8 billion years.

Towards the southwest the syncline can be traced ashore but disappears about fifty miles from the Lake under flat-lying Palaeozoic rocks. The axis of the structure was assumed to follow the mid-Continent Gravity High, the basic volcanics being a relatively dense formation. On the southeast side of the basin, on the Keweenaw Peninsula, the syncline is bounded by a high-angle thrust fault that is overthrust to the southeast.

East of the Keweenaw Peninsula much less was known of the geological structure, although Keweenawan clastic volcanic rocks had been mapped in several places. Much farther to the northeast, striking northeast through Kapuskasing and Chapleau, a gravity lineament was known. One could speculate about the relationship of this feature and the mid-Continent Gravity High.

Early seismic refraction crustal thickness determinations made by American groups both east and south of Lake Superior yielded normal thicknesses (30-40 km). In Canada, an early pioneering profile by Hodgson, south from Kirkland Lake gave similar results. The data has been summarized by Steinhart and Meyer.

The July 1963 seismic experiment revealed (Berry and West 1965, Smith and Steinhart, 1965) that under east central Lake Superior, the base of the crust reaches a depth of 60 km, and the velocity in the upper mantle is 8.1 km/sec (Figure 3). An intermediate refractor (about 6.7 km/sec) which Berry and West correlate with the top of the basic Keweenawan volcanic rocks, was traced everywhere under the shot pattern at depths reaching about 12 km. The velocities in the uppermost layers were very poorly determined however, and while the form of the intermediate refractor was defined, its depth was not well established. The July 1964 Experiment provided more detailed information on velocities above the intermediate refractor, and work by West and Halls in 1966 provides some velocity information for the top few kilometers in a number of locations around the Lake. It seems that the Lake is generally underlain by one or two kilometers of material with a velocity of 3.0 - 3.8 km/sec, beneath which velocities of about 5.5 km/sec are found. An intermediate or transition layer of velocity around 4.7 km/sec may exist in some places. No interfaces or transitions in velocity between the 5.5 and 6.7 km/sec refractors have been detected. It is hoped that a reliable geological identification of the refractors will soon be possible.

The 1966 Early Rise program has produced dual results. In the immediate Lake Superior region, it has defined the eastern and northern extent of the zone of crustal thickening (see Figure 3). It now seems clear that the thick crust is closely associated with the Keweenawan geological structure and does not have a close relationship with the Kapuskasing feature. Of wider seismological interest, the data from the long recording lines have clearly shown that under all of central North America the p velocity in the uppermost mantle increases with depth from around 8.1 km/sec at the Moho to about 8.5 km/sec at roughly 100 km. The depth at which the increase takes place has not, at the time of writing, been accurately worked out, nor is it yet clear from the data whether the increase is gradual or sudden. In any case, the crossover between apparent velocities of approximately 8.1 and 8.5 km/sec is sharp, and occurs variously at 600 - 1200 km from the shot point.

The magnetic surveys of Lake Superior have revealed much information about the Keweenawan basin structure. The structures found on the Keweenawan Peninsula can be traced eastwards off the tip of the peninsula and are seen to turn southeast. Likewise, the strike of the volcanics found on Isle Royale continues northeast for only a short distance before turning sharply southeast towards Superior Shoal, where it terminates abruptly. When combined with seismic evidence indicating the presence of a kilometer or so of sedimentary rocks underlying the Lake between Isle Royale and the mainland, the magnetic survey very strongly suggests that a fault similar to the Keweenawan thrust lies just north and west of the Isle Royale-Superior Shoal formation. Several other possible faults are indicated by the magnetics, including one striking northeast that apparently causes the abrupt termination of the Isle Royale-Superior Shoal trend. The Geological Survey of Canada - Province of Ontario surveys have clearly revealed the extent of the Kapuskasing feature. It runs northeast from Chapleau out into James Bay. Archaean, east-west trending greenstone belts which are also clearly visible on the magnetic maps, seem to be distorted over a broad zone near the feature. The surveys also reveal many of the diabase dike swarms and a number of major fault offsets.

So far, relatively few conclusions have been drawn from the gravity surveys. Since both dense (basalts, etc.) and light rocks (clastic sediments) underlie many parts of the Lake, it is necessary to have a knowledge of the thickness of one or other formation before much interpretation can be done. Seismic surveys will eventually provide the necessary information on the sedimentary rocks but these surveys have not yet covered enough of the Lake.

In summary, the geophysical surveys, done largely since 1963, have provided much new information on the Lake Superior structure. Prior to the application of geophysical techniques progress on the regional geological problems was rather slow. While it is too early to speculate on the origin of this major tectonic feature, a much clearer three-dimensional picture of its structure is now rapidly emerging.

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# GEOLOGICAL AND GEOPHYSICAL STUDIES OF HUDSON BAY

C.S. Beals and
A.S. Raffman

Hudson Bay (Fig. 1) lies in a shallow depression on the Canadian Precambrian Shield. Its shoreline is of Precambrian age except on the south where a thin plate of mainly Palaeozoic strata dips gently northward into the Bay, then reappears on the islands in the north. Until recently, little was known of the geological and geophysical features of this vast area, a problem that was once not uncommon in Canada's north.

## I. PRESENT KNOWLEDGE

### A. Geological Investigations

The success of geological mapping from a helicopter and fixed wing craft has permitted the mapping of the barrens of the north with great ease by the Geological Survey of Canada. Beginning with a successful experiment, Operation Keewatin, in 1952 and continuing through Operations Baker in 1954, Fort George in 1957, 1958, 1959, Leaf River in 1963, Wager in 1964 and Operation Amadjuak in 1965, most of the northern Shield surrounding the Bay has been mapped at 8 miles to the inch by the Geological Survey of Canada (Lord 1953, Wright 1955, Eade 1966, Stevenson 1963, Douglas and MacLean 1963, Heywood 1966 and Blackadar 1966). In the south, the provincial geologists have also been active in geological mapping programs and the geology is moderately well known (anonymous 1955, 1958, and 1965a). Reconnaissance surveys have been made of the Palaeozoic lowlands (Nelson and Johnson 1966) and a detailed survey is planned for the summer of 1967 by the Ontario Department of Mines.

Geological mapping reveals the Precambrian Shield as the stable nucleus of the North American continent for at least 600 million years. Since at least the beginning of the Ordovician the Shield has suffered little change in elevation with the exception of 5000 to 7000 ft of uplift in northern Labrador and in the eastern Arctic Islands. The entire southern coast of Quebec and eastern coast of Labrador have been uplifted to heights of 2000 ft, possibly in Pliocene time (Cooke 1947) and the old upland surface dips gently to the north and west into the Hudson Bay Basin. Essentially, the latest warpings of the Shield combined with the effects of prolonged peneplanation and recent glaciation have left the Shield saucer-shaped with high edges sloping inward toward the depression of Hudson Bay.

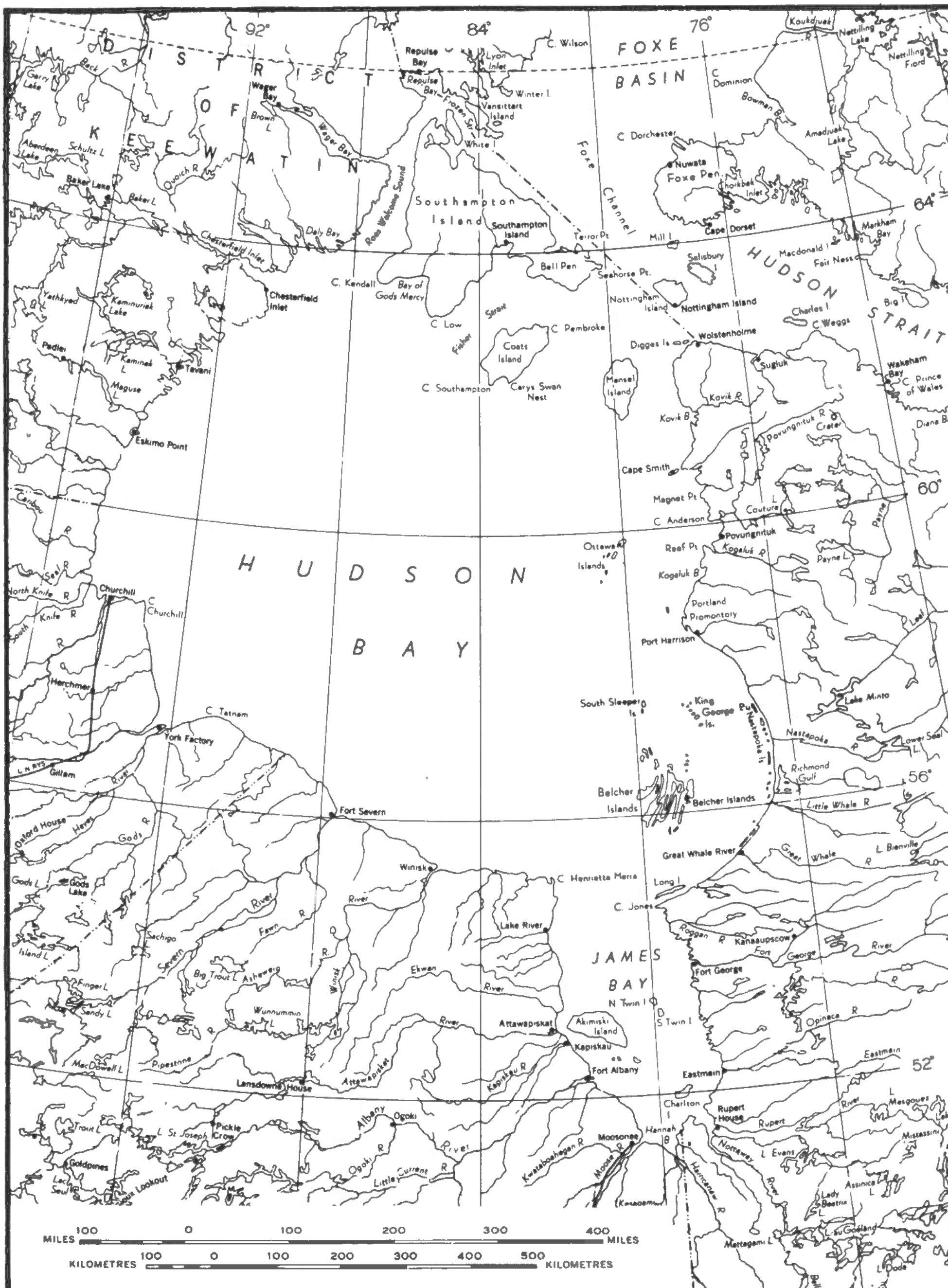


Figure 1. Index map of Hudson Bay

The Palaeozoic rocks give some indication of basement structure; namely, in the Patricia Arch, a major positive element, which trends northwest and plunges under Cape Henrietta Maria (Nelson and Johnson 1966). The Patricia Arch serves to divide the major Hudson Bay Basin from a lesser basin in James Bay. The Bell Arch is a major northwest trending uplift of Precambrian rock that forms the south side of Foxe Basin and Hudson Strait. It appears to be broken into a basin and range province by a prominent fault system (Nelson and Johnson 1966). Mansel Island on the other hand appears to be a broad anticlinal structure.

The Precambrian rocks around the periphery of the Bay are generally granites or gneisses typical of the Shield with linear belts of folded volcanic and sedimentary rocks being found to the west and in the Precambrian to the south. There is, however, an almost total lack of such greenstone belts in the granites and gneisses to the east of Hudson Bay.

Traversing the northern peninsula of Quebec from Hudson Bay to Ungava Bay is the Cape Smith - Wakeham Bay belt; an upper Precambrian sequence of sediments and volcanics intruded by basic and ultrabasic sills, folded and metamorphosed (Bergeron 1959).

The Nastapoka (Manitounuk) Group of slightly metamorphosed mechanical and chemical upper Precambrian sediments capped with basic eruptives forms a 560 km string of offshore islands running from the Portland Promontory to Cape Jones and bordering what Kranck (1951) calls the Belcher Basin. The Richmond Group of coarse ferruginous arkoses with interbedded basic eruptives underlies the Nastapoka Group in the Richmond Gulf area and like the Nastapoka sequence dips seaward with a gentle homoclinal dip.

The Belcher Group which forms the Belcher Islands is composed of 20,000 to 30,000 ft of clastic and chemical sediments interbedded with basic dykes and sills; the thickness depends on the variations of the volcanic units. The Belcher strata have been folded into a series of doubly plunging north-northeasterly trending sharp anticlines and broad synclines. These folds die out to broad gentle warps in Bakers Dozen Islands, King George Islands and other islands to the east (Jackson 1960).

The Ottawa Islands show relatively unmetamorphosed volcanic and sedimentary rocks of Precambrian age. However, they have not been systematically mapped and there is considerable doubt whether they are a direct extension of the Cape Smith - Wakeham Bay belt or the Nastapoka Group. It is also possible to relate them to the Belcher group by following the southward extension on the bathymetry map of the Bay (Grant 1966). Late Precambrian sediments and diabase flows with shallow northward dips are seen in the windows of Precambrian south of Winisk, Ontario and may also be correlated to the Nastapoka Group (Hawley 1926) as flanking deposits of an ancient Precambrian sedimentary basin (Kranck 1951).

B. Magnetic Investigation

In 1961 the Geological Survey of Canada instituted a program of increased aeromagnetic surveying of the total field intensity with the objective of having the whole Shield mapped by 1974. Flight lines are at half-mile spacing with a terrain clearance of 1000 ft. Total intensity maps at 1:63,360 scale are available for most of the western shore of Hudson Bay from Chesterfield Inlet south to the Ontario-Manitoba boundary, for much of the James Bay lowland and for all Ontario south of 53°N. The Hudson Bay lowlands are to be flown in 1967. The whole east coast of James Bay and Hudson Bay has not yet been flown.

The magnetic maps are generally correlated with the bedrock geology. Kornik and MacLaren (1966) have relocated the boundary between the Churchill and Superior blocks north of 56°N partly on the basis of aeromagnetic trends.

In 1961 a sea magnetometer was towed a total of 6500 nm in Hudson Bay. As a result of this survey Hood (1964, 1966) predicted up to 10,000 ft of Palaeozoic sediments might be found in the center of the Bay. He also interpreted the Ottawa Islands to be a seaward extension of the Cape Smith - Wakeham Bay belt.

The Geomagnetic Division of the Dominion Observatory has a number of high altitude survey lines which cross Hudson Bay and measure the three components of the earth's absolute geomagnetic field (Bower 1959).

C. Gravity Investigations

Reconnaissance mapping by the Gravity Division of the Dominion Observatory has covered all of the Shield around Hudson Bay on a 30 km spacing. As yet detailed maps from only three areas have been published: 1:50,000 sheets of west-central Quebec and of the northern part of Quebec and a large-scale map of northern Ontario and Manitoba (Tanner 1961, Tanner and McConnell 1964, Innes 1960).

The gravity maps of west-central Quebec commonly show negative Bouguer anomalies and Tanner (1961) interprets such over-compensation as the direct result of a depressed crust resulting from glacial loading. The gravity map of the northern part of Quebec shows very marked linear gravity trends running parallel to the Cape Smith - Wakeham Bay belt. The southern edge of the belt is delineated by a negative anomaly of -55 mgal with gradient of -1/2 mgal/km south from Cape Smith. Tanner and McConnell (1964) interpret the anomalies to be the result of the high density Cape Smith-Wakeham Bay rocks sitting over a 2 km trough in the Moho.

The Bouguer anomaly map of northern Ontario and Manitoba (Innes, 1960) is at a scale of twenty miles to the inch but is being reissued at a 1:500,000 scale. A main feature of the map is the Nelson River High. This feature is 80 to 110 km wide and has been traced 800 km southwest from near the Hudson Bay coast to the Melville - Yorkton area of southeastern Saskatchewan (Wilson and Brisbin 1962); Innes (1960) related the anomaly to near surface rocks. Bell (1966) has done a geological correlation in northeastern Manitoba. Shimazu (1962), analyzing a line from Great Bear Lake to Montreal, concluded that the maximum undulation of the boundary layer at the base of the crust is 2 km in the vicinity of the Nelson River High.

The map also shows a feature Innes (1960) calls the Central Patricia Low. This discordant belt of lows arcs across northern Ontario from southern Lake Winnipeg to the Winisk area. Nelson and Johnson (1966) relate the low to the Patricia Arch. A third gravity feature of Ontario is the Kapuskasing High, a wedge-shaped positive anomaly that originates north of Chapleau, Ontario and broadens to the north to encompass most of the James Bay Lowlands. This feature appears to be a tensional feature and is marked on the west by a large number of northeasterly trending dykes (Anonymous 1965b).

## D. Seismic Investigations

Until 1965 no seismic work had been done in Hudson Bay. Hodgson (1953) used rock bursts in a mine at Kirkland Lake in an early experiment. A single-layered crust 35 km thick was interpreted. In 1961-1964 the University of Manitoba obtained a profile between Flin Flon and Mafeking, Manitoba. Hall and Brisbin (1965) interpreted the results using converted waves and obtained a two-layered crust with depths of 34 and 31 km to the Moho under Flin Flon and Mafeking, respectively. The Geological Survey of Canada has done shallow seismic work in the Hudson Bay lowlands to determine Palaeozoic thicknesses (Hobson 1964 a,b). Permanent seismographs are operated by the Dominion Observatory at Frobisher Bay, Flin Flon, Baker Lake and Great Whale River.

## E. Isotopic Dating

It is only in the last few years that geologists have come to use the concept of Precambrian geologic provinces. This subdivision is based mainly on the analysis of structural trends (Gill 1949). As the concept of structural provinces developed, it was recognized that they might have time significance. The systematic program of potassium - argon dating by the Geological Survey of Canada has resulted in the publishing of the Tectonic Map of Canada (Stockwell 1965). The G.S.C. work shows that the Canadian Shield has undergone three major orogenic periods. The Kenoran orogeny, the oldest, having a potassium-argon age of 2,490 ± 100 my, is typically seen in the Superior province; the Hudsonian orogeny (1,735 ± 95 my) is seen in the Churchill province; the Grenville orogeny (945 ± 65) is typically seen throughout the Grenville province. These orogenies were generally followed by a long period of erosion and by the unconformal deposition of sediments and volcanic material (Stockwell 1964).

The boundary between the Churchill and Superior geologic provinces is quite well known in Manitoba and is nominally parallel to the Nelson River High. The contact is drawn at the sheared northwest edge of the Nelson River Gneissic Zone by Wilson and Brisbin (1962) and has been dealt with in detail by Bell (1966) and Kornik and MacLaren (1966). In northern Quebec the boundary is found at the north edge of the Cape Smith - Wakeham Bay belt. There is, however, considerable question when one seeks to extend the boundary across the Bay from Cape Smith to the edge of the Palaeozoic in Manitoba. A whole rock K-Ar age of 1,385 ± 125 my has been obtained on a Nastapoka Group basalt near Richmond Gulf and a similar age of 1,595 ± 210 my from a basalt on Gilmour Island in the Ottawa Islands (Wanless et al. 1966, G.S.C. specimen No. 64-135 and 64-72). A diabase in the Belcher Islands has given a whole rock K-Ar age of 1,620 my (no errors given) (Wanless et al. 1965, G.S.C. specimen No. 63-93). Stockwell (1965) shows the boundary between the Churchill and Superior provinces from Cape Smith around the circular Belcher Basin at the base of the rocks that form Ottawa, Hopewell, and Nastapoka Islands, and then south of the Precambrian windows near Winisk.

## F. Heat Flow Investigations

The only heat flow measurement which has been made in the area close to Hudson Bay is on Neilson Island near Great Whale River and a preliminary value of $0.62 \times 10^{-6}$ cal/cm$^2$/sec was obtained (A.M. Jessop 1966; personal communication). A few other heat flow determinations have been made on the Shield at Flin Flon and at mines in northern Ontario (Misener et al. 1951).

## G. 1965 Hudson Bay Project

The 1965 Hudson Bay Project was mounted by the Canadian Government's Department of Mines and Technical Surveys (now the Department of Energy, Mines and Resources). The project was a two-ship project designed to provide a thorough geological and geophysical reconnaissance of Hudson Bay as well as to supplement oceanographic data obtained in a 1961 cruise by M.V. THETA. The program involved five universities, eight government departments, and six industrial firms and was coordinated by B.R. Pelletier of the Bedford Institute of Oceanography. The Bedford Institute's C.S.S. HUDSON and a charter vessel, M.V. THERON were used on the project from approximately July 16 to September 25, 1965. Richfield Oil Company, now merged with Sogepet - Acquataine, operated two ships in Hudson Bay, the M.V. BRANDAL and M.V. POLARHAV. Richfield and the Canadian government shared the cost of a Decca Navigation System of electronic positioning which was installed for the duration of the project in the southwest part of the Bay.

The project was wide-ranging and involved a great deal of careful coordination even to adjusting the firing schedule of the Churchill Rocket Range. The remoteness of the recording sites for the crustal seismic program introduced extra logistic problems. Recording crews had to be flown to and from their sites by a chartered amphibious Canso or landed by barge and helicopter from C.S.S. HUDSON. Similarly temporary tide gauges had to be landed and installed by shipborne personnel. Radio was an essential means of communication.

The geological part of the project included bottom sampling, sub-bottom profiling using the ships' echo sounders, a sparker towed from a launch, use of a shipborne Hiller helicopter to make spot soundings and to investigate raised beaches for recent sealevel changes and sampling of recent shells for carbon 14 dating. The oil company also did a shoreline investigation of the Palaeozoic strata. The hydrographers carried out a reconnaissance charting of the Bay with a detailed examination of certain areas. Temporary tide gauges were established to produce a cotidal chart of the Bay.

The geophysical part of the project included a further 14,000 nm of sea magnetometer data. The Richfield Company also flew a low level magnetic survey over much of their extensive acreage. The Geological Survey of Canada flew an aeromagnetic survey over a small area in the center of the Bay using a North Star aircraft (Hood et al. 1966).

In 1961 a single line of bottom gravimeter stations was obtained and in 1965 almost 800 stations were added from gravimeters on both government ships. Whenever there were three hours of steaming available the shipborne gravimeter on C.S.S. HUDSON was used and it added an additional 2,000 to 3,000 miles of data which will eventually be incorporated with the bottom gravimeter data.

To supplement earlier onshore seismic data a marine seismic refraction program was carried out by the G.S.C. to determine the depth of the crystalline basement and to thereby delineate the Palaeozoic sedimentary basin. The two ships of the Richfield Company carried out continuous seismic profiling for much of the summer. A nine-day period was devoted to a crustal seismic experiment. Eight conventional recording stations were located around the circumference of the Bay and a ninth using hydrophones operated from C.S.S. HUDSON in the center of the Bay. Forty-one large shots, either 1800 or 3600 lbs in size, were detonated in a line from Churchill to the Ottawa Islands and from Chesterfield Inlet to the center of the Bay.

## H. Hudson Bay Centennial Volume

To date few of the results of the 1965 Hudson Bay Project have been published. However, a number of the preliminary results are being released in the Hudson Bay Centennial Volume. This volume, a centennial project of the Department of Energy, Mines and Resources, outlines the extent of present knowledge of this focal area of Canada, not only in scientific fields but also in the areas of history, geography, ethnology, natural resources and the life of the region's inhabitants; the volume is compiled for the interested public. The volume contains 11 papers devoted to earth sciences. These and other related research are briefly discussed below.

Lee (1967) reviews the quaternary geology of the Hudson Bay region. Raised beaches indicate up to 800 ft of uplift since the melting of the Pleistocene ice sheets and Lee suggests further that the presently submerged areas of Hudson Bay may represent an area of weakness in the earth's crust which has yielded more readily to ice loading than the surrounding areas. In another paper Whitmore (1967) writes of the hard-rock geology and mineral potential of the Hudson Bay area. Pelletier et al. (1967) use bottom topography and samples as well as sparker results to delineate the areal extent of the Palaeozoic rocks in the Bay. Most of Hudson Bay west of a north-south line through the Belcher Islands is underlain by Palaeozoic sediments. The results of the Geological Survey's seismic refraction program (Hobson 1967) suggest that up to 8,500 ft of Palaeozoic sediments may be present in the center of the Bay with thicknesses in the order of 2,000 ft in the Hudson Bay lowlands.

The results of the crustal seismic program are discussed by Ruffman et al. (1967). By using a time-term analysis of the first arrival data a single-layered continental crust with mean compressional wave velocity of 6.33 km/sec is found beneath the Bay overlying a mantle with a least squares compressional velocity of 8.27 km/sec. The Mohorovičić discontinuity is at a depth of approximately 40 km beneath Churchill and rises to 30 km east of the Ottawa Islands, then drops to 40 km just east of the islands. The Moho rises to approximately 28 km beneath Chesterfield Inlet. The authors relate the sudden change in depth just east of the Ottawa Islands to the extension of the Churchill-Superior boundary from Cape Smith seaward, north and west of the Ottawa Islands. The topography on the Moho is qualitatively related to the seaward extension of the Cape Smith gravity anomalies seen in Dominion Observatory free air anomaly map of the Bay (Innes et al. 1967). The Mohorovičić discontinuity rises to depths of less than 28 km beneath Chesterfield Inlet and this suggests lateral changes in the crust or mantle density and velocity may be present. In another more detailed paper (Ruffman and Keen 1967), the authors discuss the three dimensional nature of the Churchill-Superior boundary which they consider a major crustal feature, and suggest it need not be a vertical feature. A number of other interpretations have been made of the 1965 Hudson Bay seismic program (Hunter 1966) and the Canadian Journal of Earth Sciences is issuing a Hudson Bay Symposium volume in 1967 which will encompass work of the Geological Survey, Dominion Observatory, University of Western Ontario (Hunter and Mereu 1967) and Dalhousie Institute of Oceanography (Ruffman and Keen 1967). The Universities of Manitoba and Alberta are also currently investigating the Hudson Bay seismic experiment.

The Hudson Bay Centennial Volume also contains a paper by Serson et al. (1967) which interprets ground and high level aeromagnetic observations over the Bay. The large scale negative anomaly over the Bay apparently indicates a thick layer of rocks with reversed magnetism underlying the Bay. Hood et al. (1967) in a paper on low level aeromagnetic and ship magnetometer observations reviews the earlier interpretation of the Palaeozoic sedimentary basin and presents an anomaly map based on the Richfield Oil Company survey made in 1965.

Innes et al. (1967) present extensive gravity data covering Hudson Bay and its periphery in the form of free air and Bouguer anomaly maps. Local geology is correlated with the anomaly map and evidence is presented for the existence of a rift zone extending through James Bay and the Belcher and Sleeper Islands north to the vicinity of the Ottawa Islands. The analysis of isostatic anomalies suggests 180 m of post glacial rebound is still to occur in the Hudson Bay region.

A final chapter in the Centennial Volume deals with the origin of Hudson Bay. Beals (1967) presents evidence that the great arc of eastern Hudson Bay is the result of a collision of the earth with a large meteorite. This evidence includes the precisely circular nature of the arc, and radial dips of sedimentary layers near the periphery and the presence of a rudimentary rim rising 1,500 ft near Richmond Gulf. Beals further notes that such an impact could shatter the earth's crust to great depths and permit mantle material to invade the crust. Some support to the impact origin is given by gravity observations (Innes et al. 1967). Halliday (1967) carried the discussion of the meteorite impact hypothesis further by making comparisons between the Hudson Bay Arc and other circular features of the earth, moon and Mars. He uses lunar data to calculate the size of such a crater as Belcher Basin before erosion. He suggests that the original crater of 20,000 ft depth with a rim height of 20,000 ft has been reduced by erosion since impact 1 to 2 billion years ago to its present dimensions. Wilson (1967) suggests an impact origin is not necessary for the Belcher Basin and in turn suggests that the whole Bay may represent an ancient scar on the earth's surface where two Precambrian continents came together.

## II. CURENT PROBLEMS AND FUTURE RESEARCH

An obvious extension of the present work will be to combine the gravity, magnetic and seismic studies of Hudson Bay to produce an overall map of the crust-mantle interface and to establish the nature of lateral and vertical navigations in the crust and mantle beneath the Bay. Such features as shallow Moho under Chesterfield Inlet and the step in the Moho west of the Ottawa Islands must be confirmed. Shear waves and converted waves are quite evident on the seismic records and should be interpreted along with amplitude studies. The relationship between the boundaries of geologic provinces and deep seated crustal features and in turn their relationship with the Mohorovičić discontinuity will be investigated. Involved with this is the nature and origin of a sedimentary basin, whether it be a Palaeozoic or Precambrian basin, both of which are present in Hudson Bay. The origin and nature of the fracture zone running through James Bay and its relation to other continental features will be discussed. Because Hudson Bay is an area of active isostatic rebound this will afford an area for research and the nature of crustal and mantle deformation under conditions of glacial loading may be deduced. The impact origin of Belcher Basin will be hotly disputed for years to come.

For a number of reasons we perhaps should not expect another large interdisciplinary study in Hudson Bay for some years. This is partly dependent on the fact that there is considerable data yet to be evaluated and problems yet to be defined. Also there is considerable cost involved in research in such a remote area which is ice-free only from mid-July to mid-October. There are, however, a number of suggestions for further field work that could well be implemented though the onus may fall on the Canadian Government as opposed to the universities or individuals. The time seems auspicious for a detailed survey of the eastern part of the Bay, Belcher Basin and James Bay. The bathymetry is virtually unknown east of the Belcher Islands and in James Bay, there is no gravity or magnetic data from James Bay and very little such data from the shallow Belcher Basin. The geology of the Belcher Islands has been mapped in detail, but this must be extended to all the islands to the north and east. Combined with this would be a detailed stratigraphic investigation of the Cape Smith-Wakeham Bay belt with some hope of correlating the Ottawa Islands, Belcher Group, and Manitounuk Group. A fresh look at the Precambrian windows southeast of Winisk would also be desirable. For such a survey of eastern and southeastern Hudson Bay a shallow draft sealing vessel with a helicopter deck is suggested. Ship magnetometer and bottom gravimeter could be operated and sparker might even prove effective in the Belcher and Manitounuk sediments for outlining structure. The helicopter would serve to land and service geologists and add bathymetric or magnetic data. Again electronic navigation would be desirable and care should be taken not to over-extend it as happened in 1965. If any further program of large shots such as those in Lake Superior in 1966 are planned careful consideration should be given in the Hudson Bay area to using helicopter mounted portable seismic stations that could be moved and installed between shots. Such a station might allow specific crustal and upper mantle problems to be investigated.

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# THE ATLANTIC CONTINENTAL MARGIN

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## I. INTRODUCTION

This is a report on regional geophysical and geological studies of the continental margin of eastern Canada, from Nova Scotia to northern Newfoundland. Among the agencies which have been active are the Bedford Institute of Oceanography (Dartmouth, Nova Scotia), Geological Survey of Canada and Dominion Observatory (Ottawa, Ontario), and Dalhousie University (Halifax, Nova Scotia). A number of oil companies are engaged in geophysical exploration of the Nova Scotian Shelf and the Grand Banks. None of their results have been published.

## II. THE CRUST AND MANTLE OF THE APPALACHIAN SYSTEM

The Appalachian System extends from Florida to Newfoundland. It bends strikingly at the latitude of the Gulf of St. Lawrence. In Canada it is bounded to the west by the Eastern Lowlands and the Grenville Province, and to the east by Atlantic Coastal Plain sediments (Figure 1). In Newfoundland, deformed Palaeozoic rocks are bounded on the southeast and northwest by older Precambrian blocks (Williams 1964). This symmetry is less obvious in New Brunswick and Nova Scotia.

Long seismic refraction profiles have been established within the Appalachian System (Figure 2). They were located along the Atlantic coast of Nova Scotia; across the Gulf of St. Lawrence from Cape Breton Island to New Brunswick; from New Brunswick across the Laurentian Channel to Anticosti Island; along the west, northeast and south coasts of Newfoundland; and northeast from the northeast coast of Newfoundland (Barrett *et al*. 1964, Ewing *et al*. 1966, Dainty *et al*. 1966). The interpretation of the results from these seismic lines shows that the crust and mantle beneath the western margin of the System, and beneath the Atlantic coast of Nova Scotia are "normal". The crust is 30 to 35 km thick, with a compressional wave velocity approximately 6.1 km/sec in magnitude, overlying a mantle characterized by a compressional wave velocity of approximately

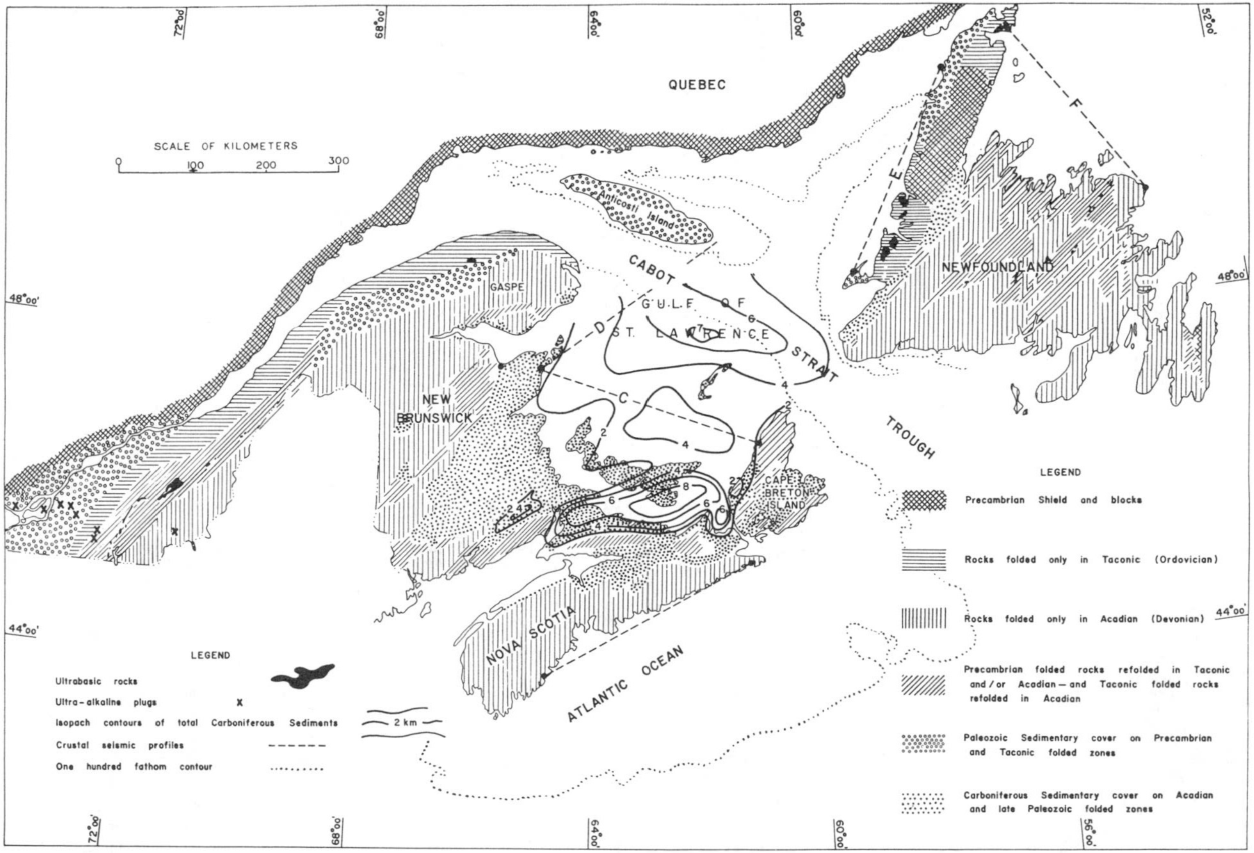


Figure 1. The Appalachian System in Eastern Canada. (After G.N. Ewing <u>et al</u>. 1966).

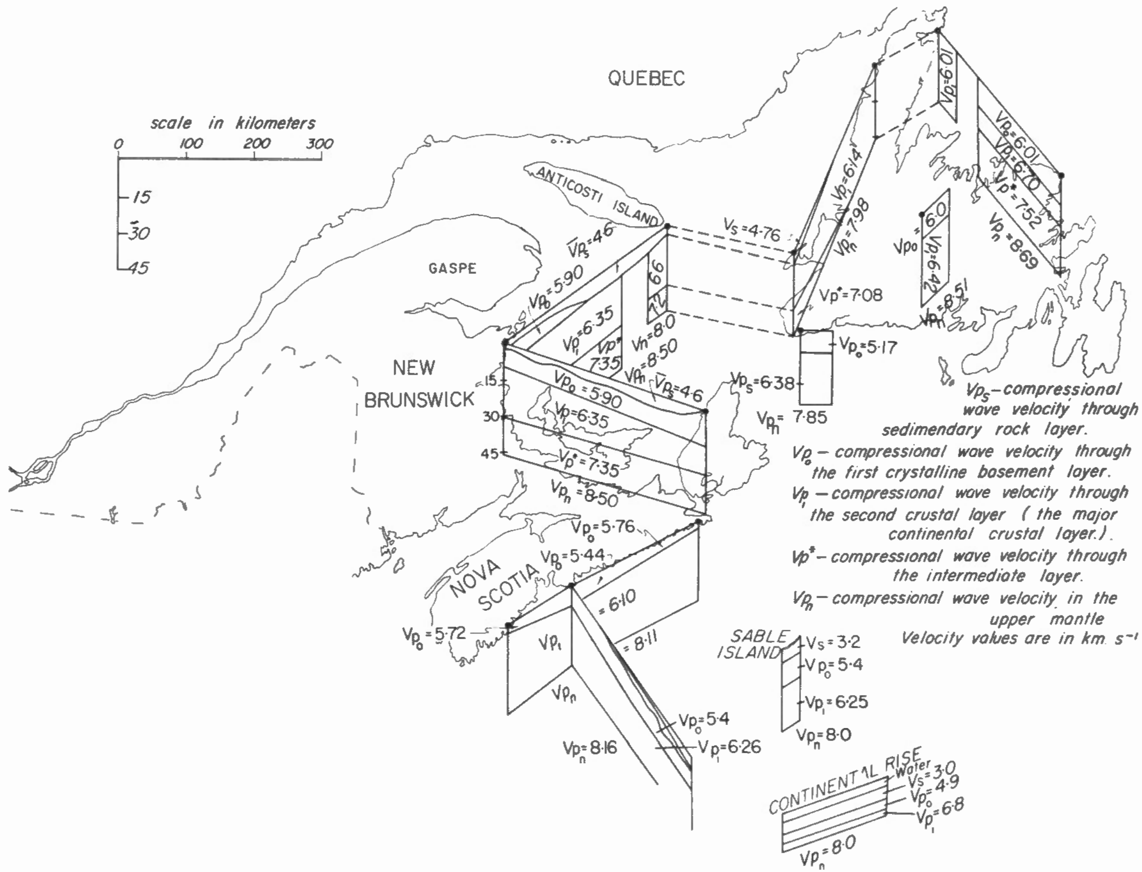


**Figure 2.** Seismic sections from refraction studies on the eastern seaboard. (After A.M. Dainty, et al. 1966).

8.1 km/sec. The crust and mantle beneath the Gulf of St. Lawrence and the central deformed zone of the Appalachian System in Newfoundland is complex. Beneath the Gulf the crust is 45 km thick, with a thick "intermediate" layer (compressional wave velocity approx. 7.2 km/sec). The mantle has a high compressional wave velocity (approx. 8.5 km/sec). These results suggest that the central deformed part of the Appalachian geosyncline is accompanied by a thick crust and an abnormal mantle. The thick sedimentary basin under the Gulf of St. Lawrence is accompanied by a thick crust of high density in its lower part. The thickness of the sediments beneath the southern part of the Gulf of St. Lawrence has been established by Drake (1963), and by Hobson (unpublished).

## III. DEEP STRUCTURE OF CONTINENTAL MARGINS

### A. The Margin off Nova Scotia

The shelf off Nova Scotia is underlain in part by sediments of the Atlantic Coastal Plain, and in part by sediments similar to the Mississippian and Pennsylvanian of mainland Nova Scotia.

Marlowe and Bartlett (1966) have described an Oligocene-Miocene section from The Gully, a submarine canyon off Sable Island. Rocks dredged from depths of 200 to 2200 metres are siltstones, containing plant fragments, microfaunal tests, and hydrocarbons. The Miocene section may be as thick as 800 metres. Marlowe and Bartlett suggest that the sediments accumulated in a deltaic environment, with water depths up to 600 m, under a warm-temperate or subtropical climate. The thick section suggests that the deposition occurred in a basin which was subsiding. The extent of the sedimentary section beneath the shelf off Nova Scotia had been demonstrated in seismic studies by Lamont and subsequently by Dalhousie University (Berger *et al.* 1965). Beneath Sable Island, close to Marlowe and Bartlett's section, seismic studies suggest that sediments (defined as rocks in which the compressional wave velocity is less than approximately 4 km/sec) extend to 5 km depth. Seismic reflection studies by K.S. Manchester (unpublished) demonstrate that they lie unconformably upon a basement of slates, quartzites and granites similar to those cropping out on the mainland of Nova Scotia. Measurements of the total intensity of the earth's magnetic field made by Bower (1962 a,b), Hood (1966, 1967) and Loncarevic and Ewing (1966) show that over a large part of the eastern section of the Scotian Shelf the total magnetic field is smooth, suggesting an increase in thickness of the coastal plain sediments towards the edge of the shelf.

Evidence that Carboniferous evaporites underlie the shelf off Cape Breton Island, east of Chedabucto Bay, has been given by Ewing and Hobson (1966) and Loncarevic and Ewing (1966). A linear belt of negative gravity anomalies, minus 60 milligals

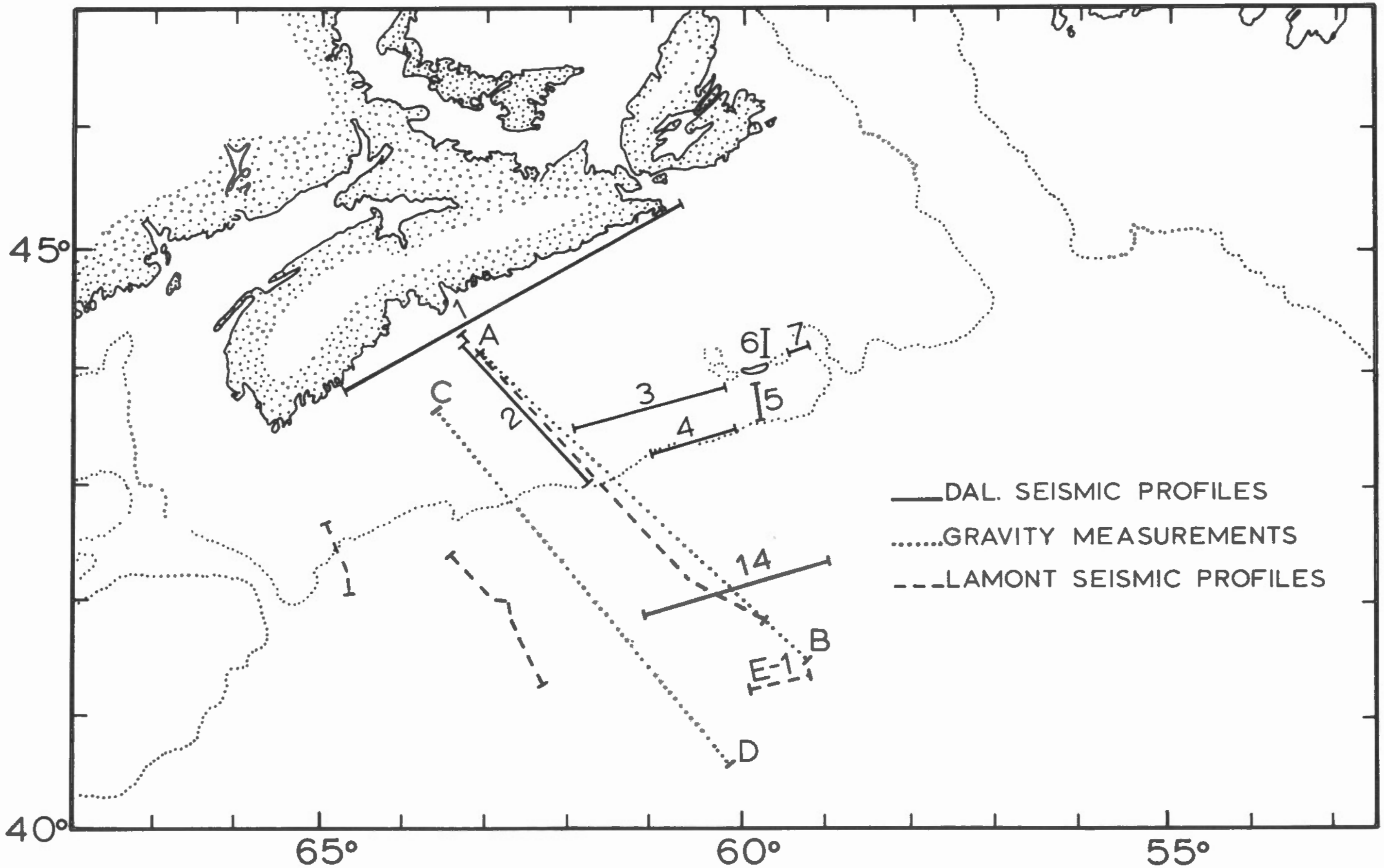


Figure 3(a). Gravity lines and seismic refraction lines on the continental margin off Nova Scotia. (After C.E. Keen and Loncarevic 1966).

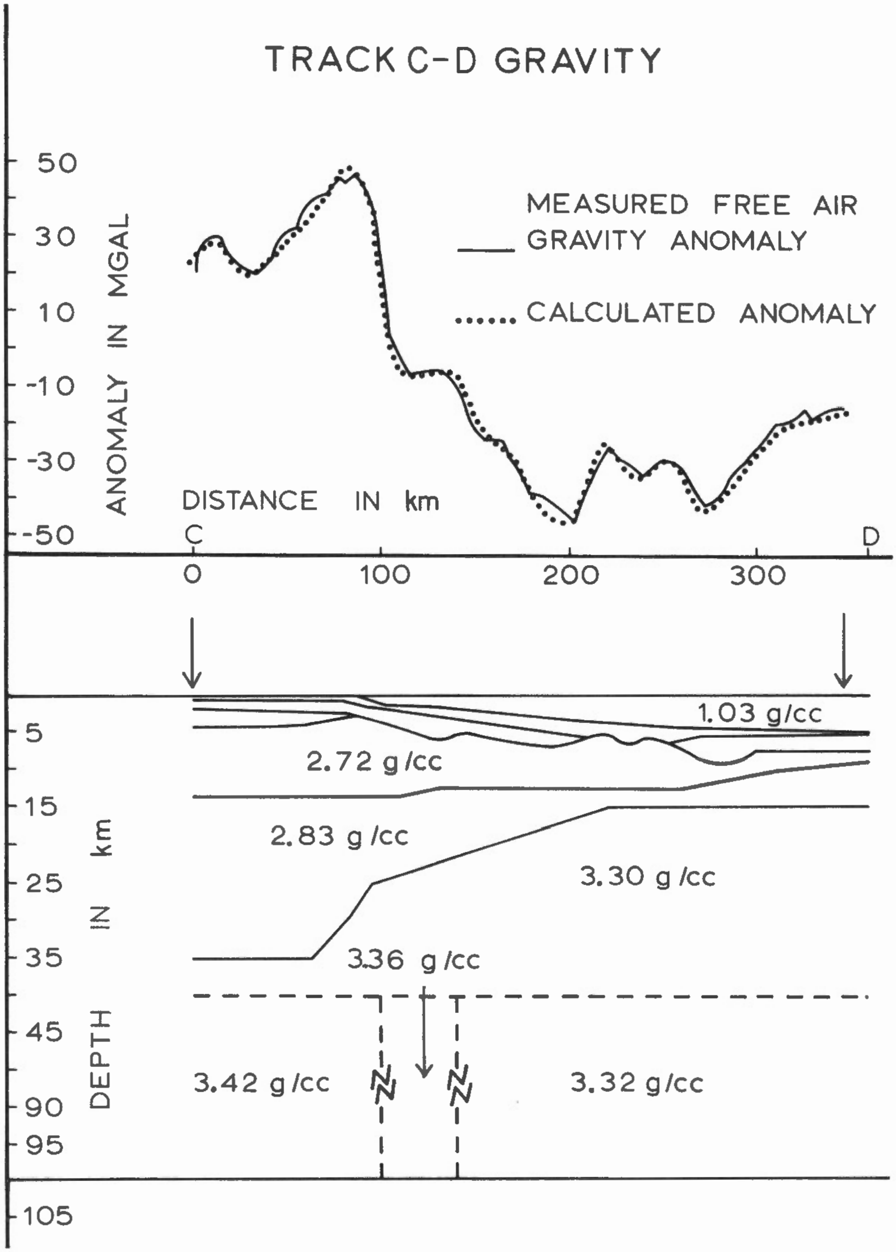


**Figure 3(b). Interpretation of seismic and gravity results. (After C.E. Keen and Loncarevic 1966).**

in magnitude, extends from Chedabucto Bay to the eastern margin of the Laurentian Channel. Seismic refraction lines across the western part of the belt gave partial control upon the possible shapes and densities of the rocks which cause the anomalies.

The gravity and seismic data (Barrett et al. 1964, Berger et al. 1965, 1966, C.E. Keen and Loncarevic 1966, Drake et al. 1959) have been combined in an attempt to provide a complete cross-section of crust and upper mantle across the continental margin (Figures 3A and 3B). The seismic results were used as control upon the possible mass configuration which would lead to the observed free-air gravity anomalies. This suggests that the mantle below 40 kilometres beneath the continent is more dense than that beneath the ocean basin. However, this conclusion is dependent upon the assumed relationship (Cook, 1962) between the compressional wave velocity and density. The high mantle density proposed could lead to compressional wave velocities greater than the so-called normal value of 8.1 km/sec. These values have not been found off the Nova Scotian coast although they have been measured in the Gulf of St. Lawrence.

B. The Margin Northeast of Newfoundland

The extension of the Appalachian System northeast of the island of Newfoundland was studied by Dalhousie University in 1966.

Seismic refraction lines show that the continental crust ends beneath the lower part of the continental slope. Magnetic field observations suggest that Appalachian structures continue to the edge of the continental shelf. Their trend appears to be interrupted over the continental slope, where large magnetic anomalies with a northwesterly trend are found.

An interpretation of the magnetic field by B. Fenwick (unpublished) is consistent with C.E. Keen and Loncarevic's interpretation of free-air gravity anomalies over the Nova Scotian margin. The difference in density which they proposed should exist between continental and oceanic mantle could be caused by temperature differences - higher temperatures under the oceans than under the continents at the same depth. Such temperature differences might lead to magnetization differences.

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# THE MID-ATLANTIC RIDGE AND NORTH ATLANTIC OCEAN

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## 1. THE MID-ATLANTIC RIDGE

The reconnaissance of the major features of the oceanic areas was well advanced by the early 1960's, and emphasis has been placed on detailed surveys in recent years. A one degree strip of the Mid-Atlantic Ridge between $45^{\circ}$N and $46^{\circ}$N was selected by the Bedford Institute of Oceanography for a detailed study. Earlier reconnaissance had shown that this area is not complicated by fracture zones, and may be representative of the Mid-Atlantic Ridge system.

The first survey in the area was carried out under the direction of M.N. Hill on board RRS DISCOVERY II. The purpose of this cruise was to investigate a blockage of the Median Valley near $46^{\circ}$N. Two seamounts which flank opposite sides of the Median Valley were mapped with the aid of two moored buoys fitted with radar reflectors. The present series of CSS HUDSON investigations was started in 1965. The area surveyed was extended in 1966 and further work is planned for 1968. The survey coverage to the end of 1966 is shown in Figure 1.

The ship's position was determined with the aid of moored radar transponder buoys. Six were used in 1965 and 15 in 1966. During the latter cruise approximately 80% of the survey lines were referenced to at least two moored buoys. The accuracy of radar fixes on moored buoys in the open ocean is now estimated as between 0.2 and 0.3 nautical miles.

The investigations to date cover an area extending from the eastern flank of the Median Valley westwards for 150 n.m. The Median Valley is a well defined linear feature trending in the direction $019^{\circ}$T. The bottom of the valley is uneven, narrow and has very little sediment. The valley is constricted at the north end by outpourings from flanking volcanoes. The depth of the floor increases from 1700 to 1900 fm in a distance of about 50 n.m. (slope of 1:250). The deepest part of the valley, 9 miles south of the northern blockage, at $45^{\circ}42'$N, $27^{\circ}46'$W, is 1924 fms. The 1400 fm contour is continuous on both sides of the valley

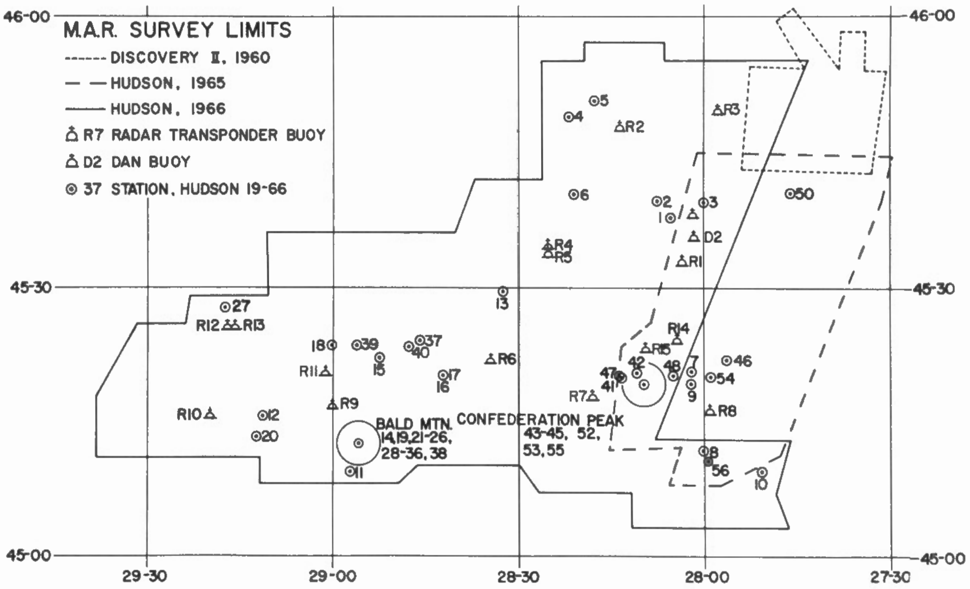


Figure 1. Area covered by Mid-Atlantic Ridge surveys at the end of 1966.

with a width of 6 miles averaged from measurements at 2 mile intervals. The average width at the 1500 fm contour is 4.8 miles. Thus the slope of the lower part of the flank walls is one in six, or an angle of about $10^{o}$.

The Rift Mountain province (as defined by Heezen et al) to the west of the Median Valley has a width of only about 20 miles. The average depth of this province is 1200 fms sloping away from the valley flanks. At least fifteen peaks rise above this average level. The most pronounced peak in the whole survey area is a large shield volcano near 45°20'N - 28°10'W, named "Confederation Peak" by the 1966 expedition, (Figure 2). Extensive dredging around this peak provided a complete suite of submarine volcanic rocks discussed in the following section on petrology by F. Aumento.

The western boundary of the Rift Moutain province is well defined by the 1400 fm contour. Westward of this boundary the character of the Ridge changes. Eight sediment cores were taken from these basins including a 1650 cm core at 45°13'N, 29°12'W, believed to be one of the longest cores taken near the crest of the Ridge. The province adjacent to the Rift Mountains was named High Fractured Plateau by Heezen. The existing detailed surveys near 45°N do not justify this name. As already mentioned, the province is characterized by sedimentary basins through which protrude well defined, elongated individual mountains. Contouring of the soundings has not revealed any features which could be explained by block faulting. The most prominent feature in this area was an elongated ridge, a few miles wide and over 20 miles long. Considerable sampling was carried out near the peak of this ridge. It was named Bald Mountain because bottom photographs showed an unusually smooth cap on top of the mountain.

Bald Mountain and other ridges in its vicinity trend north or slightly to the west of north, in contrast to the Rift Mountains which are parallel to the Median Valley and trend 019°T. The change of topographic character and the direction of major trends as one proceeds westward from the Rift Mountains may be of significance and should be taken into consideration in any discussion of the mobility of the ocean floor.

## A. Petrology

Closely spaced rock dredging, on a traverse from the centre of the Median Valley to the western slopes of Confederation Peak, yielded the first set of specimens which may approach being representative of an area of the Mid-Atlantic Ridge.

Tholeiitic, high alumina, transitional and alkali basalts have been recovered and analyzed. Chemical data show correlation with depth of extrusion and topography. Chronological data indicate that numerous extrusive cycles, in different stages of development, are currently active.

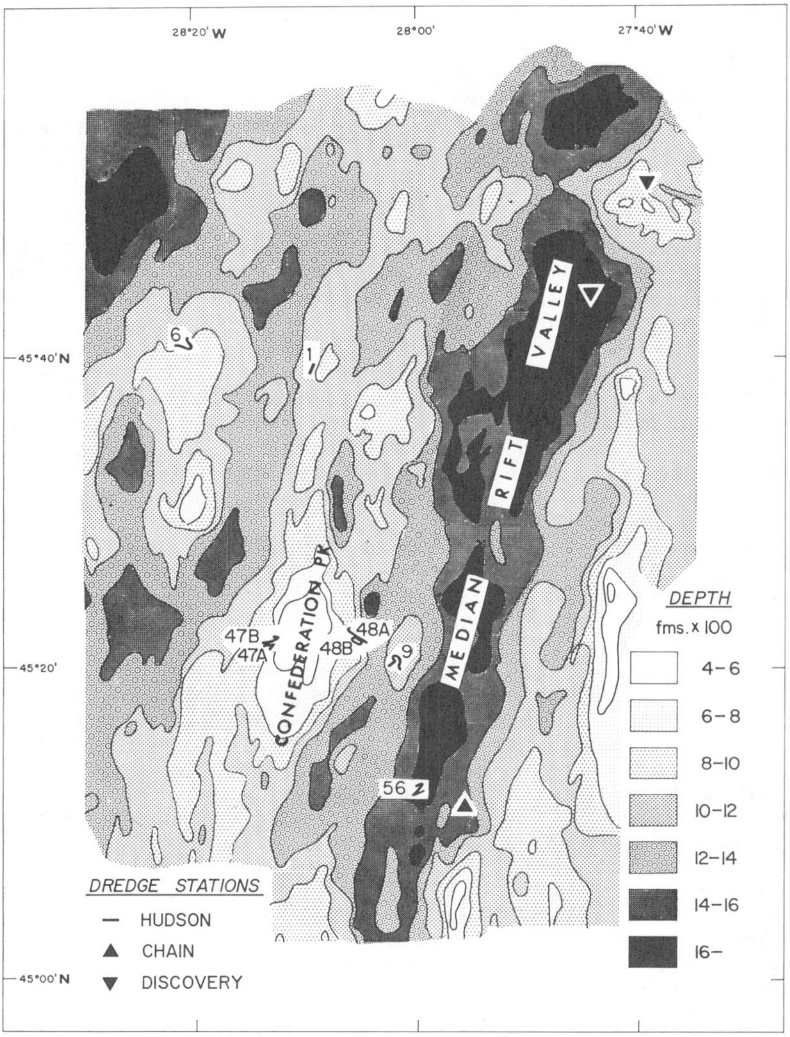


Figure 2. Bathymetry of the Mid-Atlantic Ridge near 45°N. (After Aumento 1967).

On Bald Mountain, 35 miles west of the Median Valley, repeated sampling located an unexpected occurrence of granitic and metamorphic rocks. Similar rocks, dredged previously from the ocean floor, have always been interpreted as being ice rafted. Bottom photographs of the seamount indicate a markedly different terrain; the seamount itself has also a different orientation and shape from known volcanoes in the area. Studies are in progress to account for the presence of these rocks, and for the unusual features of the seamount.

## B. Magnetics

The total magnetic field was measured on all survey lines with a towed nuclear precession magnetometer. The overall accuracy of magnetic readings is estimated to be between 20 and 50 gammas since no magnetic diurnal correction could be applied. A large positive magnetic anomaly (exceeding 1000 gammas peak-to-peak) is clearly associated with the Median Valley though the local volcanism produces isolated anomalies which are superimposed upon, and occasionally completely mask the main pattern. A magnetic low is situated over both flanks of the valley. A pronounced elongated magnetic low is situated over Confederation Peak, followed by two more parallel strips of positive and negative anomalies. In the northern part of the area the linear anomaly pattern is either absent or completely masked by the anomalies due to local volcanism. To the west of the Rift Mountains the magnetic lineation pattern is even more diffuse due to the small amplitude of the anomalies.

On completion of the 1965 survey, the anomaly over the valley and flanks was explained by a plausible arrangement of bodies of magnetized rocks beneath the sea floor. Following the hypothesis of Vine and Matthews, the linear pattern of the anomalies (where present) could be accounted for by assuming normally and reversely magnetized intrusions extending away from the centre of the ridge. The above hypothesis was based on the assumption of "normal" remanent magnetization (Jr) values for oceanic basalts not exceeding 0.005 emu/cm. The remanent magnetization of twelve of the samples dredged on Confederation Peak and in the Median Valley was measured in the laboratories of the Geological Survey. The value of Jr shows a correlation with the basalt type. Since it may be possible to correlate the basalt type with depth of extrusion, there develops an indirect correlation between Jr and depth (an increase of Jr of 0.018 emu/cm$^3$ per km of depth). The mean value of Jr for six tholeiitic basalts from the deepest station (located at the bottom of the Median Valley) was 0.033 emu/cm$^2$ with a maximum value of almost 0.04 emu/cm$^2$. Such high values for magnetization have not been reported before. If the correlation between remanent magnetization, basalt type and depth of extrusion holds in other areas of the Ridge, then it is possible to explain the pattern of observed oceanic anomalies without invoking reversed polarity of magnetization.

C. Gravity

The variation of the earth's gravitational field was measured with a gyrostabilized shipboard gravimeter (ASKANIA GSS 2-17). A preliminary quality control of 1966 data carried out on board with the aid of a PDP-8 computer showed an RMS crossover discrepancy of ± 4.5 mgal on 62 crossovers. It is expected that this discrepancy will be further reduced in the final data reduction by using upgraded navigational information and by applying a cross coupling correction.

To eliminate the effect of topography a modified Bouguer anomaly was calculated by replacing water columns above the bottom by prismatic blocks of rock density. A map of Bouguer anomaly was prepared using a value of 2.67 gm/cm$^2$ for rock density. The most important feature of this map is the lack of correlation between the Median Valley and the Bouguer anomaly, as previously noted by workers from Lamont Geological Observatory. The Bouguer anomaly map shows variations of the order of 20 mgal. The value assumed for the rock density affects the position and shape of the anomaly contours. Compressional wave velocities can be used as a guide to the selection of density. Velocities of 5.0 to 5.8 km/sec have been reported for the top layer on the basis of seismic refraction measurements. This range of velocities corresponds to densities of 2.55 to 2.77 gm/cm$^2$.

To check the above values the densities and compressional wave velocities were determined for twelve samples from the dredge rock collection. The dry bulk densities of basaltic rock samples ranged from 2.58 to 2.95 gm/cm$^2$. The compressional wave velocities (at NTP) in the samples ranged from 4.82 to 5.88 km/sec with a mean value of 5.18 km/sec. The correlation with depth was not pronounced. However, measurements showed a marked increase in velocity with pressure. For four samples, the mean velocity increased from 5.34 to 6.30 km/sec when the pressure was increased from 14 to 32,000 psi. It is obvious that the uncertainty in the choice of density greatly reduces the resolution of gravity interpretations. The most important application of the gravimetric method will be to the study of regional gravity anomalies over larger areas.

## II. MAGNETIC SURVEYS OVER THE NORTH ATLANTIC OCEAN

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Since 1962, the Geological Survey of Canada and the National Aeronautical Establishment have co-operated in a joint aeromagnetic project whose objectives are both to develop an automated high-sensitivity aeromagnetic survey system and also to carry out aeromagnetic surveys over the continental shelves and deep ocean adjacent to North America. During 1966 two low-level (500 feet) aeromagnetic profiles were obtained across the North Atlantic Ocean. The survey aircraft flew from Gander, Newfoundland, to Prestwick, Scotland via Iceland. An interesting sequence of magnetic anomalies was recorded to the south of those occurring in the Labrador Sea indicating that the two zones continue to the south. Between Iceland and the southern tip of Greenland, a number of distinct anomalies were recorded which appeared to be correlatable between the lines.

It is planned to fly several lines from the southeast coast of Greenland at right angles to the Mid-Atlantic Ridge towards Ireland to establish the total width of the symmetry about the crest of the Mid-Atlantic Ridge in this area.

Four lines were also flown across the Denmark Strait between Iceland and eastern Greenland. There appeared to be reasonably good correlation between the two westerly lines but not much correspondence was noted on the two easterly profiles. This is probably due to their proximity to the crest of the mid-Atlantic Ridge which was intersected by the most easterly track at a fairly oblique angle. The opportunity was taken at the end of this particular sortie (August 28th, 1966) to fly over the new volcanic island of Surtsey, about 20 miles south of Iceland. The main volcanic vent was still quite active and the hot molten lava could be seen bubbling up at the lip of the vent and running down the hillside into the sea. A distinct magnetic anomaly approximately 350 gammas in amplitude was recorded as the survey aircraft flew a traverse immediately south of the island at a height of 500 feet.

The aeromagnetic profiles obtained between Iceland and Scotland had higher-frequency anomalies than those observed on the profiles to the southwest of Iceland. This is probably due to the shallower depth of water which occurs between Scotland and Iceland.

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# PACIFIC CONTINENTAL MARGIN

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Papers by J. T. Wilson (1965), Vine and Wilson (1965) and Vine (1966) have discussed the interpretation of linear magnetic anomalies on the ocean floor above the northern end of the East Pacific Rise. Vine considers that oceanic crust has spread laterally away from the axis of the East Pacific Rise in the regions of the Juan de Fuca ridge. He estimates that the rate of spreading may have decreased within the Pliocene from a rate of 4 or 5 to 2.9 cm/yr for the last 5.5 my.

Wilson has interpreted the San Andreas-Denali transcurrent fault linkage as a series of transform faults that intersect the crest of the East Pacific Rise southwest of Vancouver Island. The Queen Charlotte fault, which bounds the area of north-northeast-trending magnetic anomalies, is part of the Denali linkage and is regarded by Wilson as a transform fault.

A. Sutherland Brown (B.C. Dept. of Mines and Petroleum Resources) has studied the geology of the Queen Charlotte Islands. They lie on the outer edge of the continental shelf which leads directly by a very steep continental slope to the East Pacific Rise. Sutherland Brown's summary of the geology follows........ "The fundamental building block of these islands is a thick (15,000 + feet) pillowed basalt unit of Late Triassic age and similar to what Engel and Engel call oceanic tholeiite. This unit is separated by a flysch-like sequence of Latest Triassic and Early Jurassic age from an explosive porphyritic andesite of Middle Jurassic age and largely marine deposition. Two Cretaceous sedimentary units, the first flysch-like and the second molasse-like, were deposited and are successively less involved in deformation. A final, Early Tertiary period of largely subaerial volcanism deposited some 18,000 feet of intercalated columnar alkali basalt floods and sodic rhyolite ash flows. These are gently warped, eroded, and overlain by up to 6,000 feet of Mio-Pliocene sands and shales. Large lineal bodies of hornblende diorite to quartz diorite were emplaced in the Mid-to Late Jurassic and a more varied sequence of quartz diorite to sodic granite in the Early Tertiary, mostly along major lineal faults.

Crustal fracture has been the dominant mechanism of deformation, controlling volcanism, sedimentation, intrusion, and secondary folding. Major northwesterly lineal faults form a pattern related to the Queen Charlotte fault. The trace of the latter is apparent along the continental slope. The major northwesterly faults have been active since at least the Early Cretaceous and they generally combine right-hand wrench movement with normal east-block-down displacement.

It would appear a major portion of the crust of the continental margin was formed of essentially oceanic basalts. Whether these are underlain by more sialic material - a possible source for the Tertiary rhyolites - is a major unsolved problem. Moreover the Queen Charlotte Islands present a unique opportunity in Canada for study of the continental margin. Nowhere else is any considerable exposure available at the very edge of the shelf."

The geology of Vancouver Island shows both similarities and differences to that on the Queen Charlotte Islands. The early history is the same except that Jurassic explosive volcanism started in the Early Jurassic on Vancouver Island in contrast with Middle Jurassic time on the Queen Charlotte Islands. Also Vancouver Island underwent warping, faulting and granitic emplacement during the Middle Jurassic Nassian orogeny, apparently synchronously with Middle Jurassic movements in southern and southwestern Alaska. (Detterman et al, 1965). Queen Charlotte Islands were not deformed, however, until Late Jurassic or Early Cretaceous time. A program of submarine geology and geophysics might shed some light on why these two areas within the Insular Zone of the Pacific Margin behaved differently at certain times in the past.

Submarine geology is being done in the Pacific Coast region by the University of British Columbia Institute of Oceanography under J. W. Murray. This work is concerned primarily with Pleistocene fill in the Strait of Georgia and adjoining fiords. An interesting discovery was made of manganese nodules found on the floor of Jervis Inlet which must have been formed within the last 10,000 years. There is also considerable interest in the search for oil, and a rig for offshore drilling has been built at Victoria, B.C. for lease by the Shell Oil Company.

The continental shelf off British Columbia is one of the most intriguing along the margins of North America, in that north-northeast-trending magnetic anomalies on the East Pacific Rise are truncated by the northwest-trending Cordilleran structures on Vancouver Island and the Queen Charlotte Islands. The two regions are apparently separated by the Queen Charlotte fault that has in Recent time displayed right-hand movement. It is regarded as a transform fault by Wilson (1965).

Much study is needed along the Pacific margin off British Columbia to determine if the continent - ocean basin interface lies along the Queen Charlotte fault or is spread over a broader zone. It is necessary to know whether the character and level of the crustal layers changes rapidly across this zone or if they change at all. It is desirable to try and date the material forming the various magnetic strips on the East Pacific Rise in order to check Vine's (1966) estimate of the rate of spreading and whether such is, in fact, taking place. Detailed structural studies are needed on Vancouver and Queen Charlotte Islands to learn as much as possible of structures on land nearest to the interface. In sum, a comprehensive interdisciplinary program is badly needed along the Pacific margin of the continent. Economic consideration such as current submarine petroleum exploration and mineral discoveries on the floor of coastal inlets make such programs all the more imperative.

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