GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

GEOLOGY OF CANADA

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The bedrock foundation of Canada and its adjacent continental shelves seem rigid and unchanging to human eyes, yet, in terms of geological time, these rocks and their contained mineral wealth represent only a momentary stage in the evolution of the Continent, an evolution which began more than 4,000,000,000 years ago. Geological study of most of the present land surface of Canada has shown that at various periods and in various regions dark molten rocks rose from great depths, volcanoes erupted on the ancient land and sea floors, thick sequences of sediments accumulated, granites were either intruded as molten magma or derived from earlier rocks during intense folding and mountain building, erosion wore down or subdued the older mountain chains, shallow seas repeatedly encroached on and receded from the Continent of today, continental glaciers covered most of Canada and, as part of these geological processes, valuable minerals and fossil fuels became concentrated under exceptionally favourable conditions. These interrelated geological processes have produced the buried crust and the present face of Canada. They control the distribution of its economic mineral deposits, its physiography and, in large part, its present and potential land use.

To introduce some relatively simple concepts, let us go back in geological time and select a few examples in which erosion of land, deposition of the resulting detritus, and a series of favourable circumstances have concentrated valuable minerals for man's use. Geological processes are best understood when they can be observed in action at the earth's surface or in relatively shallow lakes or oceans. Modern Atlantic waves, pounding on exposed cliffs of the Maritime Provinces, greatly accelerate the rate of erosion. Fallen blocks are rounded and abraded on the cobble beaches, while waves and currents sweep the sand and rock flour along the coast to sandy beaches or spits, or carry them seaward to add to the slowly growing sedimentary beds of the continental shelf. This natural erosion and

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* Prepared by W. D. McCartney with Grenville and Interior Plains sections from an earlier report by A. H. Lang and revision of Cordilleran section by D. J. T. Carson, Geological Survey of Canada.

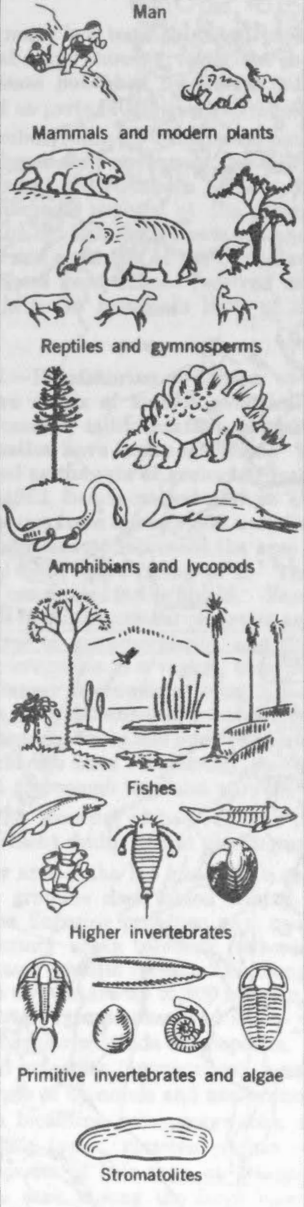
milling action also releases valuable minerals from their enclosing rock. In almost all cases, these valuable minerals are dispersed or only slightly concentrated but, given a rare combination of favourable erosional and current conditions, and because of the relatively high density and physical and chemical stability of some valuable minerals, they may lag behind their lighter fellows of equal size and become concentrated as placer deposits of commercial value. Gold has been recovered in modest quantities from the beach sands of Cunard Cove, Nova Scotia, and is still being freed from the nearby cliffs. More commonly, placer deposits result from the erosion of inland areas and subsequent river transport. The famous gold placer deposits of the Yukon were formed in river channels more than 1,000,000 years ago, at a time when mastodons and sabre-toothed tigers roamed the area. In Nova Scotia, at Gay's River, gold was similarly but less efficiently concentrated in coarse gravels about 350,000,000 years ago, at a time when giant reptiles were the dominant form of life on earth. These gravels were subsequently covered by thousands of feet of sands and muds, washed from the newly formed Appalachian Mountains.

The probable history of the vast uranium deposits of Elliot Lake, Ontario, even though it began more than 1,600,000,000 years ago, has been deciphered by geologists. Geological studies on the surface, underground and in the laboratory indicate that a granitic land mass of modest relief lay to the north of the present Elliot Lake district. Over an extended stable period, these rocks were deeply weathered and all but the most chemically inert minerals such as quartz were broken down to clay and disintegrated materials. At the beginning of Aphebian time, uplift or tilting of this weathered land occurred and mechanical, rather than chemical, erosion became dominant. Rivers swept the rotted upper layers of decomposed rock to the southeast. Quartz pebbles moved along and became rounded in the river channels and, because they were the largest remaining materials, formed blankets of gravel, and filled channels as the gradient and current of the rivers decreased. At the same localities, fine-grained sands and clays continued to be swept seaward. However, even small grains of abnormally heavy minerals such as uraninite, zircon and monazite, which had also resisted earlier chemical decomposition, could not be carried so readily by the waning currents and came to rest in the spaces between the rounded pebbles of quartz. Following this first flushing of the deeply weathered land mass, erosion and transport continued and many thousands of feet of Huronian sediments buried the uranium-rich quartz gravels. Subsequent lithification, folding, mineralogical changes, and further intervals of erosion during 1,500,000,000 years produced folded, uraniferous quartz conglomerates which lie below and locally intersect the present earth surface. These exposed rocks were used to prepare the geological map of the district published by the Geological Survey of Canada in 1925. In 1952, after the uranium content of these conglomerates had been deduced by exploration geologists, this geological map proved invaluable because it outlined the sinuous distribution of the potential ore-bearing formations and accelerated the development of this large mining camp.

The above examples outline only one set of many dynamic geological processes. Geological maps and knowledge of such things as ancient geography, direction of flow of ancient rivers, and the character and degree of weathering of ancient land masses should be known if intelligent evaluation is to be made of the long-range mineral potential of the nation for undiscovered placer deposits of the above types. Apart from uranium, most mineral production comes from a wide variety of other types of deposit. Some, such as asbestos, are formed by alteration of particular rocks of high iron and magnesium content. In other cases, under favourable conditions, major parts of the rock itself can be mined or quarried. Examples include limestone, nepheline syenite, rock salt, gypsum and potash. Space does not permit an attempt here to point out the interrelation of mineral deposits to their geological setting and, in many cases, much remains to be learned about the origin of many types of base and precious metal ores. However, ore deposits are not randomly distributed 'freaks', but comprise rare concentrations of materials formed under particularly favourable geological conditions during the building of the Continent. Efficient exploration by mining companies and evaluation of the mineral potential of the nation depend on geological information and knowledge, augmented by geophysical and geochemical tech-

GEOLOGICAL TIME CHART

ERA		PERIOD	CHARACTERISTIC LIFE	CANADIAN OROGENIES	TOTAL ESTIMATED TIME IN YEARS
CENOZOIC		RECENT	Man		
		PLEISTOCENE			1,200,000
	TERTIARY	PLIOCENE	Mammals and modern plants		
		MIOCENE			
		OLIGOCENE			
		EOCENE			
		PALEOCENE		Laramide	65,000,000
MESOZOIC		CRETACEOUS	Reptiles and gymnosperms	Columbian	
		JURASSIC		Nassian Inklinian	
		TRIASSIC		Tahltanian Appalachian	225,000,000
PALÆOZOIC		PERMIAN	Amphibians and lycopods		
	CARBONIFEROUS	PENNSYLVANIAN			
		MISSISSIPPIAN		Cariboon Ellesmerian	345,000,000
		DEVONIAN	Fishes	Acadian	
		SILURIAN			440,000,000
		ORDOVICIAN	Higher invertebrates	Taconic	
		CAMBRIAN			570,000,000
PRECAMBRIAN	PROTEROZOIC	HADRYNIAN	Primitive invertebrates and algae	Grenville	945,000,000
		HELIKIAN	Stromatolites	Elsonian	1,370,000,000
		APHEBIAN	Algae and other?	Hudsonian	1,735,000,000
	ARCHÆAN		?	Kenoran	2,490,000,000
					3,200,000,000 or more



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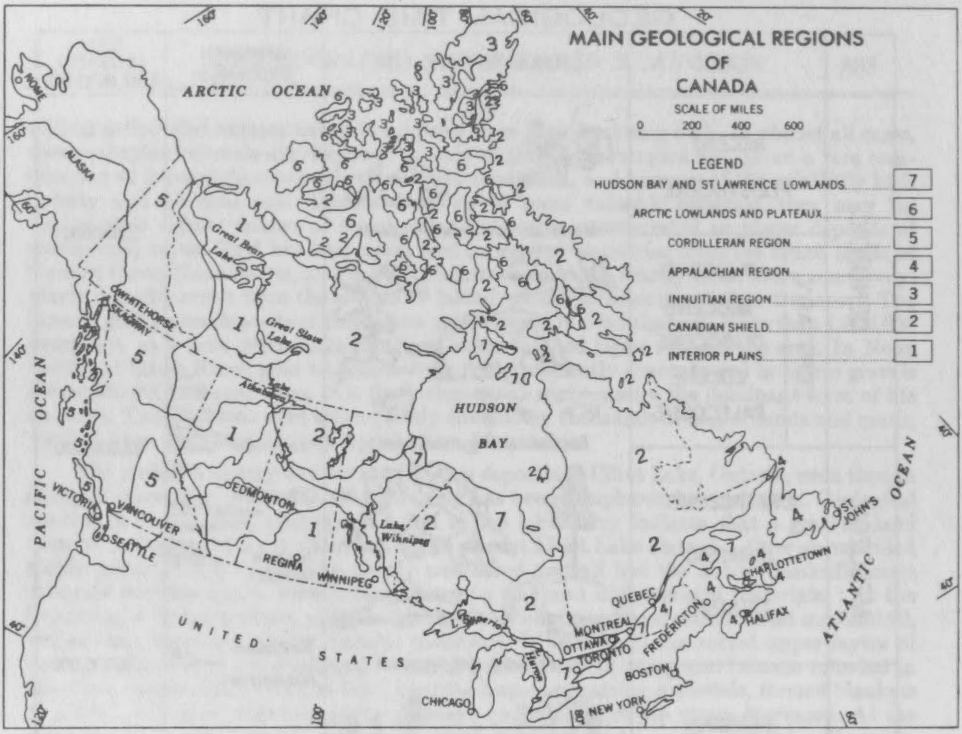
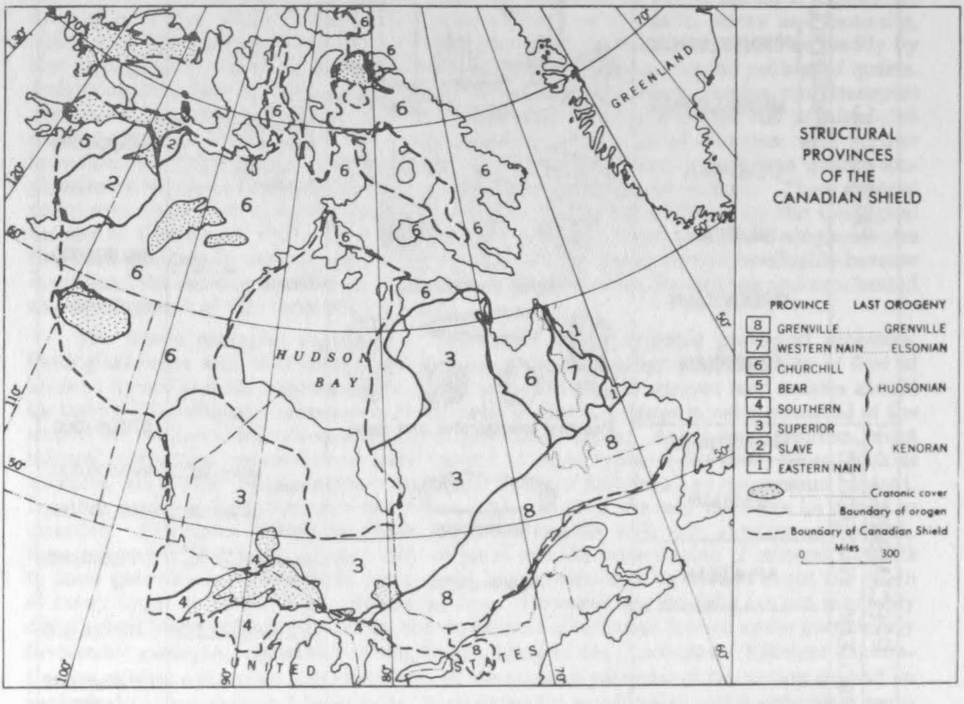

MAIN GEOLOGICAL REGIONS
OF
CANADA
SCALE OF MILES
0 200 400 600
LEGEND
HUDSON BAY AND ST LAWRENCE LOWLANDS 7
ARCTIC LOWLANDS AND PLATEAUX 6
CORDILLERAN REGION 5
APPALACHIAN REGION 4
INNUITIAN REGION 3
CANADIAN SHIELD 2
INTERIOR PLAINS 1
ARCTIC OCEAN
PACIFIC OCEAN
ATLANTIC OCEAN
HUDSON BAY
UNITED STATES
ALASKA
NOME
WHITEHORSE
SKAGWAY
Great Bear Lake
Great Slave Lake
Lake Athabaska
Lake Winnipeg
EDMONTON
VICTORIA
VANCOUVER
SEATTLE
REGINA
WINNIPEG
L. Superior
Huron
CHICAGO
QUEBEC
MONTREAL
OTTAWA
TORONTO
FREDERICTON
CHARLOTTETOWN
HALIFAX
ST JOHN'S
BOSTON
NEW YORK


STRUCTURAL
PROVINCES
OF THE
CANADIAN SHIELD
PROVINCE LAST OROGENY
8 GRENVILLE GRENVILLE
7 WESTERN NAIN ELSONIAN
6 CHURCHILL
5 BEAR HUDSONIAN
4 SOUTHERN
3 SUPERIOR
2 SLAVE KENORAN
1 EASTERN NAIN
Cratonic cover
Boundary of orogen
Boundary of Canadian Shield
0 Miles 300
HUDSON BAY
GREENLAND
UNITED STATES

niques. By 1966, geological maps had been published covering about 75 p.c. of Canada's land surface, and geophysical maps showing variations in magnetic intensity caused by various types of rocks had been published by federal and provincial agencies covering 38 p.c. of the country as well as parts of the continental shelf.

The primary geological subdivisions of Canada are outlined in the following sections. The Canadian Shield forms the ancient nucleus of the Continent. As well as comprising the vast areas exposed in Central and Northern Canada, the Shield extends beneath the veneer of younger marine sediments exposed at the present surface in the Hudson Bay region, some Arctic islands, the St. Lawrence Lowlands and the Interior Plains. West of the Interior Plains, and north and southeast of the Canadian Shield, deep, elongate troughs (geosynclines) developed. These geosynclines received sediments and volcanics which, by folding, were converted into the mountain belts of the Cordilleran, Innuitian and Appalachian regions.

The Canadian Shield.—Precambrian evolution of the present Canadian Shield extended over more than five sixths of known geological time. During this immense interval, many cycles of volcanism, sedimentation, intrusion, metamorphism, mountain building, erosion and ore formation have been completed. The complexities of this history have become better understood as the rate of geological reconnaissance mapping, with the support of helicopters since 1952, has increased and as absolute ages of minerals have been determined by isotopic ratios from about 1,500 well-distributed samples of the Canadian Shield. Many of the absolute ages represent the ages of four main orogenic periods, as indicated on the geological time chart facing p. 2. The facing map shows the eight structural provinces currently recognized in the Shield. Each structural province is defined by the equivalent isotopic ages of their terminal orogenies as well as being characterized by variations in rock types, degree of metamorphism, and dominant types of ore deposits. Following one or more major orogenies in a region, that portion involved was stabilized, and relatively undeformed younger Precambrian erosion products were deposited to form basins of cratonic cover rocks, most of which are shown on the map of the Shield. These relatively undeformed late Precambrian basins and remnants of early Palæozoic sediments show that the Canadian Shield has been remarkably stable since late Precambrian time, subject only to encroachment of younger seas and varying degrees of uplift.

Pleistocene glaciation, with scouring of bedrock and deposition of clastic materials, has profoundly affected the present drainage and physiography of the region.

The rocks of the Superior and of the far smaller Slave and Eastern Nain structural provinces were intruded by granites and folded during the Kenoran orogeny about 2,500,000,000 years ago. The Superior province now comprises a succession of folded belts of volcanic and sedimentary rocks trending east-west, separated by considerably larger areas of granite gneiss and granitic rocks. The elongate remnants of folded greenstone belts within the granitic terrane are up to 300 miles in length. Parts of these folded belts are dominantly sedimentary greywackes and slates which include iron-formations but are not known to contain major sulphide ore deposits. Other parts comprise dominantly mafic, somewhat altered volcanics (greenstones), lesser but economically significant rhyolitic volcanics, various types of economic and non-economic iron-formations which are being mined at four or more localities, some greywacke, slate and graphitic slate and, in association with these rock types, massive pyritic ore deposits containing zinc, copper, silver and gold. Deposits of this type at Noranda, Timmins, Manitouwadge, Matagami and Chibougamau rank among the large base-metal deposits of the world. Famous gold-quartz vein deposits are mined in the greenstone belts at Timmins, Kirkland Lake and Noranda–Val d'Or areas. In the Slave province, structural trends are more irregular than in the Superior province, but the important gold veins of the Yellowknife district and gold deposits being evaluated south of Bathurst Inlet also lie in volcanic belts. Deposits associated with pegmatites of the late stages of Kenoran granites contain lithium, molybdenum, beryllium and caesium.

Following the Kenoran orogeny in the Superior province, thick sedimentary beds of Proterozoic age were derived from the erosion of the deformed Archæan rocks in the region north of Lake Huron, and basal conglomerates of the Huronian beds at Elliot Lake contain about one third of the reported uranium reserves of the world. Even younger undeformed beds and diabase sills about 100 miles northeast of Lake Huron form cratonic cover rocks about 2,100,000,000 years old and contain the famous silver-cobalt veins of the Cobalt mining camp. In the same general region, the noritic intrusions near Sudbury were later emplaced during the Hudsonian orogeny to yield the world-renowned nickel-copper-platinum deposits of the Sudbury basin. As a result of these geological processes of many types and of varied Precambrian age, a belt about 150 miles wide extends northeast from Lake Huron and lies to the northwest of the Grenville province. This belt has produced a great proportion of Canada's gold and base-metal production to date.

The Churchill province is exposed as a giant arc underlying northern Manitoba and Saskatchewan, much of the Northwest Territories, the northern tip of Quebec and the Labrador Trough. The rocks of the Churchill province and the much smaller Bear and Southern provinces were folded, metamorphosed to various degrees, and intruded by granitic rocks during the Hudsonian orogeny about 1,700,000,000 years ago. The general rock types of these provinces are similar to those of the Superior province. In the southwestern Churchill province in northern Manitoba, major nickel deposits with lesser copper are being mined from both gneisses and from metamorphosed mafic intrusions which lie adjacent to the boundary of the Superior province. Nickel-copper ore is also mined from contorted gneisses at Lynn Lake, and numerous massive sulphide base-metal deposits in greenstones have been exploited in the Flin Flon district. Farther north, beginning on the north shore of Lake Athabasca at the Beaverlodge uranium camp, a belt of greenstones, sediments and their metamorphosed equivalents extend northeastward to Hudson Bay. Rankin Inlet, near which nickel was formerly mined, lies at the eastern exposed end of this imperfectly known belt. Relatively inaccessible belts such as this, although seemingly favourable for ore deposits, have not been prospected nearly as intensively as similar geological environments in more populated areas. Most of Baffin Island is underlain by contorted rocks of the Churchill province. Of particular interest is the recent discovery and serious evaluation of an exceptionally high-grade iron deposit in northwestern Baffin Island. Of geological interest are intricately folded formations of marble in southern Baffin Island, a rock type generally uncommon in the pre-Grenville portions of the Canadian Shield. A greenstone belt in the Churchill province containing nickel and asbestos occurrences of potential economic interest lies at the northern tip of Quebec and extends easterly from Cape Smith, Hudson Bay. Of major importance is the extension of the Churchill province as the Labrador Trough south from Ungava Bay to its merging and metamorphic involvement with the Grenville province. Rocks of the Labrador Trough adjacent to and east of the older Superior province are not significantly metamorphosed but are converted to schists and gneisses farther to the east. The relatively unmetamorphosed western belt comprises slate, quartzite, dolomite and cherty iron-formation, with mafic volcanics abundant farther to the east. In many parts of the western trough, iron-formation has been closely folded and much of the silica removed. These enriched portions, together with their metamorphosed equivalents which extend into the Grenville province, now provide the bulk of Canada's iron ore production.

A large part of the Shield, extending from Georgian Bay to the Strait of Belle Isle, has long been recognized as forming a distinct segment called the "Grenville". It was named after the Grenville series, characterized by crystalline limestone, impure limy strata, and large areas of sedimentary gneisses in various stages of alteration to granite. The eastern part of the province contains large igneous intrusions of anorthosite. The age relations between Grenville strata and those of the neighbouring Superior province are puzzling. Near Sudbury, as well as at the south end of the Labrador Trough, beds can be traced across the boundary into more metamorphosed rocks of Grenville type. It is believed, therefore, that the distinctive features of the Grenville may be related more to the time and degree of metamorphism than to distinctions in the original age of deposition of strata. The Grenville province contains an unusually large variety of mineral occurrences but has not been as important a producer as the Superior. Several fairly large deposits are mined, including those of nepheline syenite near Peterborough, iron of the magnetite variety at Bristol and Marmora, zinc and lead in the Ottawa Valley and iron and titanium near Havre St. Pierre. Large iron deposits are in production at the southern extension of the Labrador Trough.

The areas of undeformed Precambrian cratonic cover rocks shown on the map facing p. 3 represent dominantly clastic detritus washed into basins from the consolidated, nearby, older rocks. At times, marine incursions into these basins led to deposition of limestone and dolomite, and volcanics were deposited in others. Copper deposits similar to those of the Keweenan Peninsula of Michigan, copper-uranium-vanadium in sandstones, and base metals in some of the limestones of the cover rocks could be present in this geological environment but economic deposits of this type have not yet been discovered.

The Appalachian Region.—This region comprises the Maritime Provinces and southeastern Quebec and is the northern continuation of a long belt of folded strata extending along the eastern side of the United States. It is on the site of a long, linear trough or geosyncline that existed mainly in Palæozoic time in which great thicknesses of sedimentary and volcanic strata were laid down. The northwestern boundary of the region lies adjacent to the Canadian Shield and to the St. Lawrence Lowlands. The strata in the Appalachians have been folded and faulted along axes that strike northeasterly except for local regions such as the Gaspe Peninsula where strikes swing to the east. Thus, strata of different kinds and ages and some belts of intrusive rocks normally form northeasterly-trending bands, many of which are responsible for development and orientation of peninsulas, bays and ridges of the region. Two principal periods of orogeny called the Taconic and the Acadian have been recognized. The Taconic occurred near the close of Ordovician time and the Acadian about Middle Devonian time. In Canada the Taconic disturbances were fairly widespread, the Acadian were more so, affecting areas that were previously affected by the Taconic as well as areas that were not, and the Appalachian orogeny, which was a major feature in parts of the United States, was of minor and local importance.

Metamorphosed Precambrian rocks of Grenville type are exposed to form the Long Range of western Newfoundland and small areas in Cape Breton and New Brunswick. On the east flank of the Appalachian geosyncline, as exposed in southeast Newfoundland, younger Precambrian volcanics and sediments are relatively unaltered and were intruded by small granite bodies 580,000,000 years ago. Although Precambrian rocks probably underlie much of the central Appalachians, they are buried beneath the thick Palæozoic sequence. Pyrophylite in southeast Newfoundland is the only product being mined from Precambrian rocks in the Canadian Appalachians.

Cambrian slates, minor limestones and local areas of volcanics lie above and adjacent to Precambrian rocks. Massive sulphide deposits in schists derived from Cambrian volcanics in southern Cape Breton and southeast Quebec were formerly mined. The overlying Ordovician beds were formed at the early stage of development of the Appalachian geosyncline. From west to east, and depending on their position in the geosyncline, the thick Ordovician sections comprise limestone and/or slate in western Newfoundland and adjacent to the St. Lawrence Lowlands in southeast Quebec. Mineral occurrences of zinc and lead-zinc are currently being evaluated in dolomitic limestones. Of major economic importance are Ordovician submarine volcanic rocks and their metamorphic equivalents in north-central Newfoundland, the Bathurst district of northern New Brunswick, and the Eastern Townships of southeast Quebec. These rocks are the hosts for all the massive, pyritic base-metal deposits being mined and developed in the Canadian Appalachians. In particular, the Bathurst mining camp and its new smelter complex promises to be a major factor in the economy of the region for many years, and the Buchans mine in central Newfoundland has produced since 1928 from orebodies which contained more than 15,000,000 tons of ore. East of this Ordovician volcanic belt, thick deposits of slates and sandstones were formed at the same time as the mineral-bearing volcanics were being deposited. Mineral deposits formed during sedimentation include the Wabana iron mine in southeast Newfoundland which terminated operations early in 1966 after about 70 years of continuous production. Some 490,000,000 years ago, molten ultramafic rocks rose from great depths and were emplaced as thin, tabular bodies mainly in the volcanic Ordovician areas. Subsequent alteration of parts of these folded, elongate bodies has produced the giant asbestos deposits of the Eastern Townships of Quebec, and one deposit being mined in northeast Newfoundland. Occurrences of nickel or chromite associated with the ultramafics seem of limited economic promise to date, although minor production has been attained. Silurian strata are rather similar to Ordovician rocks but are not known to contain large mineral deposits. Unlike the Ordovician submarine volcanics, some or most of the Silurian volcanics were formed on land. This may be one factor in the marked difference in known ore content of the two volcanic assemblages.

In Devonian time, granite batholiths were emplaced in the Maritime Provinces, and smaller stocks of the same age were intruded in Gaspe and southeastern Quebec. At this time, older beds were folded and metamorphosed to varying degrees, particularly near the margins of the granites. An important deposit currently being mined and supporting its smelter at Murdochville in central Gaspe will provide several tens of millions of tons of low-grade copper ore from altered limy slates above one buried granitic stock of Devonian age. Other similar deposits are being actively explored in the district. In Ordovician sediments near granites of Nova Scotia, scores of gold-bearing quartz veins were mined from 1862 to 1957 but the individual veins are not likely to be workable under present conditions. Fluorite in veins within Devonian granitic rocks at St. Lawrence, Newfoundland, have been mined since 1933 and currently yield all of Canada's production. Tungsten and molybdenum deposits associated with granites in central New Brunswick, southeast Quebec and southern Newfoundland are re-appraised periodically but have not been mined.

Following the folding and granite intrusion that formed the Appalachian Mountains, adjacent basins were rapidly filled with coarse and progressively finer-grained detritus eroded from the adjacent mountains. Some areas included marine beds, such as the petroliferous Albert shales of eastern New Brunswick which yield oil and gas. Other areas were the sites of rhyolitic volcanism early in Mississippian time, and rocks of one such centre in southern New Brunswick contain a deposit of tin, lead, zinc and molybdenum, which has been extensively investigated. After initial infilling of basins, shallow Mississippian seas encroached on the valleys and deposited limestones. Where evaporation exceeded the rate of saltwater inflow to these marine basins, evaporites were precipitated to form commercial deposits of rock salt and gypsum, and known occurrences of potash minerals. Native sulphur in unknown quantity is associated with evaporites in central Nova Scotia. A large deposit of barite with associated lead-zinc-silver ore is mined from replaced Windsor rocks at Walton, Nova Scotia, and many rather similar occurrences are known elsewhere in Windsor limestones. Many thousands of feet of clastic sediments were deposited after the Windsor seas retreated. These beds of Pennsylvanian age contain the commercial coal measures of Nova Scotia. In Triassic time, outpourings of basalt, particularly preserved adjacent to and below the Bay of Fundy, terminated rock-forming processes in the Appalachians. Subsequent erosion has yielded the present, fairly subdued topography of this former mountain chain.

The Cordilleran Region.—The Cordillera of Western Canada consists of three parallel northwest-trending geological and topographical systems. The Eastern System of western Alberta, eastern British Columbia, eastern Yukon, and western Northwest Territories includes the Rocky, Richardson, Franklin and Mackenzie Mountains and foothills, and several intervening plateaux. Comprising the Western System are the Coast Mountains along the west mainland of British Columbia, the St. Elias Mountains in southwest Yukon, the Queen Charlotte Islands and Vancouver Island. The Interior System lies between the Eastern and Western Systems. It contains the plateaux, plains and subdued mountain ranges of the interior of British Columbia and Yukon Territory.

Unmetamorphosed Precambrian to Cretaceous sedimentary strata form most of the Eastern System. These sedimentary strata, which have been uplifted several thousand feet by fault movements, are well exposed in the Rocky Mountains. The Interior System is composed largely of metamorphic, sedimentary and volcanic rocks of Precambrian to Mesozoic ages, which are intruded by numerous, generally unconnected, granitic stocks and batholiths. In places, these rocks are overlain by great thicknesses of Cretaceous and Tertiary volcanic and sedimentary strata. Flat-lying Tertiary basalt flows form many of the plateaux. In the Western System, the rugged Coast Range consists of almost continuous exposures of steeply eroded granitic rocks of Mesozoic and Tertiary ages flanked on both sides by late Palæozoic and Mesozoic volcanic rocks and by basins of Cretaceous and Tertiary sedimentary rocks.

During late Precambrian times, beds of quartzite, argillite, dolomite and other sedimentary rocks now comprising the Purcell and Windermere beds were deposited in the eastern Cordilleran geosyncline, a vast shallow sea that extended from south of the present Canada–United States border to the Arctic Ocean. From Cambrian until mid-Devonian time, sedimentary strata consisting of shale, quartzite and limestone continued to be deposited in the area which now forms the Eastern and Interior Systems. In southeastern British Columbia, the world-famous Sullivan zinc-lead orebody lies in Purcell beds and is thought to have formed during late Precambrian time.

Beginning in the mid-Devonian and lasting until early Jurassic, the Western System and most of the Interior System consisted of a deep oceanic trough in which accumulated submarine basalts and fine argillaceous and cherty sediments such as those of the Permo-Carboniferous Cache Creek Series and the Triassic Takla Series. Meanwhile, sedimentary strata were forming in the more shallow waters of the Eastern System, east of the present Rocky Mountain Trench. Thus, in the Rocky Mountains, Palæozoic limestones, dolomite, quartzite and shale are overlain in many places by similar Mesozoic rocks.

The first large granitic bodies were intruded into rocks of the Interior and Western Systems during early Jurassic time. They were composed mainly of granodiorite and quartz diorite, but ranged in composition from gabbro to granite. These intrusions were accompanied by folding, faulting and metamorphism. Although this orogeny may have been most intense during late Jurassic to early Cretaceous time, intrusion continued until early Tertiary time. Many mines in the Cordillera are related to Mesozoic and Tertiary intrusions. Uplift of the rocks during these processes created mountain chains and, by early Cretaceous time, rhyolites, andesites, basalts and sediments were being deposited in inter-mountain basins largely separated by the uplifted areas. Erosion of the mountains followed and, in late Cretaceous time, sandstones, conglomerate, shale and extensive beds of coal accumulated in large isolated basins such as that now occupied by the Nanaimo Series on Vancouver Island. Gradual uplift continued so that by Tertiary time the basins were very local and entirely continental. Sandstones and other sediments derived from elevated areas continued to be deposited in the low-lying valleys.

Uplift and mountain-building in the Eastern System was delayed until the Laramide Orogeny in early Tertiary time. Unlike the earlier orogenies to the west, no significant granitic bodies were intruded in the Eastern System. In many parts of the Rocky Mountains, Precambrian and Palæozoic strata were thrust several miles to the east along low-angle westward-dipping fault planes. Thus, these transported older rocks commonly came to rest above younger beds. At the same time and again in late Tertiary time, the eroded Western and Interior System rocks, as well as those of the Eastern System, were again uplifted. Erosion, including glacial scouring, which in places has continued to the present day, formed deep valleys in the elevated rocks and has produced the present configuration of the Coast Range, the Rockies and the intervening mountain chains.

In the Interior System, much lava was deposited on the plateaux at various times during the Tertiary Period, mainly in or about Miocene time. The lavas are chiefly basaltic and apparently welled from long fractures rather than from individual volcanoes. Sandstone, shale and volcanic ash were deposited in local freshwater basins in the same belt.

In latest Tertiary and Pleistocene times, some uplift and minor volcanic deposition occurred in the Western and Interior Systems. Very recent, post-glacial volcanic activity is represented by several well-preserved cinder cones in north, southwest and central British Columbia.

Glaciation, as in other parts of Canada, was widespread in the Cordillera during the Pleistocene Epoch, and glaciers persist today in many mountain systems, chiefly in the St. Elias and Coast Mountains and the Columbia Ice Field in the Rockies. A large part of the Yukon Territory, however, escaped Pleistocene glaciation because the high St. Elias Mountains barred moisture-laden winds from the Pacific to such an extent that ice did not accumulate in parts of the interior, despite the depressed temperatures of the time. This lack of glaciation was largely responsible for the preservation of the Klondike placer gold deposits.

The Cordilleran region has long been an important producer of economic minerals. Coal mining thrived over 100 years ago at Nanaimo on Vancouver Island and the gold rushes to the Klondike and Cariboo–Fraser Rivers regions resulted in the economic development of the Yukon and the interior of British Columbia. Present mineral production for the Cordillera is approximately one tenth of the Canadian total.

All parts of the Western and Interior Systems, except those covered by Tertiary plateau lavas and sediments, are favourable for the occurrence of metals. Metal occurrences are very minor in the Eastern System but appreciable amounts of oil and natural gas are found, mainly in the foothills.

Many of the metallic mineral deposits are related to granitic intrusions of the Jurassic to Tertiary intrusive cycle but others may have been present before the cycle and some were probably metamorphosed by the intrusions. Copper, gold, molybdenum and iron are the main metals produced in the Western System and western portions of the Interior System, whereas lead, zinc and silver are most important in the eastern parts of the Interior System. The ores in general are complex and a single mine may supply gold, silver, copper, lead and zinc.

The lead-zinc-silver mines of the eastern part of the Interior System in the Kootenay and Slocan districts of southeast British Columbia occur in Precambrian and lower Palæozoic sedimentary rocks. The Precambrian Sullivan orebody of the Kootenay district is one of the largest lead-zinc-silver deposits in the world. Another large producing area is at Mayo in the Yukon Territory. Cadmium, antimony and bismuth are recovered from many of the lead-zinc-silver ores.

Most copper ores of the region are large low-grade sulphide deposits related to Mesozoic or Tertiary granitic bodies. These include the Bethlehem deposits at Highland Valley, British Columbia, the Britannia mine near Vancouver, and several deposits that will soon be mined in the Smithers, Stewart and Stikine areas of the northern part of the province. Many of these mines contain recoverable molybdenum. High-grade skarn copper deposits occur at Merritt in the interior of British Columbia and on Vancouver Island.

Owing to intense mineral exploration in recent years, British Columbia has become a major producer of molybdenum. Large deposits at Endako and a smaller high-grade deposit at Boss Mountain are at present being mined. They are related to Mesozoic batholiths. Other promising large deposits are undergoing exploration or development.

The gold-quartz veins of British Columbia appear to have been derived from Mesozoic and Tertiary batholiths. Only two deposits of this type are at present being mined and most gold produced in the Cordillera is derived as a by-product of copper, iron and lead-zinc mining. The rich placer deposits that sparked the beginning of the mining industry in the Cordillera are of minor modern importance.

Iron deposits containing magnetite are being mined on Vancouver Island, the Queen Charlotte Islands and Texada Island. They occur in skarn zones along the contacts between granitic intrusions and Triassic limestone. Precambrian sedimentary iron deposits in the Yukon Territory may be developed in the future.

Mercury was mined mainly at Pinchi Lake, British Columbia, during World War II. These occurrences are now being re-evaluated. Nickel is mined near Hope in British Columbia and tungsten is recovered from a deposit in the Northwest Territories adjacent to the Yukon Territory. High-grade, long-fibre asbestos is extracted from a peridotite body at Cassiar in northern British Columbia.

Coal beds in Lower and Upper Cretaceous and Tertiary sedimentary basins are found in many locations throughout the Cordillera. Past production was much greater than at present but the possibility of increased demand for coal may reactivate several mines. The main producing areas include Comox on Vancouver Island, Crowsnest coalfield in southwest British Columbia and Alberta, and Luscar in the Alberta foothills.

Although most of the oil and gas fields of Alberta and British Columbia are east of the Cordillera in the Interior Plains of Alberta, several large fields are found in the foothills. The important Turner Valley field, which was discovered in 1913 and has produced since 1936, contains large oil and gas reserves in a faulted anticline in Mississippian strata. Oil is found in Devonian reef limestone at Norman Wells in the Northwest Territories. Sulphur is an important by-product of many fields containing natural gas.

Innuitian Region.—North of the Arctic Plains and Plateaux, where Palæozoic limestones rest on Precambrian generally-stable crystalline rocks, deep crustal depressions were initiated in late Proterozoic time and received thick deposits of carbonates and shales (miogeosynclinal type) and, in northern Ellesmere Island, volcanics and greywackes (eugeosynclinal type). In the southern basins, Proterozoic sediments are mainly carbonates and coarse to fine clastic sediments. Overlying these conformably are thick layers of lower Palæozoic carbonates which are thicker and include more abundant dark shales to the north. Middle Ordovician gypsum beds extend in places across the southern basins. Carbonates are admixed with muds and sands in parts of the Upper Silurian to Middle Devonian beds, and the influx of these clastic materials probably reflects relatively minor orogenies and periodic uplifts such as the Boothia Arch in the region. Folding of the eugeosynclinal volcanics of northern Ellesmere Island produced land areas from which sands were swept southward to form Upper Devonian non-marine sandstones in the miogeosynclinal basins. The total assemblage of sediments is more than 35,000 feet thick in some districts. The dominant folding of the Franklinian geosyncline, called the Ellesmerian orogeny, occurred near the close of Upper Devonian time. With the exception of the Cornwallis fold belt discussed below, the resulting folds of the Innuitian Region trend southwesterly from northern Ellesmere Island and swing westerly through the Parry Islands. The Cornwallis fold belt interrupts this trend at right angles because it lies along a buried north-trending prong of Precambrian rocks, which extend from exposures of the Boothia Peninsula. This elongate Precambrian basement rose periodically at least six times to produce north-trending faults and folds in the overlying Palæozoic beds of the Cornwallis fold belt, whereas the Franklinian geosyncline was deformed by somewhat younger and more widespread compressional crustal forces.

Following the Ellesmerian orogeny, a vast area including the present Sverdrup Islands and much of western Ellesmere Island was depressed to form the site of deposition of a composite thickness of 60,000 feet of Pennsylvanian to Tertiary volcanics, shales, sandstones, some gypsum and, in the upper part, a thick assemblage of non-marine clastic sediments. The rocks of this Sverdrup Basin were deformed about the end of the Mesozoic Era by the Laramide orogeny. Late Palæozoic gypsum beds, which tend to flow under high pressure, were forced upward to intrude overlying Mesozoic beds. Gypsum diapiric domes later penetrated Tertiary beds. No salt or potash-bearing minerals are as yet known to be associated with the gypsum, although a few minor occurrences of native sulphur have been found. A zinc-lead deposit being evaluated in limestone or dolomite on Little Cornwallis Island is unique in Canada, because much of the zinc occurs as the carbonate smithsonite, rather than sphalerite, the usual sulphide. Coal is widely distributed in the Innuitian Region, particularly in Upper Devonian beds of the Franklin miogeosyncline and in three formations within the Sverdrup Basin. As in the case of the

Arctic Lowlands and Plateaux, geological conditions are favourable for commercial petroleum accumulation but serious exploration guided by known regional geology has only recently begun in this vast area. Lead and zinc deposits in dolomitic, reefoid limestones might be expected on geological grounds. Regions in which reefoid dolomites lie near boundaries of calcareous rocks where they change to dark shales of the same age might be most favourable, according to some genetic hypotheses. Massive, pyritic base-metal sulphide deposits would probably be most likely to lie within volcanics in the northern, eugeosynclinal belt of the Franklinian geosyncline.

Arctic Lowlands and Plateaux.—These geological and physiographic divisions lie in large basins separated by arches and belts of exposed Precambrian crystalline rocks. Gently inclined or flat sediments underlying the basins tend to be thin sandstones and limestones near the basal contact with metamorphosed Precambrian rocks but limestones and dolomites of Middle Ordovician to Early Devonian age are the principal rock types and at some localities are estimated to be up to 18,000 feet thick. Shales, sandstones and restricted areas of conglomerates of Middle Devonian to Late Devonian age are normally the youngest rocks preserved.

Reefoid, vuggy dolomites of Middle Ordovician to Middle Silurian age commonly contain bituminous residues in surface exposures, structural and stratigraphic traps are probably present, and thick sections of potential source beds of petroleum and gas are known. Active oil seepages have not been reported. Petroleum exploration, aided by prior geological knowledge and published maps, began during the mid-1950s.

Beds of gypsum admixed with some shale up to 970 feet thick are exposed in many localities in Middle Ordovician beds. If more soluble evaporite minerals such as rock salt and potash-bearing minerals had been formed with gypsum, they would be leached from surface outcrops, but could be disclosed in future drilling. Piercement domes of gypsum, locally with occurrences of native sulphur, are found in the Sverdrup Basin. Coal is rare here, although abundant in the Innuitian Region.

Arctic Coastal Plain.—This plain comprises late Tertiary or Pleistocene sand and gravels, which dip gently seaward along the northern exposed border of the Innuitian Region. The very young beds cover the extensions of eroded fold belts and the Sverdrup Basin. Although of minor land extent, they or their equivalents probably extend far out on the Arctic continental shelf.

The Interior Plains.—The Interior Plains are underlain by undisturbed or gently flexed or tilted sedimentary strata, which overlap the western border of the Canadian Shield and merge with the eastern foothills of the Cordilleran region. The Shield slopes at a rate of 15 feet per mile under the Great Plains, in the western part of which the overlying strata reach a thickness of 10,000 feet. The older overlying beds have been bevelled by erosion along the border of the Shield, exposing in central Manitoba marine beds of limestone, sandstone and shale of Ordovician, Silurian and Devonian ages. Farther north the exposed Palæozoic strata are mainly Devonian. The Palæozoic formations are overlain by early Mesozoic strata of marine origin and these by both marine and freshwater Cretaceous formations, which are the uppermost strata in much of Saskatchewan and Alberta. In places, however, as at Turtle Mountain in Manitoba and the Cypress Hills in Saskatchewan, these are overlain by remnants of early Tertiary formations.

The rich soils of the Great Plains, particularly in the Manitoba Plain, were derived from the weathering of the underlying strata and the unconsolidated deposits resulting from glaciation. Most of Canada's oil and gas is produced from Palæozoic and Mesozoic strata underlying the Great Plains, mainly in Alberta but also in Saskatchewan, Manitoba and northeastern British Columbia. The productive beds range from Devonian to Cretaceous in age, the reservoir rocks being largely reefs containing openings, although "stratigraphic" traps such as lenses of porous sediments overlain by non-porous ones are also important. Exploration for oil and gas has recently been extended through most of the plains including those in the Arctic Archipelago. The Athabasca oil sands, extending for more than 100 miles along the Athabasca River in northern Alberta, are accumulations of heavy oil and sand of Early Cretaceous age. The total amount of oil in these sands is estimated at 100,000,000,000 to 300,000,000,000 barrels, more than all other known reserves of the world. Present and potential production of potash in southern Saskatchewan represents a major source in terms of world supply. These Middle Devonian evaporites are estimated to contain more than 100,000,000,000 tons of potash. Coal is being or has been produced from many places in the Great Plains, which also yield salt, gypsum, limestone and other non-metalliferous products. Important deposits of zinc and lead are being mined in Devonian limestone at Pine Point, Great Slave Lake.

St. Lawrence and Hudson Bay Lowlands.—The St. Lawrence Lowlands are underlain by marine beds deposited during much of Palæozoic time. Rather similar late Ordovician to Devonian beds are exposed in the Hudson Bay Lowlands. Small areas of Palæozoic beds are preserved at various localities on the Canadian Shield between these two Lowlands and suggest that arms or shallow straits of Palæozoic seas may have connected the present Hudson Bay and the St. Lawrence Lowland areas. The St. Lawrence Lowlands from Quebec City to Windsor are occupied by about one half the population of Canada, supported by much arable land and major industrial concentrations. These Lowlands are divided by an exposed southeasterly-trending prong of the Canadian Shield called the Frontenac Axis, which extends into the United States northeast of Lake Ontario. Southwest of the Frontenac Axis, marine sedimentary rocks of Cambrian to Mississippian age rest on buried Precambrian rocks. Known formations there have an aggregate thickness of almost 6,000 feet. Rocks are mainly limestones, shales and sandstones deposited in generally shallow seas. During Silurian time, evaporation exceeded saltwater inflow in some areas and the salt and gypsum beds within the Salina Formation were deposited. In part because of their position near industrial centres, roughly 80 p.c. of the salt produced in Canada is recovered by evaporation of brines and from two mines adjacent to the southeastern shore of Lake Huron. Gypsum is also mined from the Salina Formation. Petroleum has been produced continuously since 1859, mainly from Devonian beds, and natural gas has been produced since 1889, mainly from Silurian beds. Fluorite was at one time produced in moderate tonnages from veins in Ordovician limestone near Madoc in Ontario.

Northeast from the Frontenac Axis to Quebec City, only lower Palæozoic beds are present. Cambrian sandstone and thick beds of Ordovician limestone and shale attain thicknesses of up to 10,000 feet. Showings of petroleum and natural gas are known in some of the 185 exploratory wells drilled but no production has been attained. Sandstones of high silica content are quarried near Montreal, Quebec. Because of the population and industrial concentration in both the above sections of the St. Lawrence Lowlands, large amounts of limestone, shale and sandstone are quarried for structural materials, cement production and chemical needs. Such products have a low unit value and can be profitably extracted only within low-cost reach of their consumption points.

Anticosti Island is an isolated, northeastern division of the St. Lawrence Lowlands. Exploratory drilling for petroleum shows a thickness of up to 6,146 feet of Silurian and older Palæozoic sediments underlying the island, with Precambrian crystalline rocks at greater depths. Showings of oil and gas in one of five holes were not considered of commercial value.

The Hudson Bay Lowlands are underlain by flat-lying Ordovician to Devonian beds and Upper Cretaceous lignite, sand and fire clay. The beds attain a variable thickness of at least 1,536 feet in southern James Bay. Post-Precambrian beds near the centre of Hudson Bay are indicated by a seismic survey made by the Geological Survey of Canada to be up to 5,905 feet thick. Deposits of gypsum and lignite are known but not exploited.

Surficial Deposits

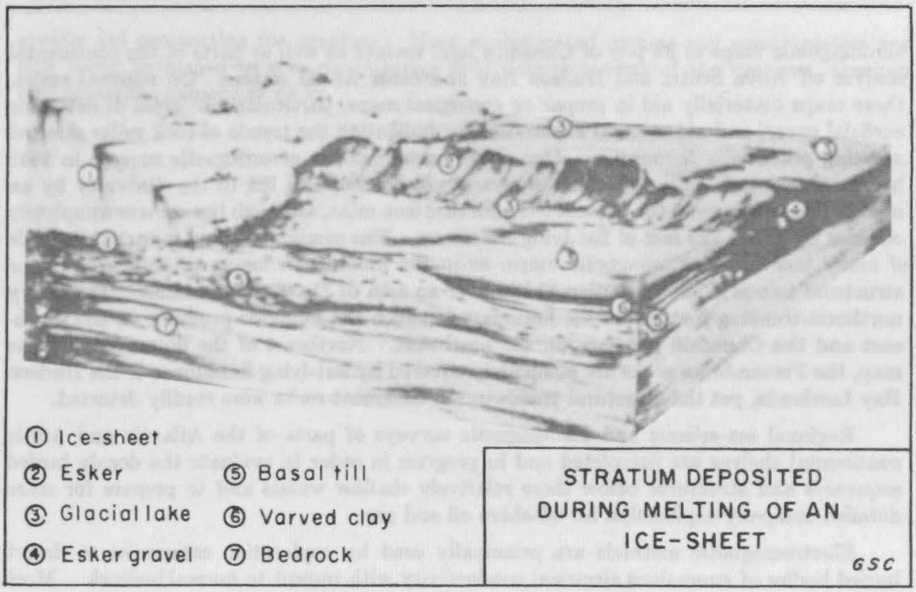
The continental glaciation of most of Canada has removed weathered bedrock and residual soils and has almost certainly removed some types of ores such as pre-Pleistocene placer gold deposits, laterites, and upper portions of metallic and manganiferous ore deposits, which had formerly been enriched under stable near-surface conditions. Material deposited includes dominantly clastic detritus such as tills, esker gravels, outwash gravels and sands, or rock flour deposited in lakes or shallow seas in the form of multiple layers of varved clay or massive clay beds. Maps showing the surface distribution of these materials are published by federal agencies and reflect some physiographic features and present and potential land use.

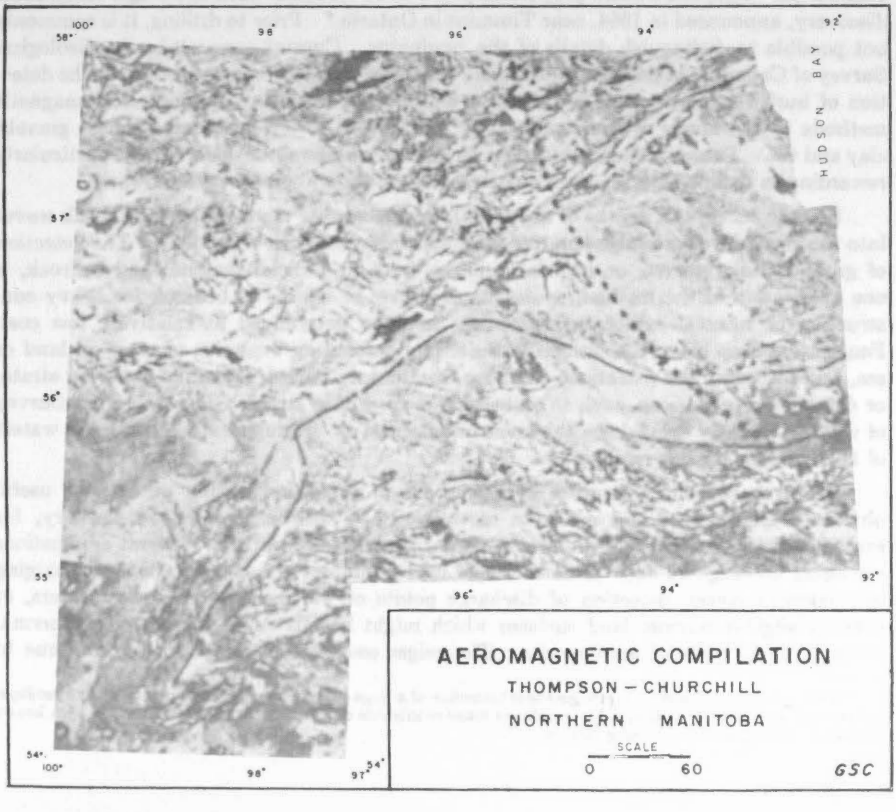
Much of Canada's bedrock surface and ore deposits are covered by such glacially derived surficial deposits. Gravel, sands and clays are extensively used in industrial regions and for earth dam construction, and coarse materials are used for road-building. Other beds or ancient river channels comprising gravels and coarse sands constitute important sources of groundwater. The nature and mechanical properties of glacial deposits must be well known for foundation design of large buildings, for dam design and for other engineering projects. Orebodies now covered by glacial material contributed blocks or grains of ore to the detritus during glaciation. Such blocks or heavy mineral grains can be found and in some cases traced back to their point of origin if the direction(s) of glacial transport can be deduced and if the history of transport is not too complex. Groundwaters circulating through ore and overlying surficial material may transfer metals in solution and enrich the nearby surface soil or stream sediments. Because so much of Canada's bedrock area is screened by surficial deposits, geochemical surveys to detect surface geochemical anomalies have been the initial clue to the discovery of some of its ore deposits. Other anomalies are known to be derived from non-economic mineralization or, where the path followed by groundwater from ore to surface is complex, the source of some surface anomalies remains unknown. Federal and some provincial geologists conduct regional geochemical surveys and supporting research, and mineral exploration companies make extensive and more detailed use of the geochemical prospecting methods.

Geophysics in Canada

Canadian scientists have played a major role in the development and application of airborne and ground geophysical instruments and techniques to probe below the surface of the land, the lakes and continental shelves. Regional surveys of variations in the earth's magnetic field are conducted with the use of aircraft by federal and joint federal-provincial agencies and results are published as aeromagnetic maps. Federal scientists have probed the Palæozoic beds and the surface of their buried basement in Hudson Bay and parts of the continental shelf by seismic methods; they make accurate measurements of the force of gravity at a network of Canadian stations, and record earth tremors and calculate their points of origin. Oil companies commonly conduct seismic and geological studies over large areas as the principal means of selecting promising drill sites. Mineral exploration companies normally select a district which they consider geologically favourable, carry out combined airborne electromagnetic and magnetometer surveys and then survey anomalous localities on the ground with more detailed electromagnetic, magnetic and/or gravity surveys. After geological examination and geochemical studies, these combined data allow selection of initial drill sites where drilling still seems warranted.

Aeromagnetic surveys measure variations in the earth's magnetic field caused by near-surface differences in the magnetic properties of bedrock and to a lesser extent by deeper bedrock features. These surveys have been vigorously conducted and have yielded


① Ice-sheet
② Esker
③ Glacial lake
④ Esker gravel
⑤ Basal till
⑥ Varved clay
⑦ Bedrock
STRATUM DEPOSITED DURING MELTING OF AN ICE-SHEET
GSC


100°
58°
98°
96°
94°
92°
HUDSON BAY
57°
56°
55°
54°
97°
AEROMAGNETIC COMPILATION
THOMPSON – CHURCHILL
NORTHERN MANITOBA
SCALE
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aeromagnetic maps of 38 p.c. of Canada's land surface as well as parts of the continental shelves off Nova Scotia and Hudson Bay and other Arctic waters. On regional scales, these maps materially aid in preparing geological maps, particularly in areas of extensive surficial cover, and aid mineral exploration by indicating the trends of rock units selected as being potentially favourable. One of the earliest of the aeromagnetic surveys in 1949 by the Geological Survey of Canada clearly pin-pointed and led to the discovery by an exploration company of the present Marmoraton iron mine, although the ore was completely covered by about 125 feet of flat-lying limestone. The compilation and reduction in scale of many individual aeromagnetic maps, as in the illustration facing p. 12, shows major structural trends in the Canadian Shield over an area of 71,000 square miles. The heavy northeast-trending line marks the boundary between the Superior province on the south-east and the Churchill province on the northwest. Northeast of the dotted line on the map, the Precambrian rocks are completely covered by flat-lying limestones of the Hudson Bay Lowlands, yet the structural trends in the basement rocks were readily detected.

Regional sea-seismic and aeromagnetic surveys of parts of the Atlantic and Arctic continental shelves are completed and in progress in order to evaluate the deeply buried sequences and structures below these relatively shallow waters and to prepare for more detailed company exploration for off-shore oil and gas.

Electromagnetic methods are principally used by exploration companies to detect buried bodies of anomalous electrical conductivity with respect to normal bedrock. Most conductors so detected prove to be caused by graphitic or barren pyritic zones and are of no commercial value, but a small proportion prove to be orebodies such as a single remarkable discovery, announced in 1964, near Timmins in Ontario.* Prior to drilling, it is commonly not possible to distinguish details of the conductor. Current research in the Geological Survey of Canada is in part directed toward the use of magnetotelluric currents in the detection of buried sulphide deposits but more effort is expended in applying electromagnetic methods to the study of the stratigraphy and nature of unconsolidated sands, gravels, clay and till. These studies, combined with shallow seismic surveys, have been particularly rewarding in defining buried river channels that contain abundant groundwater.

Seismic surveys to depths of about 180 feet are readily made by sending shock waves into the ground from a sledge-hammer blow and recording their reflections. The detection of groundwater reserves, or surficial aquifers, both in surficial material and bedrock, is one application of the method, as discussed above; or depths to bedrock for heavy construction or mineral exploration problems may be determined at relatively low cost. Penetration deep below the surface is effected by detonating explosive charges on land or sea, and recording the reflections of waves from deeply buried, folded or flat-lying strata, or detection of variations, such as oil-bearing reefs, within strata. The Geological Survey of Canada recently defined the thickness of potential oil-bearing strata beneath the waters of Hudson Bay by this method.

Research continues in other new methods of rapidly detecting potentially useful physical variations at and near the earth's surface. Airborne infra-red imagery, for example, discloses slight variations in apparent surface temperature. Several applications are being investigated such as detection of cold groundwaters or hot springs discharging into lakes or rivers, detection of discharge points of warm industrial waste waters, or possibly slightly warmer land surfaces which might be related to sources of geothermal power or some types of ore deposits. The geiger counter and scintillometer continue to

* This deposit was found by astute geological selection of a large area followed by airborne and ground geophysical surveys and, finally, drilling. No significant massive sulphide deposits of this type had formerly been known in this long-established gold-mining district.

greatly aid prospecting for uranium. More sophisticated gamma ray spectrometers are now being developed to give quantitative field determinations of the uranium, thorium and potassium content of rocks.