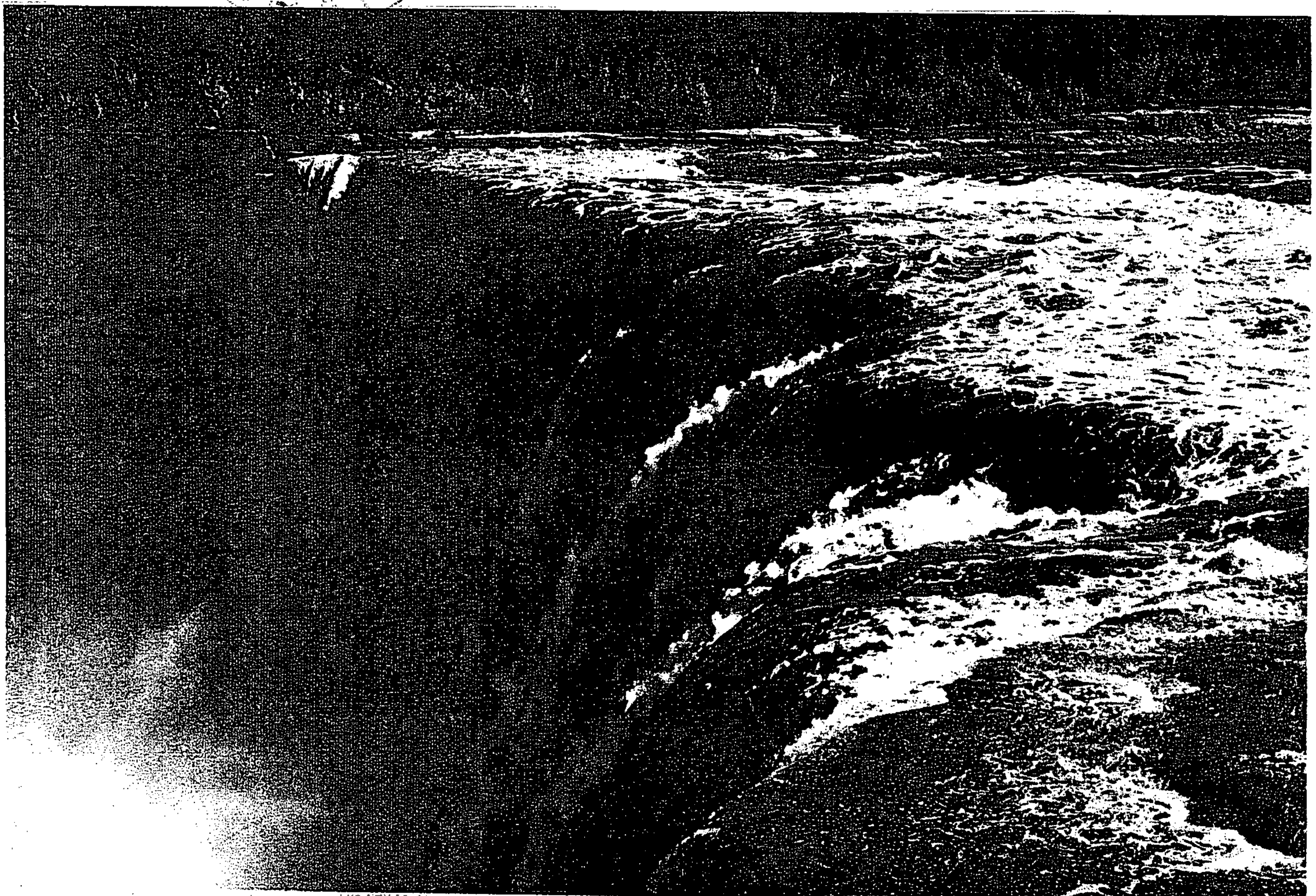
Subsurface Disposal of Waste in Canada - III

Regional Evaluation of Potential for Underground Disposal of Industrial Liquid Wastes

R. O. van Everdingen



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Introduction

Growing concern about the industrial pollution of surface waters has led to increasingly stringent controls on discharge of industrial liquid waste into streams and lakes. Consequently, subsurface disposal of such wastes by injection through wells has become an alternative with considerable attraction for industrial waste managers. It is not only technically feasible, but in many cases, economically attractive as well.

In an earlier report (van Everdingen and Freeze, 1971) the classification of waste for subsurface disposal was discussed, followed by a review of criteria to be used in the selection of disposal regions, sites and formations. At that time most of the criteria were in need of further definition and quantification, and many still are. In the next chapter an effort is made to improve this situation somewhat. The criteria are then used to (1) identify those regions in Canada where subsurface disposal of noxious, toxic or otherwise harmful wastes should not be allowed, and (2) review the regions that hold some potential for the safe disposal of selected liquid wastes by means of injection into the subsurface. An attempt is made also to identify some of the potential disposal formations within these regions. Discussion of regional stratigraphy and structure is based largely on Douglas (1970) and McCrossan and Glaister (1966).

It may of course be argued that the availability of a large subsurface disposal potential will give an advantage to certain regions of the country with respect to the establishment of certain industries. On the other hand, some of the major producers of liquid wastes that rely on underground disposal (oil-field operations, potash, and salt industries) are tied to sedimentary basins as much by their raw-material needs, as by their need for ample subsurface waste-disposal capacity. If no subsurface disposal were possible, these industries would be in great difficulties within a short time because surface disposal of their waste brines is either forbidden or excessively costly, in either monetary or environmental terms. It should be pointed out also that such industries have to abide by stringent regulations designed to avoid the problems of injected-brine migration that have plagued the petroleum industry in some areas.

Serious consideration should be given to the establishment of a classification for liquid industrial wastes in terms of their suitability for subsurface disposal. "Natural" liquid wastes, including oil-field brines, waste brines from salt, potash and soda production, and brines generated by solution of salt beds for the creation of underground storage caverns, should be qualified for underground disposal in principle. They can be injected into formations that contain natural brines with similar dissolved solids concentrations. "Foreign" liquid wastes (including "natural" wastes with "foreign" components added) should be dealt with on an individual basis. Their composition can be exceedingly complex, and it is often subject to rapid variation. Prediction of their behavior after injection is therefore difficult in many cases, and practically impossible in others. Some wastes may not be "economically" treatable on the surface at present, while they may be rendered harmless if detained underground for a sufficiently long period of time. If such detainment can be assured on the basis of detailed study, such wastes could be injected. Other liquid wastes may not degrade at all once they are injected, and still others may give rise to even more noxious or toxic degradation products. Such wastes should preferably be kept on the surface, where their disposition can be under continuous control. If, after careful consideration, it is decided to put them underground, steps should be taken to immobilize them as much as possible. This could possibly be achieved by incorporation in a cement grout, or by injection in *quasi*-stagnant areas in the deepest portions of potential disposal basins. It is not realistic to gamble on conversion of injected liquid waste to "useful resources" with the passage of time. Much research on the behavior of various liquid wastes under subsurface pressures and temperatures will be needed before any real safety can be assumed in the injection of such wastes.

Waste volumes injected into the subsurface are increasing exponentially in both Alberta and Ontario (Vonhof and van Everdingen, 1972) and the need for adequate evaluation of proposed disposal operations is thus becoming increasingly urgent.

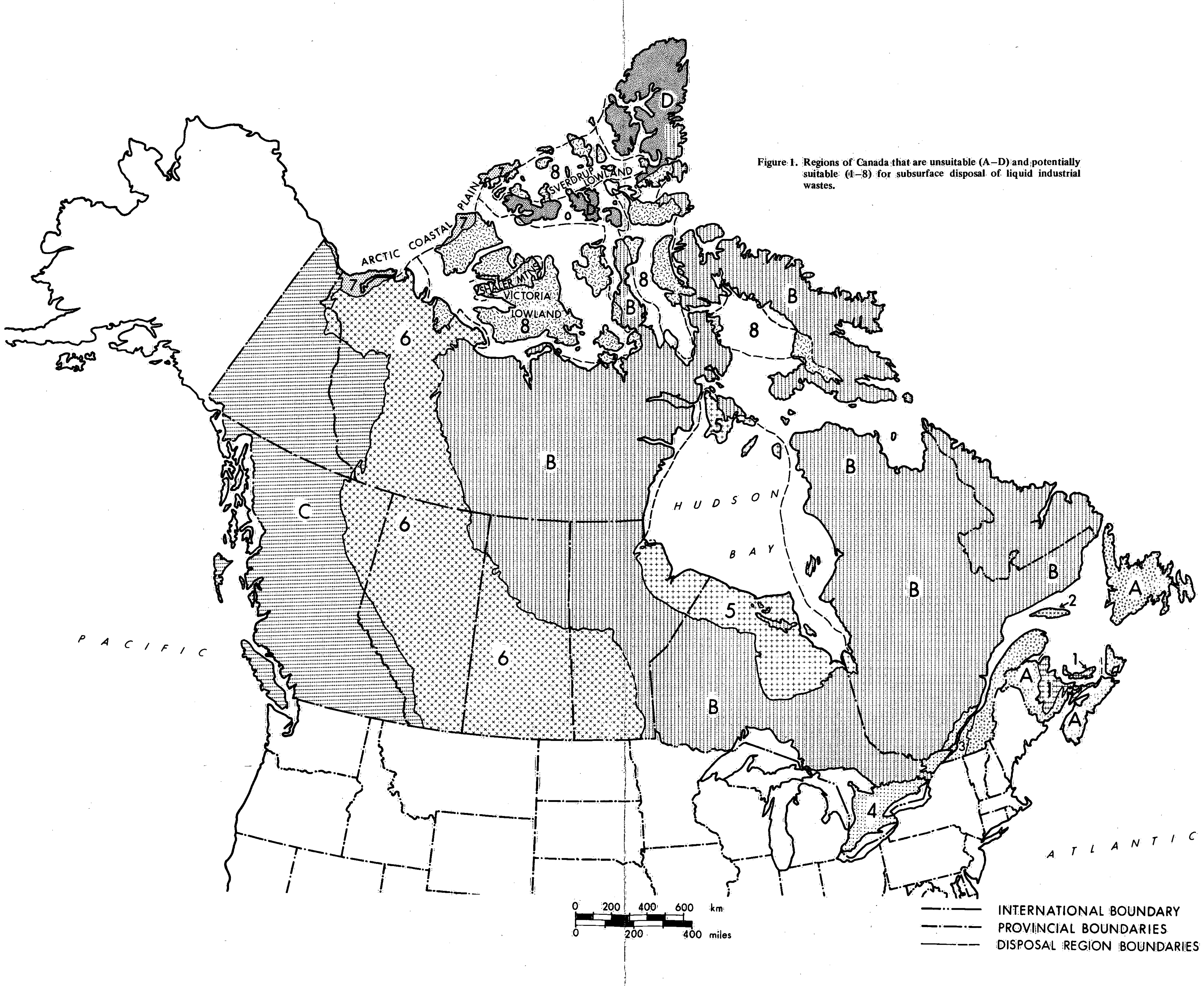


Figure 1. Regions of Canada that are unsuitable (A–D) and potentially suitable (1–8) for subsurface disposal of liquid industrial wastes.

Criteria Used in Evaluation

GEOLOGY

A number of geological requirements should be satisfied so that a region may be classified as potentially suitable for the subsurface disposal of liquid wastes.

The region must be underlain by an extensive, thick sedimentary sequence, providing at least 2,000 ft (600 m) of cover over any prospective disposal formations. The sedimentary sequence should contain at least one potential disposal formation of an adequate combination of porosity, permeability, and thickness to accomodate reasonable waste volumes at reasonable injection rates, without excessive pressure build-up. For the interrelation of these parameters, reference can be made to an earlier report in this series (van Everdingen, 1974). Confining beds overlying the potential disposal formations should have an adequate combination of low permeability and thickness to prevent escape of injected waste from the disposal formation at least for a required minimum period of time (depending on established degradation rate of the waste under reservoir conditions).

If the sedimentary sequence contains extensive evaporite beds, subsurface solution of these deposits may have resulted in collapse of overlying strata, with consequent faulting and brecciation. Where this has taken place, subsurface injection of liquid waste should be restricted to the unaffected portion of the sedimentary section underlying the evaporites. The effectiveness of confining beds in the section overlying the evaporites is doubtful in at least some instances.

Major faulting (and folding) should not be present in a potential disposal region. If major faults are present, these can provide either escape routes for injected waste, or they can put unexpectedly severe limitations on the size of the injection reservoir. The presence of normal faults usually indicates that the least compressive stress axis has a near horizontal direction. This in turn would indicate a somewhat higher probability of occurrence of vertical hydraulic fractures (under the influence of excessive injection pressures) than if the least compressive stress axis were near vertical. Extensive folding of the sedimentary section may make it difficult or practically impossible to predict movement of injected waste with any degree of accuracy.

Earthquake risk should be minimal in any potential disposal region, because the degree of seismicity has a limiting influence of the reliability and safety of subsurface disposal operations. On the one hand, damage to surface installations or to the injection well itself could result from an earthquake, leading to a pollution hazard at or near the disposal site. On the other hand, the capacity of the disposal formation or the competence of the confining beds could be adversely affected by the passage of earthquake waves, or by faulting or fracturing that may accompany an earthquake. For these reasons the degree of earthquake hazard to be expected in the various potential disposal regions outlined in later chapters of this report has to be taken into account. Unfortunately, case histories dealing with earthquake damage to deep wells and subsurface reservoirs could not be found in the literature.

The distribution of earthquake risks in Canada has been assessed by Milne and Davenport (1969). Their statistical analysis of data on a total of 2,399 earthquakes that occurred in Canada between 1899 and 1963 resulted in a number of maps giving return periods for accelerations of a specific magnitude. Distributions of return periods for accelerations of 0.1 g (acceleration due to gravity) are presented in Figure 2A for Eastern Canada, and in Figure 3A for Western Canada; distributions of accelerations (in percent of g) with a 100 year return period are presented in Figure 2B for Eastern Canada, and Figure 3B for Western Canada. In general it appears that seismic risk is minimal in all potential disposal regions, with the possible exception of part of the East St. Lawrence Lowland (3 on Figure 2).

The possible occurrence of perennially frozen ground (permafrost) should also be taken into account in an appraisal of regional disposal potential. The presence and extent of frozen ground will have a significant bearing on the feasibility of, and the problems encountered with subsurface disposal operations. Perennially frozen ground may extend to depths of more than 1,500 ft (450 m). Problems presented by the perennially frozen ground during disposal operations would be similar to those encountered during drilling for, and production of hydrocarbons. These may include: thawing of near-surface frozen materials during and after drilling operations; poor cement curing and bonding at low temperatures; thawing of frozen materials at depth around well casing as a result of injection of waste liquids at above-freezing temperatures; and possibly settling of surface casing in thawed-out ground. The latter three phenomena may lead to upward escape of waste along the outside of the well casing. It is also possible that gradual regression of the lower permafrost boundary will be caused by waste injection. This may result in the establishment of new (possibly temporary) flow systems that may

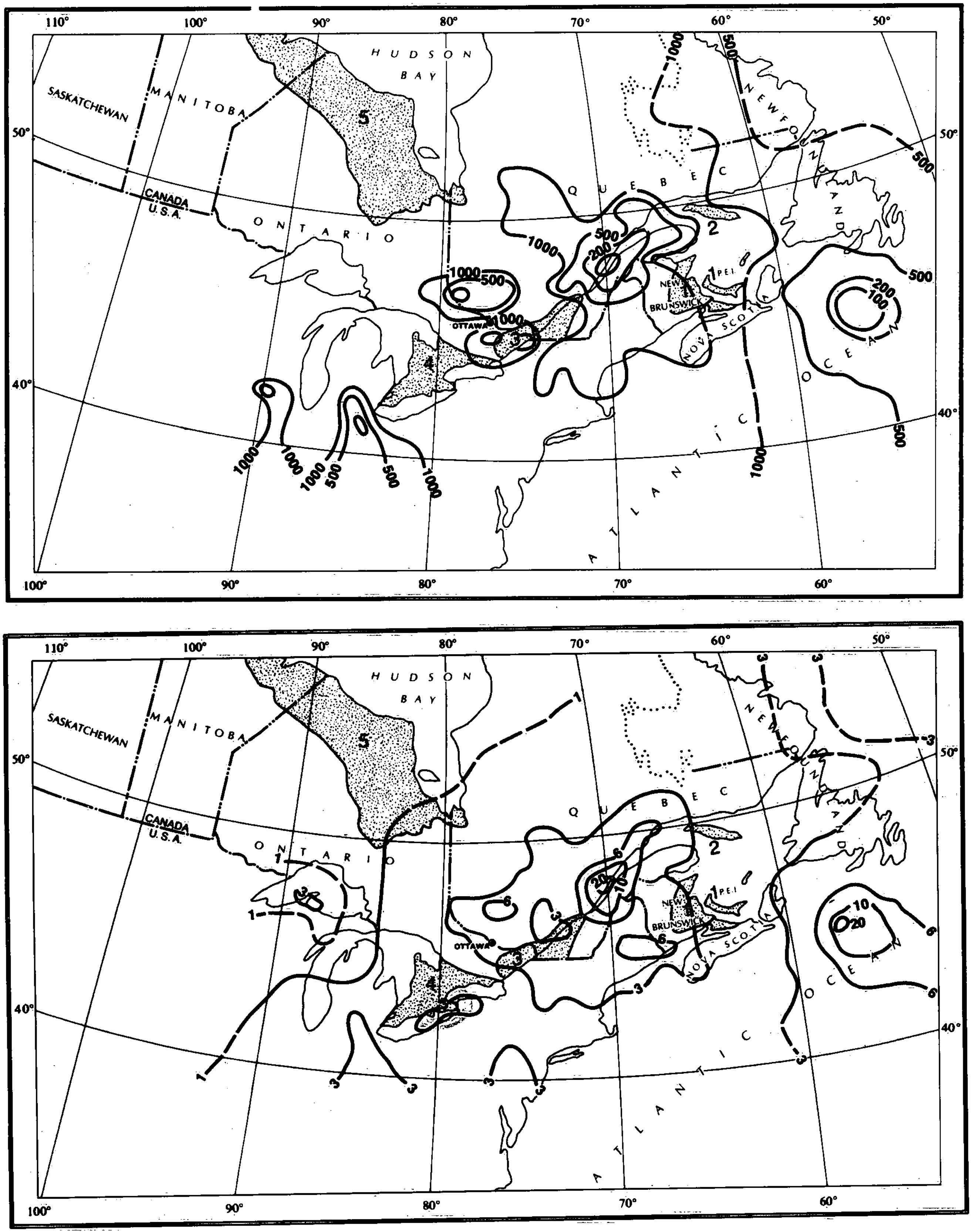


Figure 2. Seismic risk maps of Eastern Canada (after Milne and Davenport, 1969). Numbers of disposal regions correspond to those on Figure 1. (A) Contours of equal return periods in years, for acceleration of ten percent of g. (B) Contours of equal accelerations as a percentage of g, with a return period of 100 years.

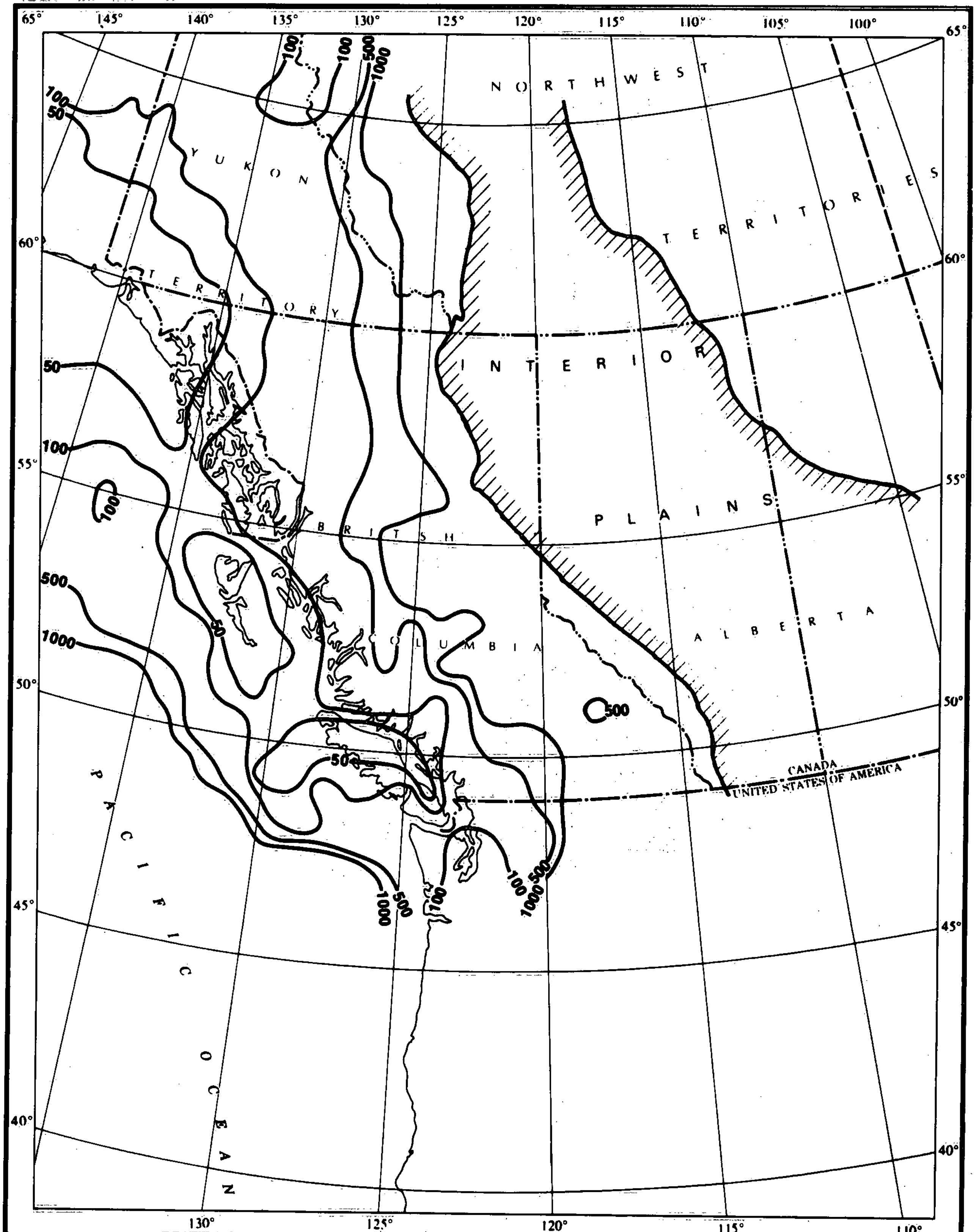


Figure 3(A). Seismic risk map of Western Canada (after Milne and Davenport, 1969). Contours of equal return periods in years, for accelerations of ten percent of g.

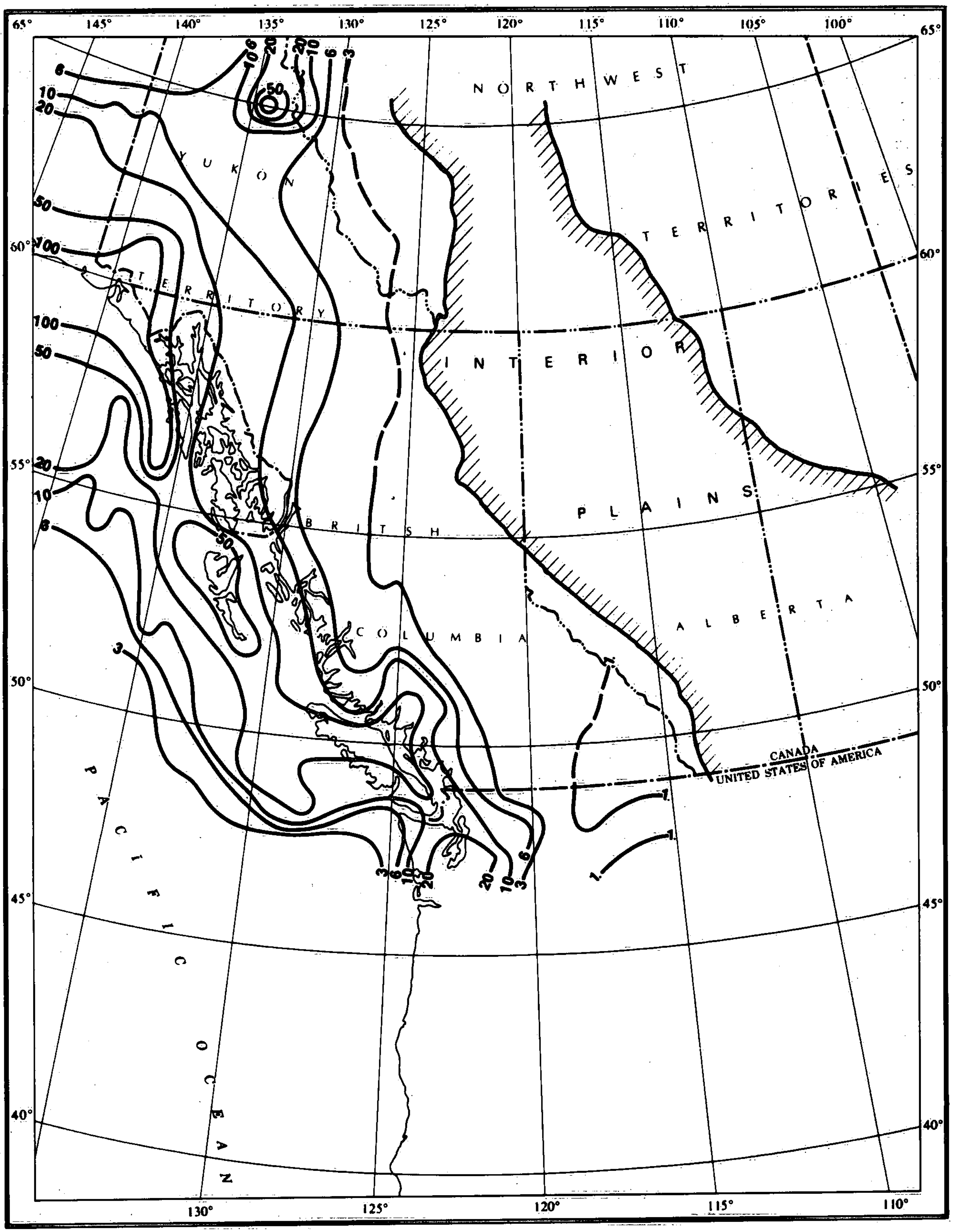


Figure 3(B). Seismic risk map of Western Canada (after Milne and Davenport, 1969). Contours of equal accelerations as a percentage of g, with a return period of 100 years.

return waste to the surface. Climatic and permafrost information has been adapted from a map published by R.J.E. Brown (1967), and added to Figures 4 and 7. In the areas where perenially frozen ground is present, the installation and operation of waste-injection facilities should be modified to conform with special requirements to ensure that only a minimum of thawing takes place in the perennially frozen layer, and that a reliable installation is obtained, with proper bonding between cement on the one hand and both well casing and formation rock on the other.

HYDRODYNAMICS

Requirements in the field of hydrodynamics are to some degree interrelated; they are also related to some of the geological requirements.

Horizontal hydraulic gradients in prospective disposal formations in a potential disposal region should be small, so that their combination with the relatively high permeabilities required for trouble-free injection will not lead to unduly rapid waste movement away from the injection site. Smaller gradients are usually associated with progressively deeper portions of large sedimentary basins.

Vertical potential gradients can be locally one or more orders of magnitude larger than horizontal gradients. Continuous upward gradients are usually found in discharge areas of flow systems of major dimensions. As these gradients may cause relatively rapid movement of injected waste to the surface, such discharge areas should be avoided in the establishment of waste-injection operations. The larger the areal extent of the basin under consideration, the farther any disposal operations can be kept away from potential discharge areas and their associated upward gradients.

Areas where prospective disposal formations possess hydraulic heads higher than local ground surface ("artesian areas") should also be avoided. Positive injection pressures would otherwise be needed for even the smallest injection rates. In case of a well failure, waste would flow back under pressure from an injection well in such a location.

Finally, it should be realized that the deeper the disposal formation is below the surface, the less likely it is to contribute to discharge of local or intermediate flow systems. Mathematical models such as those developed by Freeze (1972) should be used to enable prediction of underground waste movement under various conditions.

HYDROCHEMISTRY

In a potential disposal region, one or more prospective disposal formations should be present that contain water unsuitable for economic use (water supply, mineral recovery) in the foreseeable future. This generally will mean that dissolved-solids concentration should be over 10,000 mg/l. However the presence of particular components (e.g., arsenic) may make water with a much lower dissolved-solids concentration unsuitable for use, whereas advances in desalting techniques may convert formation waters with even higher salt concentrations into a useful resource.

ECONOMIC RESOURCES

A potential disposal region should contain one or more prospective disposal formations that are effectively separated from useable groundwater resources (see above), from fossil fuel resources (coal, oil, gas), and from useful mineral resources (including brines from which minerals could be recovered economically). It should be kept in mind that a number of mineral and fossil-fuel deposits remain to be discovered. Contamination by injected waste may make access to these deposits impossible. Use of the prospective waste disposal formations should not in any way encroach on scarce potential locations for underground storage of fresh water, fuel, or chemicals.

MAN-MADE HAZARDS

The presence of old wells and drill holes that are not plugged, inadequately plugged, or that have corroded casings or poor cementing jobs, would make at least some portions of a potential disposal region, and some parts of the available sedimentary section, unsuitable for subsurface waste disposal. These wells would provide numerous opportunities for inter-formational leakage. The use of injection under pressure would be expected to aggravate such a situation even further.

Cavities in evaporite beds, either natural or resulting from solution mining of salt or potash, may give rise to interformational leakage if roof rocks start caving above the cavity. Eventually ground subsidence may occur, which could adversely affect any nearby disposal operation. Similar effects can be expected from the presence of unfilled mine openings in the subsurface. An additional hazard in this case would be the possible breakthrough of injected wastes into such mine openings.

FORMATION AND SITE SELECTION

Further criteria for formation and site selection, as well as a list of methods employed in evaluation have been given earlier (van Everdingen and Freeze, 1971, p. 15-19). In many cases, proposed waste-injection operations will require detailed knowledge of the geology, seismicity, groundwater hydrology and hydrochemistry of the proposed disposal site and formation, as well as of the area surrounding it. Expenses involved in proper site study, testing and monitoring may be so high, that in many cases it may be cheaper to treat the waste involved for surface disposal.

Regions Unsuitable for Subsurface Disposal of Wastes

APPALACHIAN REGION

Most of the Appalachian Region (A on Figure 1), including the Island of Newfoundland, Nova Scotia, and New Brunswick (with the exception of the Maritime Plain), as well as the Eastern Townships and the Gaspé Peninsula of Quebec, is characterized by a strongly folded and faulted assemblage of sedimentary and volcanic rocks, partly metamorphosed with widespread igneous intrusions. Effective porosity and permeability of these rocks are largely provided by fractures, joints and bedding planes, the extent of which in many places decreases rapidly with increasing depth, limiting the space available for subsurface disposal of waste. The often extremely complex structure would make reliable prediction and adequate monitoring of underground waste movement impossible. In addition, the extensive faulting in parts of the region, as well as the occurrence of igneous intrusions, could present numerous opportunities for migration of waste to the surface.

CANADIAN SHIELD REGION

The Canadian Shield Region (B on Figure 1), covering all of Labrador, most of Quebec and Ontario, large parts of Manitoba, Saskatchewan and the Northwest Territories, the NE corner of Alberta, and parts of the Arctic Islands, consists of mainly metamorphic and igneous rocks, and some flat-lying sandstone formations, with a thin and discontinuous covering of unconsolidated Pleistocene and Recent sediments. The crystalline bedrock in this region generally has very little intergranular porosity and permeability. Secondary porosity and permeability, provided by joints, fractures and bedding or schistosity planes, decrease rapidly with increasing depth. Space available for subsurface disposal of waste is thus severely limited at the depths commonly regarded as safe for waste injection wells. Besides sufficiently impermeable confining beds are usually non-existent. The often complicated structures in the bedrock of the Canadian Shield Region would make adequate control of injected waste very difficult. Limited opportunity may exist for injection of easily degradable wastes into surficial sand/gravel aquifers. These may, however, be increasingly used as a source of water supply.

CORDILLERAN REGION

The Cordilleran Region (C on Figure 1), which includes most of British Columbia and the Yukon Territory and parts of Alberta and the Northwest Territories, can be divided into the Eastern, Interior, and Western systems.

In the Eastern system, the bedrock consists of a great thickness of sedimentary strata that have been subjected to extensive folding, faulting, and thrusting. The resulting complex structure would make reliable prediction and adequate monitoring of waste movement after injection impossible. Both normal faults and thrust-faults could provide pathways for rapid migration of waste fluids, often in unexpected directions.

The Interior and Western systems contain a complex assemblage of sedimentary and volcanic rocks which have undergone folding, faulting, uplifting, subsidence, erosion, and repeated intrusion by igneous rocks. The complex structures, the low porosity and permeability in the igneous rocks, and the erratic permeability in the volcanic rocks, in combination with the absence of adequate confining beds, make these parts of the Cordilleran Region unfavorable for underground waste disposal.

The one common factor that makes safe subsurface disposal of waste impossible in large parts of the Cordilleran Region is the strong topographic relief. Waste-producing industries normally are located in major river valleys which constitute groundwater discharge areas. Because of the strong upward gradients that prevail under these discharge areas, injected wastes would have the tendency to travel upward, back to the surface. Thus they would present a threat both to the increased use of the freshwater aquifers existing in the unconsolidated Pleistocene and Recent deposits in most of the larger valleys, and to the quality of the surface waters in the major rivers.

The often very high artesian pressures encountered in the subsurface of the intermontane valleys (J. S. Scott, 1968) would necessitate high injection pressures to maintain adequate disposal rates. This would lead to an increase in the chances of occurrence of hydraulic fracturing and possible subsequent leakage of waste fluids out of the disposal formation. In the case of a well-head failure, the high injection pressures would result in waste flowing back out of the well at a relatively high rate. The close proximity of disposal operations to the major rivers in this region would lead relatively rapidly to surface-water pollution in case of such a waste spillage on the surface.

A possible exception to the generally "unsuitable" classification of the Cordilleran Region might be found in the *Fraser Lowland*, a part of the Pacific Coastal Lowlands. This area is underlain by unconsolidated deposits commonly ranging in thickness from more than 600 to 1800 ft (180 to 450 m). The unconsolidated sediments are in turn underlain by as much as 10,000 ft (3,000 m) of Lower Tertiary and Cretaceous sediments that consist of conglomerates, sandstone and shales, partly of marine and partly of terrestrial origin. These sediments are only moderately folded and faulted. Aquifers in the unconsolidated deposits south of Fraser River provide more than 20 million gallons (90,000 m^3) of water per day for domestic use and irrigation. Artesian flows of as much as 200 gpm (gal/min) (55 m^3/hr) have been obtained from single wells tapping the confined aquifers below the valleys in this area. Any attempts at underground waste disposal in the Fraser Lowland would have to provide extensive safeguards for these useable water resources. Observations made earlier regarding artesian pressures that require high injection pressures with the attendant chances of hydraulic fracturing, and the possible consequences in the case of a wellhead failure, also apply to the Fraser Lowland. Furthermore, the area is one of moderate seismic activity (Fig. 3).

INNUITIAN REGION

The Innuitian Region (D on Figure 1), covering the northern third of the Arctic Islands is underlain by moderately to intensely folded rocks that range in age from Precambrian to Tertiary. They are predominantly of sedimentary origin, little metamorphosed, with some volcanics. Granitic intrusions occur in the northern part of the region, and basic intrusive dykes are common in other parts. Detailed knowledge of the geology of this region is still scarce, but sufficient to indicate that the potential for safe subsurface disposal of liquid waste is limited. Although industrial development is unlikely in this region for some time to come, it is of importance to establish the extent of the disposal potential, in view of the possible future need for subsurface disposal of the salt water that can be expected as a by-product, if and when petroleum is going to be produced in this region. In a number of cases such salt water could undoubtedly be disposed of in the sea.

Regions Potentially Suitable for Subsurface Waste Disposal

THE MARITIME PLAIN

The Maritime Plain (Bostock, 1969) consists of a number of lowland areas in New Brunswick, Nova Scotia, and Prince Edward Island, some of which may hold potential for subsurface waste disposal (area 1 on Figures 1 and 4). In the New Brunswick Lowland, Prince Edward Island Lowland, and the Cumberland Lowland (Nova Scotia), Carboniferous formations, ranging from Mississippian to Pennsylvanian, lie with pronounced angular unconformity on a basement of earlier Paleozoic and Precambrian rocks. The older rocks include gneiss, slate, quartzite, schist, and greenstone, with acidic and basic intrusives. The early Paleozoic sediments of Ordovician, Silurian and Devonian age (Table I), comprising crystalline limestone, slate, arkose, sandstone, and quartzite, were considerably metamorphosed by earth movements and intrusions of granite during the Acadian orogeny in Devonian time. They are exposed in the areas surrounding the lowlands. The pre-Carboniferous rocks offer no immediate potential for safe subsurface disposal of waste, as a result of their metamorphosis, folding and faulting.

The Carboniferous sediments, subdivided into the *Horton, Windsor, Canso, Riversdale, Cumberland,* and *Pictou Groups*, appear to present some potential for underground waste disposal in the three above-mentioned lowland areas. The thickness of these sediments is relatively and uniformly small in the New Brunswick Lowland, increasing rapidly to the east and southwest in the Moncton area. The maximum thickness of Carboniferous rocks, 14,696 ft (4480 m), was encountered beneath Hillsborough Bay. Isopach maps for the major Carboniferous units were published by Howie and Cummings (1963).

The *Horton Group* in Nova Scotia consists of up to 3,400 ft (1035 m) of basal conglomerate, sandstone and dark shale of the *Horton Bluff Formation*, overlain by about 6,000 ft (1830 m) of arkose, sandstone, and red and grey shales of the *Cheverie Formation*. In New Brunswick the Horton Group grades from red conglomerate, shale and sandstone of the *Memramcook Formation* into the 4,000 ft (1220 m) thick *Albert Formation* which consists of grey bituminous shales, sandstone with limestone layers, and up to 1,600 ft (490 m) of salt. Fluvio-lacustrine deposits of the Albert Formation contain commercial accumulations of oil and gas which are exploited in the Stony Creek field south of Moncton. The upper part of the Horton Group is known as the *Moncton Formation*, consisting of 1,500 ft (460 m) of red shales and sandstones of the *Weldon Member* which is uncomformably overlain by 2,400 ft (730 m) of conglomerate and red feldspathic grit of the *Hillsborough Member*.

The *Windsor Group* in Nova Scotia is made up of up to 1550 ft (470 m) of limestone conglomerate, sandstone, shale, gypsum, salt and marine limestone. In New Brunswick the *Windsor Group* consists of 50 to 700 ft (15 to 214 m) of limestone, gypsum, anhydrite, salt, shale, and sandstone. It is overlain by the Maringouin Formation with up to 1600 ft (490 m) of red shale and sandstone.

The *Canso Group* of non-marine sediments is restricted in distribution. In New Brunswick it consists of the *Shepody Formation*, 900 ft (275 m) of grey sandstone grading into red sandstone with shale beds. It is represented by the *Lismore, Mabou* and *Point Edwards Formations* in Nova Scotia. Thickness ranges to about 4,000 ft (1220 m) NW of Sussex, N.B., and to 6,000 ft (1830 m) under George Bay and near Port Hawkesbury. The *Canso Group* and the overlying Riversdale Group are locally absent in the Cumberland Lowland as a result of salt intrusion. The Canso Group is unconformably overlain by the *Enragé Formation*, the basal unit of the *Riversdale Group* in New Brunswick, and by the *Clairmont Formation* in Nova Scotia. The Maringouin, Shepody, and Enragé Formations are grouped together in the Hillsborough area, N.B., as the *Hopewell Group*.

The *Riversdale Group* which takes in the lower part of the *Petitcodiac Group* of the Hillsborough district, has a maximum thickness of 7,000 ft (2135 m). The basal unit, the *Enragé Formation*, consists of about 800 ft (244 m) of conglomerate, red shale, and sandstone. The *Boss Point Formation (Port Hood Formation)* overlying the Enragé (or the Clairmont Formation) is made up of non-marine pebble conglomerate and grey sandstone, and red and grey shales.

The *Cumberland Group* is restricted to the area immediately north of the Cobequid Mountains, where as much as 10,000 ft (3050 m) of non-marine conglomerate, sandstone, shale, and coal beds belong to this group. They thin rapidly in all directions.

The *Pictou Group*, which takes in the upper part of the *Petitcodiac Group*, is represented by the *Stellarton* and *Inverness* sediments in Nova Scotia, and by the *Grande Anse Formation* in New Brunswick. The *Grande Anse*

Table I. Hydrostratigraphic Units in Consolidated Bedrock.*

	Hydrogeologic Character		Dominant Lithology
Mesozoic	Triassic	Undisturbed, flat-lying. Very little H_2O from basalt, much more from sandstone (35 - 400 gpm yield, 50 - 200 mg/l TDS); some seawater intrusion.	Basalt Sandstone
	Permian Pennsylvanian	Post Windsor sediments; permeable, non-deformed, not well indurated (5 - 600 gpm yield, 100 - 300 mg/l TDS). Some seawater intrusion.	Sandstone, claystone
Paleozoic	Mississippian	Windsor group sediments: folded, faulted, solution channels, poor quality (yield variable, up to 10,000 mg/l TDS); contaminates some overlying fresh water.	Limestone, gypsum, anhydrite, salt, red beds
		Pre-Windsor sediments: folded, low permeability (3 - 25 gpm yield, 100 - 300 mg/l TDS), except where derived from Windsor.	Sandstone, siltstone shale, some conglomerate
	Devonian and older	Pre-Carboniferous Basement Complex: very little water; deformation and metamorphosis (yield 1 - 5 gpm; TDS 50 - 100 mg/l).	Granites, slates, phyllites, argillites

*After Carr, in Brown, I.C. 1967.

Formation consists of at least 1,200 ft (365 m) of reddish brown sandstone with pebble conglomerate and arkose. In the Minto area coal is being mined from the *Grand Lake Formation* which is also of Pictou age. The *Stellarton* sediments in Nova Scotia comprise sandstone, grit, and shale, with a total thickness of up to 9,000 ft (2745 m). The Pictou sediments cover the entire New Brunswick and Prince Edward Island Lowlands, as well as the northern portion of the Cumberland Lowland.

Prince Edward Island is underlain by a sequence of lenticular, extensively cross-bedded red sandstones, mudstones and mudstone breccia, with minor shale and conglomerate, with a demonstrated thickness of at least 10,415 ft (3175 m). The precise age of these sediments is uncertain, but they are generally designated as Permo-Carboniferous, probably Lower Permian and younger.

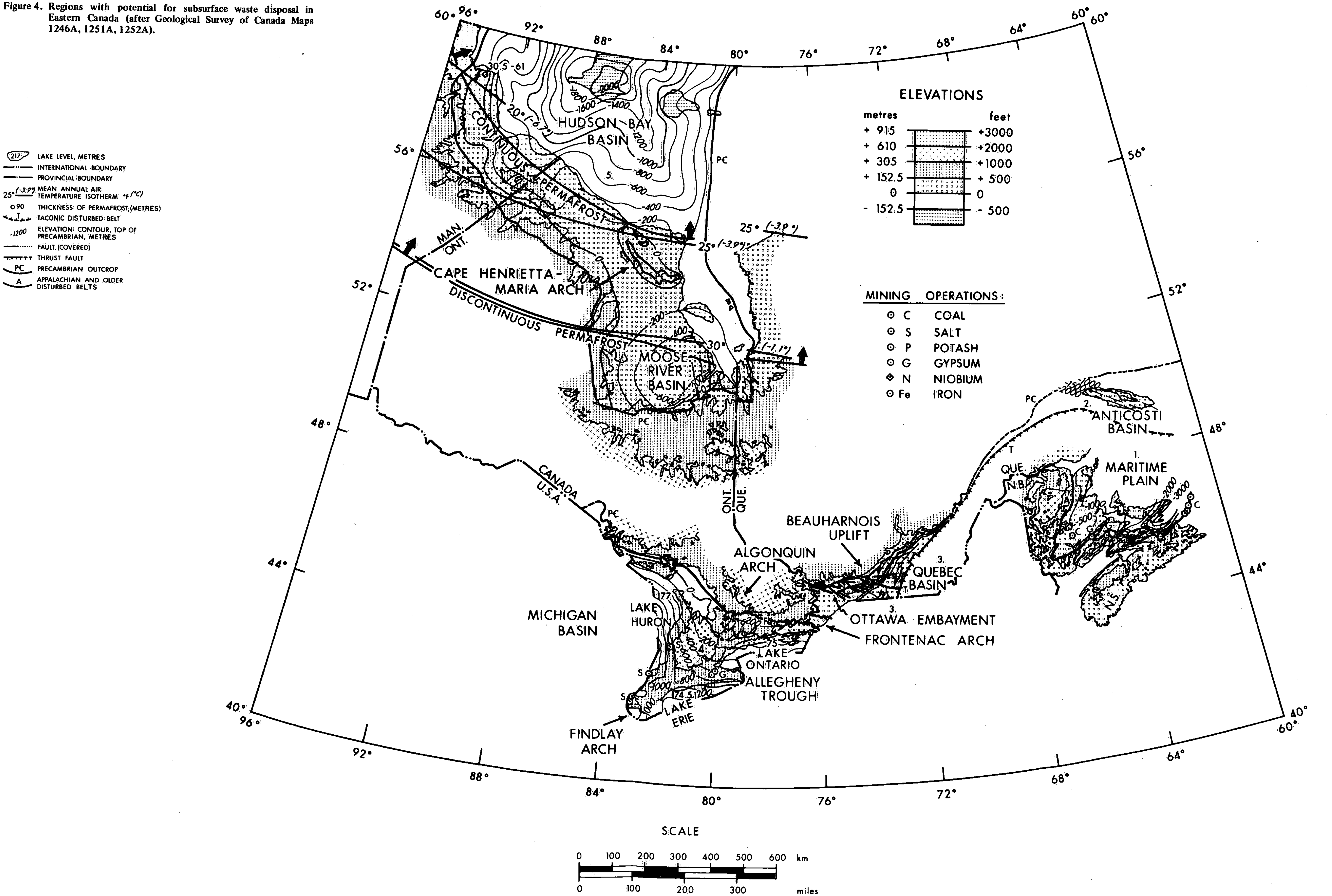
The Triassic is represented by red sandstone, shale, and conglomerate of the *Annapolis Formation* which underlies a series of about 1,000 ft (305 m) of amygdaloidal basalt lavas of the North Mountain Upland. The Triassic sediments underlie the Annapolis-Cornwallis Valley and border both sides of the Minas Basin.

General structural trends are northeast, probably controlled by pre-existing trends within the pre-Carboniferous basement complex. The compressive stresses during folding and mountain building were from the NW and SE.

A first period of deformation followed deposition of the Weldon and is pre-Hillsborough. It affected all pre-Hillsborough formations, and was followed by a period of erosion. The second period of deformation took place before the close of Hopewell time (Enragé Formation). The major faulting in the area appears to be related to this second deformation. Minor normal faulting resulted from readjustments. The deformation was followed by a period of peneplanation.

Four master fault systems affect the Mississippian Formations in New Brunswick. From NW to SE these are: the Belleisle fault; the Peekaboo – Petitcodiac-Berry Mills fault; the Clover Hill – Peck Creek – Dorchester fault

Figure 4. Regions with potential for subsurface waste disposal in Eastern Canada (after Geological Survey of Canada Maps 1246A, 1251A, 1252A).



system; and the Harvey – Hopewell fault. On the first three, the fault planes dip northwest, overthrusting being from the northwest; on the fourth fault the dip is to, and the overthrusting from, the southeast. Both *subsidiary* folds and faults are associated with these master fault systems.

The structure of the Pennsylvanian formations is regional, characterized by flat-lying beds, with a general easterly dip. Some local structures seem to be caused by salt migration in the Windsor Group, some others by gentle deformation during postdepositional sliding.

Coal is produced from the Pictou group in the Minto area in New Brunswick, mostly by stripmining. Just outside the potential disposal region in Nova Scotia, coal is produced in the Pictou fields (from coal measures in the Pictou Group), and the Springhill and Joggins fields (from the Cumberland Group).

Salt is produced within the potential disposal region from saltbeds in the Windsor Group, at Nappan, near Amherst, N.S., and at Pugwash, N.S. At Nappan the salt is about 500 ft (152 m) thick, starting at a depth of 2990 ft (911 m). At Pugwash the salt is found from 100 to more than 1000 ft (30 to at least 300 m) below the surface.

Judgement of the disposal potential of the various stratigraphic units underlying the Maritime Plain can be facilitated by the use of hydrostratigraphic units as introduced by Carr (in: I.C. Brown 1967). In Table 1 is presented a description of the stratigraphic units of the area in terms of their hydrogeological character.

The disposal potential of the *pre-Carboniferous* basement rocks is generally low, in view of the small permeabilities and relatively complicated structure in the deformed and metamorphosed rocks. A similar rating applies to the *pre-Windsor* sediments of Mississippian age, although deformation in these is less intensive and permeabilities are generally somewhat higher.

The *Windsor Group,* although folded, faulted and traversed by solution channels, may offer some possibilities for safe waste disposal. The basal limestones could form the disposal formation, with gypsum, anhydrite, salt and/or shale acting as confining beds. The formation is not used as a source of water, because of the generally high salinity of the Windsor water, caused by the presence of evaporites. However, the necessity for caution in the use of the Windsor Group for disposal purposes is indicated by existing contamination of water supplies from both pre- and post-Windsor sediments with saline Windsor water. The gross permeability of the Windsor sediments is highly variable as a result of the presence of solution channels.

The *post-Windsor* sediments usually contain water of good quality, which is used for water supplies in a number of places although along the coast the aquifers are subject to seawater intrusion. Because of the water-supply potential of these formations and the general absence of adequate confining beds, the post-Windsor sediments should generally be classed as having no disposal potential. Limited potential may be present in the deeper parts of the basin underlying Prince Edward Island. Spatial relations and circulation patterns would have to be investigated very carefully.

Permeabilities and porosities reported by Gussow (1953) are low, even in the oil-bearing Albert Formation: permeabilities range from 0.3 to 60 md. (millidarcy), with more than half the values below 1.0 md.; porosities range from 0.1 to 19% with an average near 10%. Brandon (1966) reported results of tests on four random sandstone samples from Prince Edward Island. Porosity ranged from 14.4 to 27.0%; horizontal permeability ranged from 33 to 2055 md.; and vertical permeability ranged from 2.6 to 661 md.

EAST ST. LAWRENCE LOWLAND

The only part of the East St. Lawrence Lowland that seems to offer any potential for underground disposal of liquid waste is Anticosti Island (area 2 on Figures 1 and 4). The island is about 140 miles (225 km) long and at least 32 miles (51 km) wide near the centre. Elevations range generally between 300 and 700 feet (90–210 m) asl. in the western and northeastern parts, reaching just over 1000 ft (300 m) in the southeast between the Jupiter and Shallop rivers.

A sedimentary sequence of Ordovician and Silurian strata, ranging in thickness from less than 1,000 to about 7,100 ft (300 to 2165 m) overlies the Precambrian basement. The sedimentary strata dip to the south at an angle of less than 2°. Table II presents a summary of the stratigraphy, lithology, and thickness of these Paleozoic sediments.

The Lower Ordovician *Romaine Formation* consists of stromatolitic dolomite with a thin basal veneer of orthoquartzitic sandstone. The formation reaches a thickness of 1200 ft (365 m) beneath central Anticosti Island. The Early Middle Ordovician *Mingan Formation* overlies the Romaine disconformably. On Mingan Island it consists of up to 39 ft (12 m) of basal conglomerate, sandstone and shale; 30 ft (9 m) of bioclastic limestone and coarse calcarenite; and 96 ft (29 m) of finely crystalline and aphanitic limestone. The formation increases in thickness southward to about 700 ft (213 m) in the subsurface of Anticosti Island. The late Middle Ordovician is represented by approximately 1000 ft (300 m) of unnamed cherty limestone strata, equivalent to the Black River and Trenton Groups in southwestern Ontario, that overlie the Mingan Formation disconformably.

Upper Ordovician limestone and shale with a total thickness of about 3100 ft (945 m) overlie the unnamed limestone on Anticosti Island. They are lithologically similar to Upper Ordovician in southwest Ontario. The *Macasty Formation* forms the bedrock surface beneath part of the Gulf of St. Lawrence north of the island. It consists of black bituminous shale, 200 ft (60 m) thick and equivalent to the Utica and Lachine shales of the Quebec Basin. The lower *English Head Formation* consisting of 750 ft (228 m) of alternating shale and limestone, overlies the Macasty conformably. The overlying upper *English Head* and *Vauréal Formations* consist of more than 1,000 ft (300 m) of finely crystalline to semi-lithographic limestone and interbedded greenish grey shale. The silt and shale content increases towards the northeast end of Anticosti Island. The Vauréal is overlain by the *Ellis Bay Formation,* which on western Anticosti Island comprises some 270 ft (82 m) of argillaceous limestone, shale and limestone with bioherm reefs. On the northeastern portion of the island the Ellis Bay grades to a dominantly sandstone facies, increasing in thickness to 300 ft (91 m).

The Silurian *Becscie* and *Gun River Formations,* equivalent to the Cataract Group in southwestern Ontario, reach a combined thickness of about 600 ft (183 m) on Anticosti Island. The Becscie, consisting of a lower, finely crystalline limestone which grades upward into green shale with nodular limestone beds, has a thickness of 265 ft (80 m). It overlies the Upper Ordovician Ellis Bay conformably. The succeeding Gun River which ranges in thickness from 308 to 343 ft (94 – 104 m), consists of limestone, alternating with shale in the upper part of the formation. Ripple marks and infraformational conglomerate in both the Becscie and Gun River Formations indicate shallow water deposition.

The youngest Paleozoic strata exposed are the Silurian *Jupiter* and *Chicotte Formations,* equivalent to the Clinton and Amabel Groups of southwestern Ontario. They have a combined thickness of about 725 ft (220 m). The Jupiter Formation, which is 650 ft (198 m) thick, consists of finely crystalline limestone with thin shale interbeds, grading upward into light calcareous shale and argillaceous limestone. The Chicotte Formation, 73 ft (22 m) thick, rests on the Jupiter with an abrupt contact. It is composed of bioclastic limestone with fragments of crinoid columns and corals. It resembles the Wiarton Formation of the Amabel Group in Ontario.

Abundant vertical joints in directions N50° – 60°W and at right angles to this, observed in outcrops, presumably decrease in magnitude with increasing depth. Adequate porosity and permeability could, however, still be available at greater depth, in the non-argillaceous limestone and sandstone members of the various Ordovician formations. It is felt that the absence of adequate confining beds may be a serious shortcoming in this area. For this reason the Lower and Middle Ordovician Mingan and Romaine Formations, overlain by Macasty shales, may offer the only real disposal potential. The scarcity of subsurface data precludes a more definite assessment of the disposal potential at this time.

In view of the restricted industrial development on the island, other than logging, pulp and paper industry, a demand for subsurface disposal of industrial waste may not be present as yet. If such demand should arise, however, then the initial investigations should be concentrated on the pre-Silurian, starting with the Romaine and Mingan Formations. Until more is known about subsurface conditions, Anticosti Island is classed as having *limited potential* only, as far as subsurface disposal of wastes is concerned.

CENTRAL ST. LAWRENCE LOWLAND

The Central St. Lawrence Lowland, covering the Quebec Basin between the Canadian Shield and the Appalachian Geosyncline, is separated from the East St. Lawrence Lowland by 260 miles (418 km) of the lower St. Lawrence River. It extends from a few miles east of Quebec City to a line connecting Arnprior and Brockville in Ontario (area 3 on Figures 1 and 4).

Precambrian rocks of the Frontenac Arch separate it from the West St. Lawrence Lowland. The Beauharnois Uplift, which crosses the Central St. Lawrence Lowland near the confluence of the Ottawa and St. Lawrence rivers, separates the Ottawa Embayment from the main Quebec Basin.

The Ottawa Embayment portion of the Central St. Lawrence Lowland covers an area of about 4500 sq. miles (11,650 km^2), the Quebec Basin portion about 5000 sq. miles (13,000 km^2). Land elevations in the Central St. Lawrence Lowland do not exceed 500 ft (150 m) above sea level, except at the Monteregian Hills. East of Montreal elevations vary between 100 and 300 ft (30 – 90 m) above sea level.

The Central St. Lawrence Lowland is underlain by unfolded Paleozoic sediments ranging in age from Upper Cambrian to Upper Ordovician. In the area east of Montreal the sediments have been intruded by the Monteregian igneous intrusions of Early Cretaceous age. The maximum thickness of the Paleozoic in the Ottawa Embayment is about 2200 ft (670 m); in the Nicolet River area of the main Quebec Basin it reaches more than 10,000 ft (3000 m).

A number of major faults affect the entire sedimentary sequence in the Central St. Lawrence Lowland. The faults are steeply dipping; the major trends are east and southeast. Although the faulting and associated fracture development may provide pathways for the movement of both groundwater and injected wastes, many of the fault zones in the region appear to act as barriers to such movement, as a result of sealing by calcite deposition (Scott, in Brown, I.C. 1967, p. 107). Knowledge of the geology of the Ontario portion of the Central St. Lawrence Lowland is largely based on studies of outcrops, as relatively few holes have been drilled through the sedimentary sequence in this area. Recent drilling and logging programs may well alter present ideas about the structure of the basin. They will undoubtedly assist in a more precise definition of the fault systems in the basin. The latter would be of great importance to any future subsurface disposal project.

In Table III is presented a summary of the stratigraphy and lithology for the Central St. Lawrence Lowland. The most complete stratigraphic sections are present near the intersection of the major faults in Russell Township in the Ottawa Embayment, and southwest of Nicolet in the main Quebec Basin.

The upper Cambrian *Nepean Formation*, consisting of orthoquartzitic sandstone, ranges in thickness from zero to more than 1100 ft (335 m). The somewhat more silty equivalent in Quebec, the *Potsdam Formation*, varies in thickness from zero to about 2000 ft (610 m); the greatest thickness is found in southwestern Quebec, thinning to the northeast, while it is absent beyond the Nicolet area. Both formations are extremely variable in porosity and permeability. Measured porosity values range from less than 5% to as high as 40%. Permeability depends strongly on the degree of development of the vertical and horizontal joint systems in the rocks; measured values are often less than 1 md, but have been found as high as 30 md. The larger permeability values occur in the upper and lower beds of the formation where the joint systems are best developed.

The Lower Ordovician *March Formation* overlies the Nepean and Potsdam Formations comformably. Consisting of interbedded orthoquartzitic sansdstone and dolomite, it averages about 30 ft (9 m) in thickness in the Ottawa Embayment, increasing to about 250 ft (76 m) in the main Quebec Basin. In the northern part of the Ottawa Embayment, it is a source of potable water.

The March Formation is overlain by the *Oxford Formation* in Ontario, and by the *Beauharnois Formation* in Quebec. Both consist of massive and finely crystalline dolomite and limestone with minor shale. The thickness of the Oxford ranges from zero to about 400 ft (120 m), that of the Beauharnois to about 1000 ft (300 m). Yields of individual wells in the March, Oxford and Beauharnois Formations range from 5 to 15 gpm (1.3 to 4.0m^3/h). Some large water-supply wells in Quebec, west of Montreal, produce up to 490 gpm (132 m^3/h) from the March and Oxford Formations. The water is often high in NaCl, especially in the deeper parts of the basin.

Formations of Middle and Upper Ordovician age are found only in the central portion of the Ottawa Embayment, and in the main Quebec Basin to the north, east and southeast of Montreal. The *Chazy Group* is represented by the *Rockcliffe Formation* in Ontario, and by the *Laval Formation* in Quebec. The Rockcliffe Formation consists of shale and siltstone with lenses of coarse-grained sandstone. The Laval Formation comprises a basal unit of protoquartzitic sandstone, shale and siltstone that grades vertically and laterally basinward into interbedded limestone, shale and shaly dolomite. Small bioherm reefs occur in the Upper Laval. Thickness ranges up to 250 ft (76 m) for the Rockcliffe and to more than 600 ft (185 m) for the Laval Formation. Water wells in zones with well developed joint systems in these formations produce from 5 to 15 gpm (1.3 – 4.0 m^3/h).

The Middle-Ordovician carbonate series comprises the Black River and Trenton Groups, with a combined thickness varying from 700 ft (213 m) north of the St. Lawrence east of Montreal, and 730 ft (223 m) in the Ottawa Embayment, to as much as 2000 ft (610 m) in the southeastern Quebec Basin. The *Black River Group* consists of three formations. The *Pamelia*, 70 ft (21 m) of sandy shale, grades upward to interbedded dolomite, lithographic limestone and minor shale; it thins eastward and is probably absent in southeastern Quebec Basin. The *Lowville Formation*, 40 to 155 ft (12 – 47 m) of lithographic limestone, overlaps the Laval and earlier formations in the northeastern part of the basin. The *Leray Formation* consisting of interbedded lithographic limestone and calcarenite, thins from 65 ft (19.5 m) in the Ottawa Embayment to 21 ft (6.4 m) near Montreal. The *Trenton Group* sequence in western and northwestern Quebec Basin is similar to that in southwestern Ontario, but differs from that in eastern and southern Quebec. The *Rockland Formation* in the Ottawa Embayment is 55 ft (16.8 m) thick and consists of argillaceous finely crystalline limestone. It thins eastwards and grades into the 19 ft (5.8 m) thick microcrystalline limestone of the *Ouareau Formation* near Montreal. The northeast Quebec equivalent is the 32 ft (9.8 m) thick *Pont Rouge Formation.* The *Hull Formation* in the Ottawa Embayment consists of 180 ft (55 m) of finely crystalline limestone with shale partings, overlain by coarse-grained calcarenite. The western Quebec equivalent is found in the 300 ft (91 m) thick bioclastic limestone and calcarenite of the *Deschambault Formation*. The upper 180 ft (55 m) of these are replaced by the varied limestone facies of the *St. Casimir Formation*. The next formation in the Ottawa Embayment, the *Sherman Falls*, consists of 25 ft (7.6 m) of interbedded calcarenitic limestone and shale, presumably equivalent to the 375 ft (114 m) thick *Montreal Formation.* The latter merges with aphanitic limestones of the *Neuville Formation,* which is 470 ft (143 m) thick. The uppermost Middle Ordovician unit in the Ottawa Embayment, the 180 ft (55 m) thick *Cobourg Formation*, consists of aphanitic limestone. It thickens to 500 ft (152 m) near Montreal, grading into interbedded dense limestone and shale of the *Tetreauville Formation*. The latter thins eastward and merges with the Neuville Formation. In the southern portion of the Quebec Basin the Tetreauville limestones pass abruptly into black shales.

Except for the upper part of the Trenton Group, few water recoveries have been recorded for the carbonate series in Ontario. Average well yields here vary from 5 to 15 gpm (1.3 – 4.0 m^3/h). In the Ottawa area several hundred feet of massive carbonate section yield no water at all. A few large wells in the Quebec portion of the basin produce more than 400 gpm (108 m^3/h) from rocks of the Trenton, Black River and Chazy Groups.

The Upper-Ordovician shale and interbedded limestone series composed of the *Eastview, Billings, Carlsbad, Russell,* and *Queenstown Formations* in Ontario and the *Utica, Lachine, Nicolet River, Pont-Gravé River* and *Bécancour River Formations* in Quebec could form adequate confining beds for underlying disposal formations, if they are not adversely affected by faulting and jointing. The thickness of the shale series ranges up to 1200 ft (366 m) in Ontario, and up to almost 5500 ft (1676 m) in Quebec. Fracture zones in the shales locally yield a few gallons per minute to individual wells. The water is usually of poor quality, containing sodium carbonate and often hydrogen sulphide.

According to McLean (1968), disposal possibilities in the Ontario part of the Central St. Lawrence Lowland appear to be favorable as far as available porosity and permeability are concerned, only in the central portion of the Ottawa Embayment. They are limited to the Nepean (Potsdam) Formation. It should be stressed, however, that the extensive faulting in the area, combined with a maximum available disposal depth of only 2200 ft (670 m) will severely limit the potential of the area. In addition to this, the carbonate rocks of the Trenton and Black River Groups would have to serve as confining beds over most of the area; the shales of the Upper Ordovician are present only locally.

In the Quebec portion of the Central St. Lawrence Lowland the greater thickness of the Potsdam Formation (up to 2000 ft or 610 m), and the greater thickness of the sediment cover on the Potsdam (more than 6000 ft or 1830 m, of which more than 5000 ft or 1525 m consist of *shales*), as well as the lesser incidence of faulting in the areas north, east and southeast from Montreal, may indicate a somewhat better potential for subsurface waste disposal. Zones with well developed joint systems in the Lower and Middle Ordovician sandstones and carbonates in the deeper central part of the main Quebec Basin may hold additional potential for waste disposal.

More than 350 exploratory wells for oil and gas have been drilled in the Central St. Lawrence Lowland. None of these found hydrocarbons in commercial quantities, although many recorded oil and gas shows, while some encountered substantial gas flows. In the Ottawa Embayment only four of the 25 wells drilled to 1968 penetrated to basement, most of the others were terminated in the Trenton and Black River Groups. Gas shows were reported from the Trenton Group and from the overlying marine shales of the Billings and Carlsbad Formations.

In the main Quebec Basin more than 150 wells have penetrated to depths of more than 500 ft (152 m); less than 15 of these reached the crystalline basement. Few tests have been drilled to the basement in the deepest part of the basin. Both oil and gas shows were reported from the Potsdam sandstone; from the Beekmantown, Black River and Trenton carbonates; and from sandstones in the Upper-Ordovician marine shale series. Many shallow water tests encountered gas flows, commonly at or near the contact between surficial cover and bedrock of the Utica and Nicolet River Formations. Some of the formations are used as reservoirs for the storage of natural gas.

Of the 124 wells with depths exceeding 500 ft listed in the 1964 report on well data for the St. Lawrence Lowlands area in Quebec, 8 were reported not plugged (3 of these penetrated the Potsdam); for 29 it was not known whether they were plugged or not (3 of these penetrated the Potsdam); for 78 plugging was not mentioned; and only 9 were stated to have been plugged when abandoned.

Careful study of the local geology, with particular emphasis on the location and character (open or sealed) of faults, the degree of development of joint systems, and the presence and adequacy of confining strata, would have to precede any attempt at subsurface disposal operations in the Central St. Lawrence Lowlands. Studies of deep groundwater movement in the area, in relation to the two major rivers (Ottawa and St. Lawrence) and the influence of the Monteregian intrusives, would also be required for a proper evaluation of the disposal potential. Seismic risks appear to be somewhat higher in the Ottawa Embayment portion of the Central St. Lawrence Lowland than in other potential disposal regions. Such risks will have to be assessed in more detail if subsurface waste disposal is contemplated.

WEST ST. LAWRENCE LOWLAND

The St. Lawrence Lowland west of the Frontenac Arch covers southwestern Ontario between the Canadian Shield and the United States border; it includes the Niagara and Bruce Peninsulas and Manitoulin Island (area 4 on Figures 1 and 4). It comprises an area of 25,000 sq miles (65,700 km^2); an additional 15,000 sq miles (38,800 km^2) are covered by the waters of the Great Lakes inside the International Boundary. Elevations in the area range from 246 ft (75 m) along Lake Ontario, and 572 and 580 ft (174 and 177 m) along Lake Erie and Lake Huron, respectively, to about 650 ft (198 m) along the Niagara Escarpment, and to somewhat more than 1000 ft (305 m) in the central area south of Georgian Bay.

The West St. Lawrence Lowland is underlain by gently dipping, unfolded Paleozoic marine sediments of Cambrian, Ordovician, Silurian and Devonian age, that were deposited in the Michigan Basin to the west and the Allegheny Trough to the east. East of the Niagara Escarpment only Upper Ordovician and older rocks are present. The Algonquin Arch, extending in a northeast-southwest direction through the area, separates the Michigan Basin and the Allegheny Trough. In the extreme southwestern part of the province the Findlay Arch, extending northward from Ohio, is also reflected in the structure contour map (Figure 4). The Algonquin and Findlay arches are separated by a structural depression which encompasses a fault complex known as the Chatham Sag. The latter is the location of the youngest strata of the Paleozoic succession in Ontario. The maximum aggregate thickness of the sedimentary formations in southwestern Ontario is about 5900 ft (1800 m) (300 ft or 91.5 m Cambrian, 2500 ft or 762 m Ordovician, 1900 ft or 580 m Silurian, and 1200 ft or 366 m Devonian). Large parts of southwestern Ontario, however, have only a relatively thin veneer of sediment. The sequence thickens westward into the Michigan Basin, to about 15,000 ft (4575 m) and southward into the Allegheny Trough, to more than 20,000 ft (6100 m). Some of the formations described below are absent in some areas, either through erosion or non-deposition. Major faulting does not affect the sedimentary sequence underlying the West St. Lawrence Lowland outside the Chatham Sag.

Extensive knowledge about the subsurface in southwestern Ontario has been obtained from wells that were drilled in exploration for oil and gas. The distribution of subsurface information is quite irregular in general, and almost non-existent in some areas. Outcrop sections, in quarries along the Niagara Escarpment and elsewhere, may also aid in the evaluation of some prospective disposal formations. The following analysis relies heavily on the work of McLean (1968).

Table IV presents a summary of the stratigraphy and lithology in the West St. Lawrence Lowland.

The Cambrian rocks overlying the Precambrian basement in southwestern Ontario are the *Mount Simon, Eau Claire,* and *Trempealeau Formations* of the Michigan Basin, and the *Potsdam, Theresa* and *Little Falls Formations* of the Allegheny Trough, respectively. Although it is not certain that direct correlation exists between the two sequences, they will be treated as equivalent for the purpose of this report. The Cambrian strata cover a limited area only. Their present limits are the result of erosion during the Lower Ordovician. The strata dip generally to the south in the Allegheny Trough, northeastward on the Findlay Arch, and westward into the Michigan Basin. The only notable faults affecting the Cambrian strata are found in the Chatham Sag area.

The thickness of the *Mount Simon* and *Potsdam Formations* ranges from 0 to slightly over 100 ft (0 - 30 m). They consist primarily of coarse to medium grained quartzose and calcareous sandstones. They are water-bearing over much of their extent and are used as a source of water supply in some areas where they occur at depths of less than 1000 feet (300 m).

The *Eau Claire* and *Theresa Formations* are the most widespread of the Cambrian formations in southwestern Ontario, and range in thickness up to 250 ft (76 m). In some areas they rest directly on the Precambrian. They are rather heterogeneous, and consist of shaly, coarse- to fine-grained quartzose sandstone, interbedded with finely crystalline dolomite. They tend to have lower porosity and permeability than the Potsdam and Mount Simon, as a result of carbonate cementation and the presence of an appreciable clay-size fraction.

The overlying *Trempealeau* and *Little Falls Formations* have a more limited areal distribution and their thickness exceeds 150 ft (46 m) only locally. They consist of finely crystalline dolomite, and contain a thin sandy member in the upper part of the formation. Porosity and permeability are generally poor.

Figure 5 presents an isopach map of the total Cambrian in southwestern Ontario, with the locations of oil fields producing from the Cambrian, and an indication of the areas of different disposal potential as suggested by McLean (1971). Few wells have been drilled into the Cambrian. Data on which to base an evaluation are therefore scanty, and the evaluation implied in Figure 5 may have to be changed considerably as more data become available.

In Lincoln County (area IA) the Cambrian has a thickness ranging from 25 to 100 ft (7.6 to 30.5 m), with good aquifer properties. The elevation of the top of the Cambrian ranges from 1500 to 1900 ft (457 - 580 m) below sea level; combined with surface elevations of 250 to 650 ft (76 - 198 m) above sea level, these would give depths of between 1750 to 2550 ft (534 - 778 m). Cover on the Cambrian in area IA reaches up to the Guelph Formation and includes the Upper Ordovician shales. In Lambton County (area IB) the Cambrian ranges in thickness from 25 to over 200 ft (7.6 - 61 m); the top of the Cambrian is found between 3500 and 4000 ft (1067 - 1220 m) below sea level, with ground elevations between 580 and 700 ft (177 - 213 m) above sea level, giving depths ranging from 4000 to 4600 ft (1220 - 1403 m). Cover on the Cambrian includes the shales of the Hamilton and Kettle Point Formations in area IB. Both areas appear favorable for waste disposal in the Cambrian. In area II, insufficient data exist for adequate appraisal; physical conditions, however, appear favorable. In areas IIIA and IIIB no water recoveries were recorded for the Cambrian, pointing to low porosity and permeability values. In the Niagara Peninsula the Eau Claire and Theresa Formations might offer some potential, but aquifer characteristics are poor. The restricted depth and thickness of the formation would also tend to rule out the use of the Cambrian in these areas. Areas designated IV are unfavorable on account of limited thickness, insufficient depth, presence of commercial hydrocarbon accumulations, etc.

Water quality in the Cambrian Formations ranges from 200,000 to 400,000 mg/l total dissolved solids. Useful minerals might be extractable from the more concentrated Cambrian brines. Porosity in the Cambrian strata ranges from 5 to 15 %, and values of up to 20 % have been found in clean sandstones, and up to 10 % in clean dolomites. Permeabilities range from less than 1 md to more than 250 md the average being around 50 to 60 md. Subsurface disposal of waste into Cambrian formations may affect hydrocarbon accumulations or commercial brines. Some

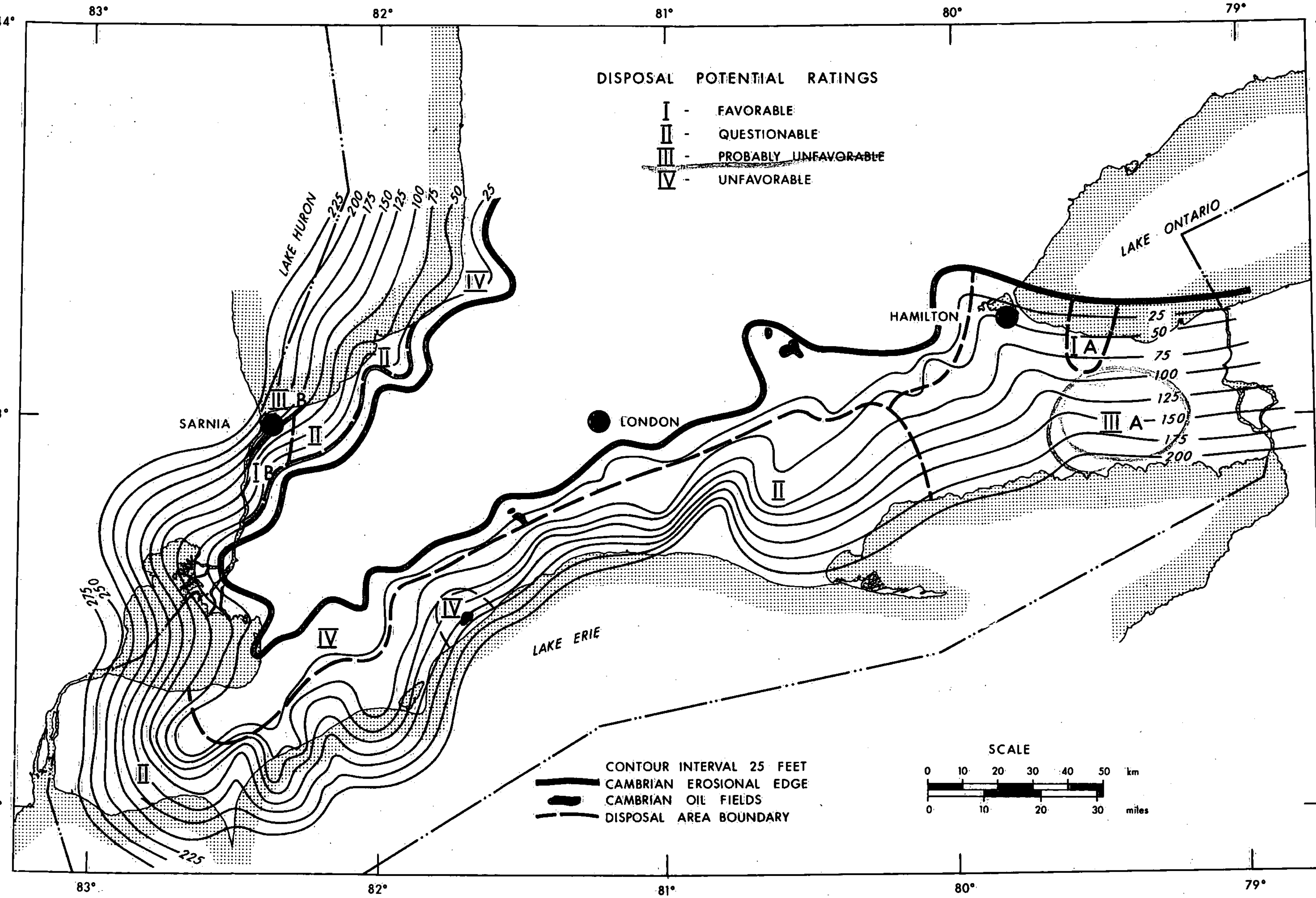


Figure 5. Isopach map of total Cambrian in southwestern Ontario, with indication of disposal potential (after McLean, 1971).

restrictions on its use will have to be imposed for this reason.

By 1971 two disposal wells had been drilled in the Cambrian in Ontario, one near Sarnia where the formation was tight, and one in Essex County. In Kent County, oil field brine is injected into Cambrian strata.

It is thought that the Cambrian may offer some better disposal potential, and that it may be more suitable than other Paleozoic strata in Ontario, because of adequate depth, adequate seals, relatively wide distribution, and limited proven potential for either hydrocarbon or fresh water production.

Ordovician formations are separated from the Cambrian strata by an unconformity resulting from erosion during the Lower Ordovician.

The Middle Ordovician *Black River Group* consisting of sandy and shaly dolomite and dolomitic shale (*Shadow Lake Fm.*), fine-grained limestones (*Gull River Fm.*), and finely crystalline to granular limestones (*Coboconk Fm.*), is present over much of southwestern Ontario. The rocks of the Black River Group crop out along the Precambrian Shield between Lake Simcoe and Kingston. Their thickness increases to over 200 ft (61 m) south and east of Toronto, and to more than 500 ft (152 m) in Lambton and Essex counties in the Lake St. Clair area.

The Middle Ordovician *Trenton Group,* made up of the argillaceous and bioclastic limestone of the *Kirkfield* and *Verulum Formations,* and fine-grained argillaceous limestones of the *Cobourg Formation,* has a distribution similar to that of the Trenton Group. It crops out over a wider area, south of the Black River outcrop. The group is about 500 ft (152 m) thick in the central portion of the area thinning to less than 300 ft (91 m) both to the northwest and southeast.

Generally the Middle Ordovician possesses poor porosity and permeability; few water recoveries have been recorded, and average yields to individual wells are less than 10 gpm (2.7 m^3/h).

Gas is being produced from Black River strata, from anticlinal structures that have been partly dolomitized, in Halton County just east of the Niagara Escarpment (Acton and Hornby Fields). Other similar structures, that may have adequate porosity for waste injection, are likely of limited areal extent.

To the west of the Niagara Escarpment evaluation is less reliable through lack of adequate subsurface information. Narrow synclinal structures may contain hydrocarbon accumulations, as in Essex County (Colchester Pool) and Kent County (Dover Pool). Other minor Ordovician oil pools, now depleted, were present in Prince Edward County (Picton Field), and on the Bruce Peninsula (Hepworth Field).

Upper Ordovician strata include bituminous shales (*Collingwood Fm.*), soft grey and bluish shales (*Blue Mountain Fm.*), shales with interbedded siltstones (*Meaford-Dundas Fm.*), and shales with dolomite interbeds (*Queenston Fm.*). The combined thickness of the first three formations ranges from about 300 ft (91 m) in the Lake St. Clair area to over 900 ft (275 m) east of Hamilton. The Queenston Formation increases in thickness from about 100 ft (30 m) in the Bruce Peninsula to near 1000 ft (300 m) in the extreme southern part of the Niagara Peninsula; it ranges in thickness between 160 and 300 ft (49 and 91 m) in much of Essex, Kent, and Lambton Counties. It crops out just east of the Niagara Peninsula.

Both porosity and permeability are generally poor in the Upper Ordovician. Average well yields are less than 5 gpm (1.35 m^3/h). The water in these formations is usually highly mineralized.

An unconformity separates the Silurian from the underlying Ordovician in southwestern Ontario. The Lower Silurian *Cataract Group* and the Middle Silurian *Clinton Group* occur throughout the area west of the Niagara Escarpement, where they outcrop. They consist of sandstone, dolomite, shales, and limestone. Their combined thickness varies from less than 100 ft (30 m) near the Bruce Peninsula (Grey County) to about 230 ft (70 m) near Lake Erie.

In the Niagara Peninsula region, and underlying the eastern part of Lake Erie, the fine-grained *Whirlpool* and *Grimsby* sands of the Clinton Group, and the *Thorold* sands of the Cataract Group occur as blanket sands containing widespread natural gas reservoirs. The porosities and permeabilities of these sands are erratic and since the pools are associated with permeability pinchouts, they are relatively ill-defined. Although some water recoveries have been recorded in these formations, the widespread distribution of gas and the proximity to the Niagara Escarpment tend to rule out the use of these reservoirs for waste disposal. Certain depleted gas reservoirs in these sands, that might be unsuitable for gas storage, may have possibilities for limited volumes of waste, but such a project would require a very thorough study. Many old unplugged wells exist in this area.

The overlying Middle Silurian *Lockport* and *Amabel Groups* and the *Guelph Formation* are the most prolific hydrocarbon sources in Ontario, and contain the better sources of potable water supply, mostly near the outcrop areas. They also appear to offer some possibilities for waste disposal in certain areas.

The formations consist largely of medium crystalline fossiliferous dolomite in the lower unit, crystalline argillaceous dolomite in the middle unit, and argillaceous, finely crystalline dolomite in the upper unit. The combined formations in the Brant-Oxford County area have a regional thickness ranging from 200 to 400 ft (61 - 122 m), decreasing northwestward into Huron County to about 100 ft. Southward from Oxford County the formations thicken to over 400 ft in central Lake Erie and to over 500 ft (152 m) in the Essex County and Kent County areas.

The Guelph Formation is characterized by areas of pinnacle, patch and barrier reef development. The patch reef area contains some of the more prolific Guelph gas reservoirs, the most important of these being located in Kent County. The pinnacle reef development within the structurally lower areas of the Guelph occurs primarily in Lambton County and provides a number of the important gas storage areas. The barrier reef area to the east has not shown any indications of hydrocarbon accumulations.

The physical character of the rock units of the Lockport, Amabel, and Guelph will, in many areas, make the prediction of waste movement difficult, and a careful study and test programme before disposal will be necessary in every single case. Where the transition zone to potable or otherwise useable waters is nearby, no waste injection should be permitted. Although fresh water areas are normally updip from areas that could be considered for brine or waste disposal, the combined effect of injection pressures and natural hydrodynamic gradients could cause the injected fluids to migrate updip.

Water analyses from potential disposal zones in the Guelph formation are sparse and have been obtained mainly from the upper and middle units. Values of over 300,000 mg/l of total dissolved solids are on record for the Lambton County area; records for other counties are practically non-existent. The Guelph Formation, where tested, generally has porosities in the order of 5 to 15 % and permeabilities in the 10 to 50 md range, with streaks exceeding 250 md; the pinnacle reef developments may have values much higher than these. Average water well yields are about 10 gpm (2.7 m^3/h), but yields of over 600 gpm (162 m^3/h) have been recorded.

The Upper Silurian *Salina Formation* is a complex of salt, anhydrite, dolomite, and limestone beds with shaly interbeds. The Salina is subdivided into a number of units as illustrated in Figure 6, and may provide adequate confining beds for the potential Guelph disposal areas. The salt areas are, for the most part, restricted to the less favorable Guelph areas, but the Salina A-1 and A-2 sequences in the potential Guelph disposal areas are often quite impervious and anhydritic. The lower Salina A-1 and A-2 sequences are potential hydrocarbon reservoirs, and are often associated with underlying Guelph production. Water recoveries in the A-1 and A-2 units are erratic in the Lambton County area; these members are generally unsuitable for waste disposal because of the proximity to hydrocarbon accumulations. Wells in the upper part of the Salina average 5 to 15 gpm (1.3 - 4.0 m^3/h). The water is commonly highly mineralized.

There are three areas of the Salina Formation in southwestern Ontario that can be considered for the mining of salt: the Sarnia-Goderich, Windsor and Chatham areas. At present there are two mines operating, one within the F unit at Windsor, and the other within the A-2, B, D, and F units in the Goderich area. In addition, there are six brining operations—three near Windsor, two at Sarnia and one at Goderich. The B salt unit in the Chatham area is thinner in comparison to the other areas and has not, as yet, been exploited. Two mines at Hagersville and Caledonia produce gypsum from the Salina in Haldimand County. The proximity to mining operations such as these or to areas with mining potential, must be given careful consideration when planning waste disposal in these beds, to assure that contamination of these resources does not occur, and that mining operations are not endangered. The use of brine cavities should be reserved for limited volumes of highly toxic wastes or semi-solid wastes that are difficult to treat on the surface, and for ones that would not otherwise react with, or further dissolve the salt. One such disposal operation takes place near Sarnia on a limited scale. Suitable areas for brine cavity operations may be found in the Lambton County area, and parts of Huron, Essex, and Kent Counties. The expense of developing such a system would be quite high, as the displaced brine must also be disposed of.

The waste disposal potential of formations overlying the Salina may have been affected adversely in areas where Salina salts have been removed by subsurface leaching, either naturally or artificially (Figure 6). Natural subsurface leaching, according to Sanford (1965), occurred at various time intervals; it started soon after deposition, initially along the inner margin of the carbonate fringe. The most extensive period of leaching in Kent and Essex counties began during late Bass Island time and continued into the Lower Devonian. In northern Kent County and the adjoining portions of Lambton County, large-scale leaching took place after the Upper Devonian, resulting in major collapse of overlying Devonian strata. Some concentric and elongated collapse structures occur above small reefs. Others are in no way related to reefs, and some of these may have resulted from leaching along fault planes. Artificial leaching, for salt production or the creation of caverns, may also lead to fracturing, brecciation, subsidence or collapse of overlying strata. A case in point is the February 19, 1954 collapse at Windsor, Ontario (Terzaghi, 1970). Both the disposal formation and its confining beds should be tested in detail when any further waste injection in post-Silurian strata is contemplated in the areas where the Salina is affected by subsurface salt leaching (either natural or artificial).

The *Bass Islands Formation* which overlies the shaly dolomite of the Salina "G" unit, consists of fine-grained dolomite, with shaly interbeds. It has a thickness of 150 ft (45 m) in the southern part of the basin. The formation does not produce hydrocarbons, but locally, in parts of Kent County, water shows have been recorded and possibilities for disposal may exist where the overlying Bois Blanc Formation provides an adequate seal. Where developed for water supply, well yields range from 5 to 15 gpm (1.3 - 4.0

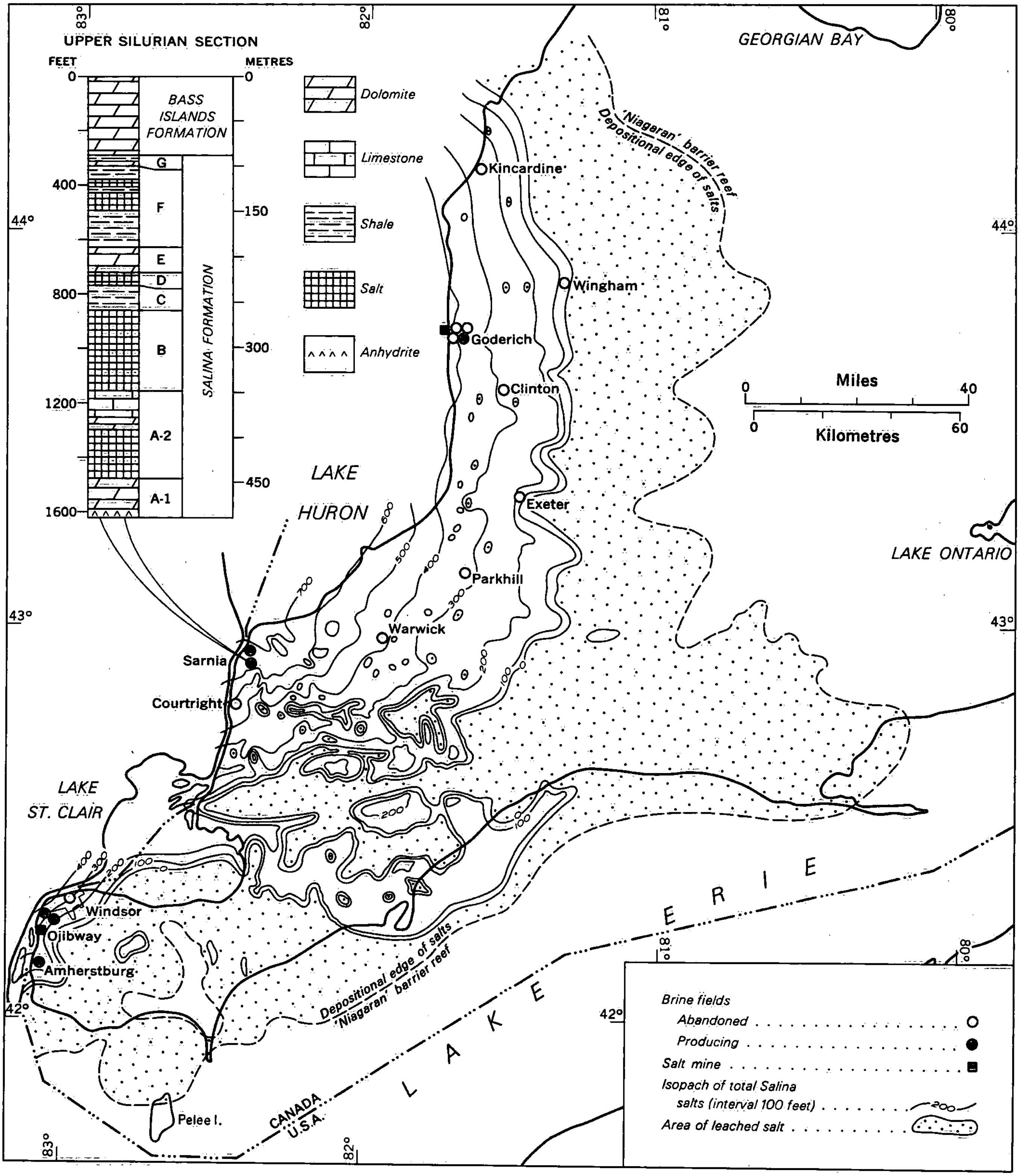


Figure 6. Stratigraphy and isopach map of the Salina salt beds (from Sanford, 1965).

m^3/h). The Bass Islands Formation is used for pulp liquor waste disposal in one well in Pennsylvania. Its use for disposal purposes in Ontario does not, however, appear very promising because of its relatively poor porosity and permeability on the one hand, and its potential for water supply on the other.

Devonian rocks overlie those of the Upper Silurian unconformably. The Lower Devonian *Oriskany Formation,* a quartzose sandstone, exists only as minor remnants in the Lake Erie region. The formation is used for disposal in one well in Pennsylvania. Its use in Ontario does not appear feasible because of its erratic and limited distribution.

The *Bois Blanc Formation* consists of finely cyrstalline cherty limestones and dolomites and varies in thickness from less than 50 ft (15 m) in the Niagara Peninsula and Lake Erie regions to over 150 ft (45 m) in Kent, Essex, and Lambton Counties. Locally in these Counties, 200 to 300 ft (61 - 92 m) of Bois Blanc occurs in northwest-southeast trending lows as a result of leaching of the underlying Salina salts. In the Lake Erie region, the base of the Bois Blanc is characterized by lenses of glauconitic, quartzose sandstones known as the *Springvale Member.* The Springvale attains a thickness of 30 ft (9.1 m) in the salt solution lows in the western part of the basin. The Bois Blanc has shown a number of water recoveries both from the porous Springvale member and from the limestone and dolomite sections. Individual well yields ranged from 10-30 gpm (2.7 - 8.1 m^3/h); the water is moderately mineralized. These occurrences are erratic and aquifer conditions associated with the formation are of insufficient areal extent for long-term waste disposal.

The Middle Devonian *Detroit River Group* overlies the Bois Blanc; it consists of the *Amherstburg Formation* and the *Lucas Formation.* These formations outcrop in Oxford County and in Essex County, which limits the use of the Detroit River for disposal purposes to Lambton and parts of Middlesex, Elgin and Kent Counties.

The Amherstburg consists of finely crystalline limestones and dolomites and granular dolomites. The lower portion of the Amherstburg in Essex County is a fine quartzose sandstone known as the *Sylvania Member,* which attains a thickness of 80 ft (24.4 m) in Ontario and is known to thicken in the Michigan Basin to over 300 ft (92 m). The Sylvania is water bearing throughout much of its areal extent in Michigan. Its proximity to outcrop in Ontario prohibits its use for waste disposal. The Amherstburg Formation is 200 ft (61 m) thick throughout Elgin, Kent, Essex, and Lambton Counties. It is erratic in water recoveries and is generally unsuitable for waste disposal purposes.

The Lucas Formation ranges in thickness from zero feet in the Lake Erie region to over 300 ft (92 m) in the northern part of Lambton County and the southern part of Huron County. Its thickness increases in the Michigan Basin where, in addition to the dolomites, interbeds of salt, gypsum, and anhydrite occur. The Lucas Formation has shown widespread water recoveries; individual well yields range from 10 to 30 gpm (2.7 - 8.1 m^3/h).

Few core and water analyses are available for the Lucas Formation. Core data and gamma-ray-density logs indicate that porosities range from 8 to 20% in the Lambton County area, and permeabilities from 10 to over 50 md. Lost-circulation zones, used for waste injection in a number of cases, exhibit much higher permeabilities; considerably lower values exist in other areas. Formation waters in the Detroit River Group contain over 100,000 mg/l of dissolved solids in the Lambton County area, up to 40,000 mg/l in Elgin County, and 5,000 mg/l or less in Huron County. Economically extractable minerals do not exist in the brine.

Proximity to outcrops and the presence of freshwater resources restrict the potentially useable disposal area in the Detroit River Group. The Lucas Formation, although apparently not the most desirable for waste injection, on account of shallow depth and the presence of large numbers of uncharted, unplugged or inadequately plugged old drill holes, was the only formation used before 1972 for disposal of liquid industrial waste in Ontario. Most of the existing 18 waste-injection wells are in close proximity to each other, but injection rates for a given pressure are quite variable in the Lucas Formation. On the average, a 400 psi (28.1 kg/cm^2) pressure is required to inject 100 gpm (27 m^3/h), but occasionally a much lower rate is developed using the same pressure. Where injection is into a "lost-circulation" zone, rates of 50 gpm (13.5 m^3/h) or more can sometimes be developed without the application of pressure at the well head (McLean, 1968).

Widespread use of the Lucas Formation in the Sarnia area (Lambton County) has led to a number of problems related to pressure build-up (oil, gas, or brine "blowouts" from old abandoned wells) and rapid waste migration in lost-circulation zones (McLean, 1971).

The use of the Lucas Formation for disposal of liquid wastes from chemical plants and refineries in the Sarnia area is being phased out at present. However, increasingly large volumes of waste brine result from petroleum production and from salt solution for the creation of storage caverns for natural gas. The concentration of these brines is such that their use is not economically attractive to the salt and chemical industry in Ontario, and the brines are therefore injected into the subsurface, mainly in the Lucas Formation. Meanwhile, the salt industry maintains its own brining operations, and some salt is even imported from outside the province. Unless the economic considerations change in importance, large volumes of waste brine will likely continue to be injected into the subsurface in southwestern Ontario.

The overlying Middle Devonian *Dundee Formation* consists mainly of fine-grained limestones, and has an areal extent similar to the Detroit River Group, outcropping in

Essex and Oxford Counties. The formation is about 400 ft (122 m) thick in Michigan, thins to between 60 and 120 ft (18.3 – 36.6 m) in Lambton and Kent Counties, and thickens again eastward to over 150 ft (46 m) in the Lake Erie region. The Dundee is an oil-producing formation, notably in the Petrolia, Oil Springs, Rodney and Glencoe fields. These pools occur on anticlines of low amplitude which have resulted from leaching of the underlying Salina Salts during early middle Devonian times. Although the Dundee has given some water recoveries, and individual wells may yield from 1 to 10 gpm (0.27 – 2.7 m^3/h), it does not appear to be a widespread aquifer. In addition to its petroliferous nature in certain areas, its shallow depth would seriously restrict waste volumes and allowable injection pressures. Both the Dundee Formation and the Detroit River Group are, however, used for waste disposal purposes in Michigan, where the strata are deeper and possess better aquifer properties.

The Upper Middle Devonian *Hamilton Group* overlies the Dundee Formation. It is composed mainly of interbedded calcareous shales and shaly limestones. This Group is relatively thin in Ontario, ranging from 100 ft (30 m) in the southern part of the basin to 300 ft (91 m) in the north; it thickens to about 800 ft (245 m) in the central part of the basin in Michigan. The Hamilton Group and the overlying Upper Devonian *Kettle Point Formation,* which consists of bituminous shales with calcareous concentrations up to 3 ft (0.9 m) in diameter, cover large portions of Lambton County, and parts of Kent and Elgin Counties, and provide thick, impermeable strata which could prevent the vertical migration of wastes into the overlying potable water horizons. The Kettle Point Formation is about 200 ft (61 m) thick in Lambton County and thickens gradually southward into Lake Erie, except for a thinning in the region of the Chatham Sag. Although fractured shales are suggested as suitable rocks for limited volumes of radioactive wastes, the proximity to surface of these formations would prohibit their use for such a purpose in Ontario.

The *Bedford, Berea and Sunburn* members of the Upper Devonian *Port Lambton Formation* are present only in Moore Township, Lambton County, and consist of approximately 100 ft (30 m) of grey shales and dolomitic sandstones. Potential for radioactive waste disposal in Bedford shale and industrial waste disposal in Berea Sandstone does not exist in Ontario, because of limited areal extent and shallow depth.

The Lucas Formation appears to be the only Devonian formation suitable for injection of liquid waste, but only in Lambton and parts of Kent and Elgin Counties. The overlying impermeable strata may be adequate to protect groundwater resources but, with a depth of less than 1000 ft (300 m), the allowable injection pressures and volumes should be carefully controlled, and waste movement carefully monitored.

Detailed studies for any particular waste disposal project planned in southwestern Ontario, whether in the Cambrian or younger formations, should be concerned with the following points: proximity to outcrops, to potable or otherwise useable water, and to known or potential hydrocarbon accumulations; proximity to faults; presence of unplugged drillholes or old and possibly leaky wells; adequacy of depth below surface; adequacy of disposal formation and confining strata; and position in local and regional flow systems. Existing subsurface waste disposal operations in southwestern Ontario, dating back to 1958, could provide information on feasibility, reliability, and safety of this method. Unfortunately, at least part of the data from the early period are no longer available (McLean, 1968, p. 55).

HUDSON BAY LOWLAND

The Hudson Bay Lowland lies along the southwest portion of Hudson Bay (area 5 on Figures 1 and 4). It extends from North Knife River, 25 miles (40 km) northwest of Churchill, Manitoba, to a short distance south of the southern end of James Bay, a distance of about 825 miles (1327 km). The Lowland varies in width from less than 100 miles to almost 260 miles (161 – 418 km). It covers an area of more than 130,000 sq. miles (377,000 km^2). Elevations range from sea level along the shores of Hudson Bay and James Bay, to 600 ft (183 m) in the Sutton Ridge. The northwestern portion of the Lowland lies in Manitoba, the extreme southeastern corner in Quebec, and the remainder in Ontario.

The Hudson Bay Lowland forms part of the 365,000 square miles (945,000 km^2) of the Hudson Platform which comprises the remnants of two sedimentary basins. A major portion of the Hudson Bay Basin is covered by the water of Hudson Bay; the smaller Moose River Basin borders on and extends beneath James Bay. The two basins are separated by a northeast trending high in the Precambrian basement, known as the Cape Henrietta Maria Arch. Archean and Proterozoic rocks of the Cape Henrietta Maria Arch are exposed in several large inliers near Sutton Lake. On the south and west the Lowland is bordered by the Precambrian rocks of the Fraserdale and Severn Arches, respectively; on the North by Bell Arch.

The sedimentary strata of the Hudson Platform are gently dipping to almost flat lying. In Hudson Bay Basin shallow-marine deposits of Ordovician, Silurian and Devonian age reach a thickness of about 3000 ft (915 m) on the mainland. A sequence of as much as 6000 ft (1830 m) may be present in the central part of the basin beneath Hudson Bay. In the northern part of the basin, on Southampton, Coats and Mansel Islands, only Ordovician and Silurian strata are exposed. In the Moose River Basin, non-marine sediments of Lower Cretaceous age are present in addition to the Paleozoic sequence. The total sedimentary sequence in this basin reaches a thickness of about 2500 ft (762 m).

Similarities in facies and fauna indicate that the

Hudson Platform, during various intervals of the Paleozoic, must have been interconnected with the Williston, Michigan and Appalachian Basins.

The stratigraphy and lithology of the Hudson Platform are presented in summary form in Table V. The following descriptions are based largely on the work of Norris and Sanford (1969).

Rocks of early Late Ordovician age form the *Bad Cache Rapids Group* in the Hudson Bay Basin; they may also be present in the Moose River Basin. The group can be divided into two distinct formations. The basal *Portage Chute Formation* consists of arkose, orthoquartzitic sandstone, and argillaceous or calcareous sandstone and shale, from 4 to 31 ft (1.2 – 9.5 m) thick; and 71 ft (21.6 m) of microcrystalline, dolomitic, locally bioclastic and nodular limestone. The overlying *Surprise Creek Formation* is composed of 64 ft (19.5 m) of finely crystalline, cherty, dolomitic limestone. A similar lithologic assemblage overlies the Precambrian on Southampton Island, indicating a possibly wide distribution of the Bad Cache Rapids Group. It is lithologically similar to, and correlated with the Red River Formation of the Lake Winnipeg area in southern Manitoba.

The *Churchill River Group,* of Late Ordovician age overlies the Bad Cache Rapids Group disconformably in the Hudson Bay Basin. Churchill River strata outcrop in the Western Hudson Bay Lowland; they are in fault contact with the Precambrian along the southwestern margin of the Moose River Basin, rising to the surface immediately south of James Bay, as well as on Southampton Island. In the southern part of the Hudson Bay Basin the Churchill River Group can be divided into the *Caution Creek Formation,* consisting of bioclastic, cryptocrystalline dolomitic limestone, with a thickness of 42 ft (12.8 m) and the *Chasm Creek Formation* of massive to rubble-bedded, microcrystalline limestone, about 190 ft (58 m) thick. A lithologically and faunally similar succession is present on Southampton Island, with the addition of oil-shale interbeds in the uppermost finely crystalline limestones.

In the central part of Moose River Basin a possible equivalent to the Churchill River Group consists of 300 ft (91 m) of microsucrosic dolomite with interbeds of anhydrite and gypsum. The dolomite becomes increasingly arenaceous towards the southern margin of the basin; eventually it grades into 70 ft (21.3 m) of arkose, granite-pebble conglomerate, some shale, dolomitic sandstone and sandy dolomite along the border of the Canadian Shield. The Churchill River Group is correlated with the Stony Mountain Formation of southern Manitoba, and is coeval with the Queenston-Kagawong-Meaford Formations of southern Ontario.

The Silurian *Severn River Formation* is a relatively distinct uniform rock unit throughout the Hudson Bay and Moose River Basins, whereas the succeeding *Ekwan River* and *Attawapiskat Formations* are closely related lithologically, forming separate map units only along the margins of the basins. The *Severn River Formation* disconformably overlies the Upper Ordovician Churchill River Group. In the vicinity of Churchill, Manitoba, and on Cape Henrietta Maria Arch it overlaps the Ordovician to rest directly on the Precambrian. The formation rises to the surface along the western margin of the Hudson Bay Lowland and it forms the youngest Paleozoic rocks over the Cape Henrietta Maria Arch. It is in fault contact with the Precambrian on the southern margin of the Moose River Basin; and it outcrops on both Coats and Southampton Islands. The maximum thickness of the formation in the Moose River Basin is between 150 and 200 ft (45.7 – 61 m), and it reaches 700 ft (213 m) along the southern margin of the Hudson Bay Basin. The Severn River Formation is composed of finely crystalline to aphanitic limestone and dolomite, with coarse, bioclastic, and fragmental limestone, and flat-pebble conglomerate locally present. Generally thin bedded, the formation may be massive, swelling into thick biostromal lenses. The Severn River Formation correlates approximately with the upper part of the Cataract Group of southwestern Ontario, and with the lower part of the Interlake Group of southern Manitoba.

The *Ekwan River Formation* overlies the Severn probably disconformably and, where combined with the succeeding and, in part, laterally equivalent Attawapiskat fringing reef facies, probably reaches thicknesses of 500 to 700 ft (152 – 213 m) along the margins of the Hudson Bay and Moose River Basins. Because of the rapid change to inter-reef facies, the Ekwan River-Attawapiskat interval thins to 200 ft (61 m) or less in central Moose River Basin, and perhaps to a comparable thickness in Hudson Bay Basin. The Ekwan River Formation is composed of fine-to-medium crystalline, locally bituminous, limestone and dolomite. It is thin to thick bedded and locally biostromal. The formation contains varying amounts of bioclastic, mainly crinoidal detritus and fragmental limestone, and in southern Moose River Basin, particularly in Quebec, sandstone interbeds and lenses. The Ekwan River Formation is tentatively correlated with the Fossil Hill and Amabel Formations of southwestern Ontario, and with part of the Interlake Group of southern Manitoba.

The *Attawapiskat Formation* succeeds the Ekwan River conformably, reaches its maximum development along the Cape Henrietta Maria Arch, and changes basinwards to inter-reefal carbonate rocks. The Attawapiskat is a reef complex composed of small bioherms that consist of thick structureless masses of vuggy, cavernous limestone. Flanking the bioherms are thick beds of carbonate and bioclastic detritus that dip at steep angles away from the reef cores. These beds become finer and more thinly bedded where they grade into the inter-reef facies. Succeeding the biohermal facies and forming a dominant part of the Attawapiskat Formation are thick biostromal beds of massive, vuggy limestones and dolomites. At numerous localities these strata form domes, apparently draped over buried bioherm reefs lower in the

Attawapiskat. The bioherms and associated carbonate rocks of the Attawapiskat Formation are similar in lithological character to the barrier reef facies of the late Middle Silurian Guelph Formation of southwestern Ontario, and are tentatively correlated with that formation. The Attawapiskat is also probably equivalent to the Chemahawin Member of the Cedar Lake Formation (Upper Interlake Group) of southern Manitoba.

The Upper Silurian/Lower Devonian *Kenogami River Formation* conformably succeeds the Attawapiskat Formation, or the partly equivalent Ekwan River. The formation has a known thickness of 835 ft (255 m) in eastern Moose River Basin, and its thickness in the Hudson Bay Basin is presumably comparable. It is divisible into three members. The lower member is a uniform sequence, 74 to 174 ft (22.6 – 53.1 m) thick, of thin to thick-bedded, finely crystalline dolomite, containing thin interbeds of gypsum or anhydrite. The middle member consists of gypsiferous siltstone, mudstone, sandstone, minor argillaceous dolomite, and honey-comb limestone, 475 to 552 ft (145 – 168 m) thick. The upper member is a uniform succession of oölitic dolomite, and dolomite breccia, 37 to 109 ft (11.3 – 32.2 m) thick. The Kenogami River Formation is considered coeval with the lithologically similar Salina and Bass Islands Formations of southwestern Ontario, and the Ashern Formation of southern Manitoba.

The early Devonian is represented in the Hudson Platform by two formations: the non-marine *Sextant Formation,* restricted to the southern part of the Moose River Basin, and its marine equivalent the *Stooping River Formation.* Where the Sextant Formation overlies the Archean rocks of the basement it consists of up to 175 ft (53.4 m) of quartz-feldspar conglomerate, coarse feldspathic sandstone and, locally carbonaceous, siltstone and shale. Basinward the Sextant Formation grades into thin-bedded, nodular, finely crystalline cherty limestone and dolomite of the Stooping River Formation, which is about 300 ft (91 m) thick. In the central Moose River Basin and in the Hudson Bay Basin, the Stooping River Formation succeeds the upper member of the Kenogami River Formation disconformably. In the southern part of the Moose River Basin the Stooping River overlaps the Sextant Formation transgressively, to rest directly on the Precambrian. The marine fauna in the Stooping River Formation indicates correlation with the Bois Blanc Formation of southwestern Ontario. The Sextant Formation may be the equivalent of the Springvale Sandstone in Ontario.

The Middle Devonian *Kwataboahegan, Moose River, Murray Island,* and *Williams Island Formations* are composed predominantly of marine limestones, with some shale and evaporites; the combined thickness of the Middle Devonian sequence is about 700 ft (213 m). The sequence is well developed in the Moose River Basin. In the Hudson Bay Basin only the Kwataboahegan has been identified on the mainland; a more complete sequence may be present beneath Hudson Bay.

The *Kwataboahegan Formation* overlies the Stooping River disconformably. It consists of bituminous coral limestone, commonly thin to medium bedded, but becoming thick bedded to massive, and locally biostromal, along the southern margin of the Moose River Basin. The thickness of the formation is slightly more than 400 ft (122 m). It has been correlated with the Amherstburg Formation of the Detroit River Group in southwestern Ontario.

Carbonate and evaporite deposits of the *Moose River Formation* succeed the Kwataboahegan with an abrupt but conformable contact. In the central part of Moose River Basin, aphanitic to microsucrosic limestones and dolomites, containing thick beds of gypsum of high purity, give the Moose River a total thickness of almost 110 ft (33.5 m). Gypsum is only sporadically present along the southern margin of the basin; it has been removed, presumably by leaching, leaving the overlying limestones and dolomites contorted and brecciated, with individual fragments of up to several feet in diameter. The Moose River Formation has been correlated with the Lucas Formation, Detroit River Group, in southwestern Ontario.

The *Murray Island Formation* overlies the Moose River Formation disconformably. It consists of thick-bedded, crinoidal limestone which grades upward into thin-bedded, finely crystalline to aphanitic limestone, with a total thickness of about 20 ft (6.1 m). The formation shows a closely-spaced fracture pattern that may have formed as a result of subsidence caused by leaching (and/or compaction) of the underlying Moose River evaporites. The fauna in the Murray Island Formation suggests correlation with the Elm Point in southern Manitoba, and with the lithologically similar Dundee Formation in southwestern Ontario.

The *Williams Island Formation* succeeds the Murray Island Formation with a possibly disconformable contact. The lower strata of the Williams Island are blue-grey to red shales, locally with interbeds of gypsum and coarse crinoidal limestone. They grade upward into finely crystalline to granular, high-calcium limestone with traces of gypsum and some limestone breccia. The total thickness of the Williams Island Formation ranges between 150 to 200 ft (45.7 – 61 m). Its fauna indicates correlation with the Hamilton Formation of southwestern Ontario.

The Upper Devonian *Long Rapids Formation,* resting with an abrupt, and possibly disconformable, contact upon the Williams Island Formation, represents the youngest known Paleozoic of the Hudson Platform. The formation consists of 285 ft (87 m) of sparsely fossiliferous, black, carbonaceous, fissile shales, with interbeds of soft green shale and hard grey-green dolomite. It has been tentatively correlated with the lithologically similar Kettle Point Formation of southwestern Ontario.

Rocks of the Sextant, Stooping River and Kwataboahegan Formations along the Abitibi River have been intruded by lamprophyre and kimberlite dikes and sills.

Sediments of Mesozoic age are present only in the Moose River Basin. The Lower Cretaceous *Mattagami Formation* overlies the bevelled edges of various formations ranging in age from Upper Silurian to Upper Devonian. Locally it rests on the Precambrian. The lower part of the Mattagami Formation consists of fire clays and micaceous sands with fragments of carbonized plant stems, and thick seams of lignite. These are succeeded by a sequence of plastic clay, white sand, and clay. The combined thickness is about 170 ft (52 m). About 10 million tons of lignite at or near the surface have been delineated by drilling in two areas; much larger reserves occur beneath a greater thickness of overburden.

No more than 25 exploratory holes had been drilled in the Hudson Bay and Moose River Basins to the end of 1966. Consequently the hydrocarbon potential of the sedimentary sequence in these two basins has not been fully tested. However, the Ordovician, Silurian, and Devonian systems in these basins contain potential reservoir rocks that are lithologically similar to their counterparts in southwestern Ontario.

Upper Cambrian and Middle Ordovician strata that are commercially productive in southwestern Ontario and Michigan are absent in the Hudson Bay and Moose River Basins. Dolomitized fracture systems in the somewhat younger carbonates of the Bad Cache Rapids and Churchill River Groups, possibly related to the fault system in the Moose River Basin, may hold potential similar to that of the Black River and Trenton Groups in southwestern Ontario.

The reefs of the Silurian Attawapiskat Formation offer possibilities in the Moose River Basin and the offshore portion of the Hudson Bay Basin, similar to the gas producing reefs in the Silurian Lockport and Amabel Groups and the Guelph Formation in Ontario.

The bulk of oil production in Ontario (and Michigan) is obtained from Devonian reservoirs in the Lucas and Dundee Formations, which are similar in lithological character to their counterparts, the Moose River and Murray Island Formations, in the Moose River Basin. A number of structures occurring near the margins of the Moose River Basin presumably originated as a result of subsurface leaching of evaporites in the Moose River Formation.

As far as waste-disposal potential is concerned, it appears that this is restricted, in the mainland portion of the Hudson Bay Basin, to the area adjacent to Hudson Bay between the Severn and Nelson rivers where the total sediment thickness reaches more than 1000 ft (300 m), up to 2600 ft (793 m). The Portage Chute Sandstone of the Bad Cache Rapids Group, and the Attawapiskat Formation may be suitable for waste disposal in this area. Sediment thickness also exceeds 1000 ft (300 m), reaching more than 2500 ft (763 m), in the central portion of the Moose River Basin. Both the Portage Chute equivalent and the Attawapiskat Formation may be suitable for waste disposal in parts of the Moose River Basin. It may also be possible to make use of the deeper portions of the Sextant Formation near the southern margin of Moose River Basin. Careful study of spacial relationships and of hydrodynamic patterns would be required in this area. The presence of widespread perennially frozen ground over a large portion of the Lowland should be taken into account in any such feasibility studies.

THE INTERIOR PLAINS

The Interior Plains Region (area 6 on Figure 1, and 7) covers an area of approximately 775,000 square miles (2,000,000 km^2), and comprises southwestern Manitoba, southern Saskatchewan, most of Alberta, the northeast corner of British Columbia, and the western portion of the District of Mackenzie in the Northwest Territories. The southern part of the Interior Plains Region is covered by a relatively thick blanket of Mesozoic and Tertiary clastic rocks that overlie a Paleozoic sequence of carbonate rocks and evaporites, with minor clastics. The sediments rest on the Precambrian crystalline basement, the structure of which is presented in Figure 7. The geology of this part of the region is relatively well known as a result of extensive exploration for petroleum, natural gas, potash and coal. In the northern part of the region few drill holes have penetrated the complete sedimentary sequence. Devonian and older carbonates, evaporites and clastic rocks rest on crystalline and partly sedimentary Precambrian strata and are covered by a thin veneer of Lower Cretaceous sediments. A more complete stratigraphic sequence is present only near the Cordilleran Geosyncline and the Arctic Continental Shelf. Table VI presents a summary of stratigraphy and lithology for the Interior Plains Region. For further detail reference should be made to Douglas (1970) and to McCrossan and Glaister (1966).

The oldest sediments resting on the Precambrian basement belong to the Middle Cambrian. They are orthoquartzites of the *Old Fort Formation* and dolomites of the *Mazenod Formation* in the Horn River – Great Slave Lake area. In central and southern Alberta they comprise an unnamed 200 to 800 ft (61 – 244 m) thick sandstone sequence; up to 300 ft (92 m) of limestone and shale of the *Cathedral Formation*; 100 ft (30 m) of shale of the *Stephen Formation*; 100 to 300 ft (30 – 92 m) of dolomite and shale or limestone of the *Pika Formation*; and up to 200 ft (61 m) of shale belonging to the *Arctomys Formation*. In east-central Alberta and the western part of Saskatchewan the sandstones, siltstones, shales and dolomite of the *Deadwood Formation* range in age from upper Middle Cambrian to Lower Ordovician. The Deadwood Formation reaches a maximum thickness of 1100 ft (335 m), of which 500 to 700 ft (152 –

213 m) belong to the Upper Cambrian. It consists of glauconitic, quartzose sandstones and fine conglomerate, grading upward and westward into an off-shore facies of fissile shale and thin-bedded siltstone and fine sandstone. Nobs on the underlying Precambrian surface cause local thinning and irregular isopachs in the Deadwood Formation.

Lower Ordovician, where present, overlies the Cambrian conformably. Upper Ordovician overlies all older systems unconformably, and is itself succeeded conformably by Silurian strata. In the Northern Interior Plains the *Ronning Group* comprises about 300 ft (92 m) of dolomite, partly silty and anhydritic; 635 to 1500 ft (193 – 457 m) of porous dolomite with chert; and as much as 1400 ft (427 m) of finely crystalline dolomite. On the northern flank of the Williston Basin, in southeastern Alberta, southern Saskatchewan, and southwestern Manitoba, the Lower Ordovician is represented by the upper part of the Deadwood Formation. The Middle Ordovician is missing, and the Upper Ordovician and Silurian form a conformable sequence starting with the *Winnipeg Formation* which may be up to 200 ft (61 m) thick. Basal, fine to medium-grained, porous, quartzose sandstone with calcareous or ferruginous cement is overlain by non-calcareous, pyritic shales, siltstone and sandstone. Locally, cementation appears to be absent and the sandstone of the Winnipeg Formation therefore may present well-completion problems in some areas. Limited erosion of Winnipeg strata may have taken place before deposition of the overlying *Red River Formation*. Up to 400 ft (122 m) thick, the Red River comprises a basal unit of 100 to 300 ft (30 – 92 m) of dolomitic limestone and locally cherty dolomite, known as the *Yeoman Member*, and an upper unit of dolomitic limestone, dolomite and anhydrite, the *Herald Member*. Shaly limestones and shales of the *Stoughton Member* of the *Stony Mountain Formation* (40 – 90 ft or 12.2 – 27.5 m) overlie the Red River with a sharp, probably disconformable, contact. They grade into the dolomitic limestone – dolomite – anhydrite repetition of the *Gunton Member* (55 ft or 16.8 m). Silty dolomite forms the top of the Gunton. The overlying *Stonewall Formation* consists of 30 to 100 ft (9.2 – 30 m) of rythmic carbonate – evaporite deposits, separated by basin-wide beds of argillaceous dolomite and shale that contain lenses of coarse, rounded quartz sand, and fragments of dolomite and shale. The upper part of the Stonewall Formation is probably of Lower Silurian age.

The Silurian *Interlake Group* consists of up to 500 ft (152 m) of dolomitized limestone, stromatolitic-oölitic dolomite, porous-vuggy dolomite and biostromal dolomite. The lower Interlake contains some shaly to silty anhydritic layers with salt-crystal casts; the middle Interlake contains a few dolomitic limestone and cross-bedded sandstone layers; dolomitic mudstones occur in the upper part of the sequence. In southern Manitoba the Interlake has been divided into the *Fisher Branch, Moose Lake, Atikameg, East Arm* and *Cedar Lake Formations*. The *Chemahawin Member* of the Cedar Lake Formation is probably equivalent to the reef bearing Attawapiskat Formation in the Hudson Bay Lowland.

Middle Devonian rocks rest with angular unconformity on the Precambrian in northeastern British Columbia, District of Mackenzie, and northern and northeastern Alberta. A disconformity separates them from Middle and Upper Cambrian in central and southern Alberta, and from the Upper Silurian in southern Saskatchewan and Manitoba. *Arnica* dolomites, up to 300 ft (92 m) thick in southwestern District of Mackenzie and northeastern British Columbia, are finely crystalline and locally brecciated. They grade eastward into the *Cold Lake* salt and associated red beds and dolomite, and northward into a sequence of 1200 ft (366 m) of anhydrite, salt and dolomite. These are overlain in northern Alberta by argillaceous, anhydritic dolomite, anhydrite and shales of the lower *Chinchaga*. The upper part of the latter contains waxy, pyritic, non-calcareous shales.

In the Elk Point Basin basal sandstones and red beds occur on both sides of the Peace River Arch; evaporites of the *Lotsberg Formation* are found in central Alberta. Up to 500 ft (152 m) of clastics, and up to 400 ft (122 m) of salt may be present. The Lotsberg is succeeded by red claystone and fine-grained limestones of the *Ernestina Lake Formation*, which is in turn overlain by the massive anhydrite, claystone and salt of the *Cold Lake Formation*. Limestone, anhydrite, and dolomite of the upper *Chinchaga Formation* are equivalent to argillaceous dolomites of the *Contact Rapids Formation* farther southeast. These in turn appear to be equivalent to the lower part of the *Methy Formation* in eastern Alberta, and to the 50 ft (15.3 m) of varicolored siltstone, shale and argillaceous carbonate of the *Ashern Formation* in Saskatchewan and Manitoba.

This sequence is overlain in the northwestern part of the basin by the *Keg River Formation*, 100 to 170 ft (30 – 51.8 m) of argillaceous dolomite and limestone, and bituminous shale, followed by the laterally contiguous shale, carbonate and evaporite facies of the *Horn River Formation*, the *Pine Point* and *Sulphur Point Formations*, and the *Muskeg Formation* respectively. The *Horn River* consists of 100 to 200 ft (30 – 92 m) of bituminous shales, interbedded with fine-grained limestone and calcareous shales *(Evie Member)*; about 550 ft (168 m) of calcareous shales *(Otter Park Member)*; and 20 to 150 ft (6.1 to 45.7 m) of bituminous and siliceous shales *(Muskwa Member)*. The latter reaches into the Upper Devonian. The *Pine Point* and *Sulphur Point Formations* consist of carbonate-bank and island-reef limestone, locally completely dolomitized and vuggy. They form the boundary between the shale and carbonate facies. The carbonate facies of the Upper Keg River is represented by up to 800 ft (244 m) of organic reef, reef detritus, and back-reef to lagoonal calcarenites and calcisiltites locally altered to dolomite, of the *Rainbow Member*. Eastward, in Saskatchewan and Manitoba, the Keg River is known as the *Winnipegosis Formation*, which consists of a lower unit of argillaceous dolomite (30 ft or 9.2 m), and an upper unit of crypto to finely crystalline dolomite. The formation contains stromatoporoid, bryozoan and coral reefs. Total thickness ranges from 50 to at least 345 ft (15.2 – 105 m).

Between the high areas represented by the Keg River and Winnipegosis reefs, salt was deposited throughout the Elk Point Basin. In the northwestern part of the basin this formed the *Black Creek* salt beds at the base of the *Muskeg Formation*; to the southeast it formed the *Prairie Evaporite* (250 – 600 ft or 76 – 183 m in Saskatchewan and up to 1000 ft or 300 m in northeastern Alberta). Sylvite and carnallite occur in the upper 200 ft (61 m) of the Prairie Evaporite in Saskatchewan south of Saskatoon. Along the eroded northeastern margin the salt beds were removed by leaching. Extensive channeling, brecciation, slumping and subsidence were caused by subsurface solution of halite from the Black Creek and Prairie Evaporite Formations (de Mille *et al*, 1964; Holter, 1969; Hriskevich, 1970).

The Pine Point, Muskeg and Prairie Evaporite Formations are overlain by a thin shale in the northwest, grading to red claystone to the southeast (*Second Red Beds* of the *Dawson Bay Formation*). These are followed by 25 to 300 ft (7.6 – 92 m) of *Sulphur Point* limestone in the northwest, known as the *Presqu'ile Formation* where it is altered to coarsely crystalline dolomite, and grading southward into rapidly thinning limestone and anhydrite. In the Williston Basin the *Dawson Bay Formation* grades from 30 ft (9.2 m) of Red Beds into shaly limestone and dolomite, followed by fine- to coarse-grained limestone which contains stromatoporoids and corals, partly altered to dolomite with halite-filled pores. In Saskatchewan the so-called *First Red Beds* of the Dawson Bay are coeval with the shale of the *Watt Mountain Formation* that overlies the Sulphur Point Formation. Carbonates of the *Slave Point Formation*, ranging in thickness from 0 to 500 ft (0 – 152 m) northwest of the Peace River Arch, and evaporitic dolomite and anhydrite of the *Fort Vermillion Member* overlie the Watt Mountain shale.

In the northwestern part of the Interior Plains the Upper Devonian starts with the *Fort Simpson Formation*, 2000 to 2500 ft (610 – 762 m) of shales, with siltstone and silty carbonate layers. Its equivalent in the Great Slave Lake area is the *Hay River Formation*, 1200 ft (366 m) thick, overlain by 500 ft (152 m) of stromatoporoid and coral limestone bioherms and associated carbonates of the *Twin Falls Formation*. The Twin Falls grades southward into the *Grosmont* dolomite and the upper part of the *Leduc Formation*. Up to 450 ft (137 m) of silty limestone, calcareous siltstone and shale of the *Tathlina Formation* overlie the Twin Falls. The overlying limestones and shales (up to 500 ft or 152 m) of the *Redknife Formation* grade northward into the upper part of the Fort Simpson Formation. The basal 500 ft (152 m) of the Redknife are formed by bioclastic to reefoid limestone of the *Jean Marie Member*. Reefs, calcarenite and cryptocrystalline limestone of the *Kakisa Formation* overlie the Redknife. An erosional contact separates the former from the overlying *Trout River Formation*, which consists of almost up to 200 ft (61 m) of sandstones, siltstones and shales that thin rapidly eastwards. Limestone of the *Tetcho Formation* (200 ft or 61 m) and shales and limestones of the *Kotcho Formation* (700 ft or 213 m) complete the Devonian in this part of the region.

The *Beaverhill Lake Formation* in northeastern Alberta, and the *Waterways Formation* of east-central Alberta, are 500 to 700 ft (152 – 213 m) thick. They comprise a sequence of alternating limestones and shales: calcareous shales of the *Firebag Member*; medium-grained limestones of the *Calumet Member*; shales of the *Christina Member* grading into the limestone, anhydrite and shale complex of the *Moberley Member*, and interbedded shale and fine-grained limestone of the *Mildred Member*. To the east, in Saskatchewan, the Beaverhill Lake equivalent is the *Souris River Formation*, 400 to 600 ft (122 – 183 m) thick, and consisting of claystone, locally brecciated; crypto-grained argillaceous or dolomitic limestone; fine to medium-grained limestone; and halite (*Davidson Member*), grading upwards and westwards into anhydrite. The upper part of the Souris River Formation contains cyclic alternations of shale, fine-grained limestone and anhydrite (or halite).

The succeeding rock sequence is represented by the platform carbonate facies of the *Woodbend* and Lower *Winterburn Groups* in Central Alberta, and by the evaporite facies of the *Duperow* and *Birdbear Formations* in Saskatchewan. The basal carbonate of the sequence, the *Cooking Lake Formation*, consists of 200 ft (61 m) of interbedded fine-grained limestone, calcarenite and anhydrite. The shale equivalent is the *Majeau Lake Formation*, ranging in thickness from 300 to 800 ft (92 – 244 m). Post Cooking Lake carbonates, biostromal reefs, skeletal calcarenites and laminated limestones of the *Cairn Formation* and of the *Wymark Member* of the Duperow Formation form a continuous arcuate front from the Rocky Mountains into southeastern Saskatchewan. The lower part of the *Leduc Formation*, forming the base of the reef-chain dolomites, is equivalent to these. The overlying carbonate sequence comprises the *Peechee Member* of the *Southesk Formation* in southern Alberta, and the *Seward Member* of the *Duperow Formation* in Saskatchewan, as well as the reef carbonates of the Upper *Leduc*, and the *Grosmont* dolomite of northeastern Alberta. They consist of 200 to 500 ft (61 – 152 m) of medium to coarsely crystalline to vuggy dolomite, limestone, calcarenite and laminated mudstones as well as reefs. The reefs consist of massive stromatoporoids, separated and flanked by coarse reef detritus.

The shale facies of the Woodbend Group to the east of the major reef chains, starts with the *Duvernay Formation*, which overlies the Cooking Lake, and comprises 180 ft (55 m) of limestone, shale, and thin sandstone laminae. It passes northward into the Hay River shale and northeastward into Majeau Lake shale, and grades upward into shales of the *Ireton Formation* (500 – 900 ft or 152 – 275 m). The *Camrose Member* and the *Grotto Member* of the Southesk Formation in southern Alberta form carbonate tongues into the clastic facies. Both of these contain corals and stromatoporoids in a bituminous argillaceous matrix. The succeeding *Nisku Formation* in Alberta and the coeval *Birdbear Formation* in Saskatchewan, as well as the *Arcs Member* of the Southesk, consist of 100 to 200 ft (30 – 61 m) of crystalline dolomite, grading into anhydrite and siltstone in eastern Alberta and Saskatchewan.

The carbonate facies of the uppermost Upper Devonian, the *Wabamun Group* of Alberta, consists of 700 ft (213 m) of fine-grained limestones, locally dolomitized in northern and western Alberta. Dolomitization increases in south-central Alberta; interbedded dolomite and anhydrite, locally halite, form the *Stettler Member*, which is up to 500 ft (152 m) thick. Thinning eastward it grades to alternating shale, dolomite and anhydrite of the 60 to 130 ft (18.3 – 40 m) thick *Torquay Formation*, changing into the red sandy facies of the *Lyleton Formation* in Manitoba. Shale and argillaceous limestone of the *Big Valley Formation* overlie the Torquay and Stettler; they grade into the *Wabamun* limestone towards the northwest. Black shale of the lower Mississippian *Exshaw* and *Bakken Formations* overlie the Wabamun in Alberta and Saskatchewan, respectively.

In the Liard Plateau the 80 ft (24.4 m) of Exshaw shales are overlain by up to 550 ft (168 m) of non-calcareous black shale of the *Clausen Formation*, followed by almost 2000 ft (610 m) of argillaceous calcarenite, crinoidal limestone and shale of the *Flett Formation*. An unnamed sandstone and shale unit of Upper Mississippian age overlies the Flett conformably, being separated in turn from the youngest Paleozoic rocks in the area, an unnamed Upper Permian chert and sandstone sequence of about 20 ft (6.1 m) by an erosional unconformity.

South of the Liard River massive cherty limestone of the *Prophet Formation* grades eastward into the *Pekisko* limestone, *Shunda* shale and limestone, and *Debolt* limestone, shale and minor anhydrite, with an aggregate thickness of about 1000 ft (300 m). The Prophet and Debolt are conformably succeeded by the *Stoddart Group* in the Peace River region, comprising shales of the *Golata Formation* (up to 200 ft or 61 m), and black shales, siltstone, sandstone, cherty limestone and dolomite of the *Kiskatinaw Formation* (about 500 ft or 152 m). The latter grades eastward into more sandy beds and upward into the probably partly Pennsylvanian carbonate sequence of the *Taylor Flat Formation*. A period of extensive erosion led to unconformity between the Taylor Flat and the overlying glauconitic sandstone, silty limestone, and cherty conglomerate of the Permian *Belloy Formation*, which is about 150 ft (46 m) thick.

Beneath the southern Interior Plains the Mississippian sequence was truncated by pre-Mesozoic erosion. Only a small part of its original extent remains. The basal 20 ft (6.1 m) of black shales of the *Bakken Formation* are overlain in the Williston Basin by 60 ft (18.3 m) of fine-grained calcareous sandstone of the *Colville Member*, and by 25 ft (7.6 m) of Upper Bakken slightly calcareous shale. In southern Alberta the base of the succeeding *Banff Formation* is formed by thin dolomitic siltstone, followed by alternating shales and argillaceous limestones, grading upwards into calcareous to dolomitic shale and limestone. It may reach a thickness of 500 ft (152 m) and grades to shale and shaly limestone and then to cherty limestone, topped with glauconitic shale and siltstone. The coeval *Souris Valley* (or *Lodgepole*) *Formation* of the Williston Basin comprises a lower shale unit of 20 ft (6.1 m), overlain by 400 ft (122 m) of argillaceous cherty limestone, and 100 ft (30 m) of argillaceous limestone.

In Southern Alberta the Banff Formation is overlain transitionally by the *Rundle Group* which comprises three formations. Massive crinoidal limestones and dolomites of the *Livingstone Formation* thin and change facies north and eastward, and become subdivided into units with independent formation status: *Pekisko Formation*, coarsely crystalline crinoidal limestone with finely crystalline argillaceous and dolomitic limestone beds with chert nodules, grades eastward to about 200 ft (61 m) of coarse-grained chalky limestone with some shale and siltstone, and northward into shale; finely crystalline limestones of the *Shunda Formation* grade northward into shale and eastward into argillaceous silty dolomite with some anhydrite; the *Turner Valley Formation* consists of coarsely crystalline limestone, locally altered into porous, coarsely crystalline dolomite, with a middle member of fine-grained silty and cherty dolomite. The *Mount Head Formation* of the Rundle Group contains mainly sandstone and silty dolomite, with some crinoidal limestone, grading eastward into anhydrite, evaporitic dolomite and red sandstone, and porous dolomite. The Mount Head and Turner Valley Formations pass northward into the Debolt Formation which was described earlier. The overlying *Etherington Formation* consists of thin alternating beds of shale and dense, silty, finely crystalline limestone and dolomite.

In the Williston Basin the progressively truncated members of the Mississippian sequence comprise the *Mission Canyon* and *Charles Formations*, with a maximum preserved thickness of about 1000 ft (300 m). They are made up of cyclical deposits of carbonates and evaporites, with minor clastics. Cycles in the Mission Canyon are represented by the *Tilston, Alida, Frobisher*, and *Midale Beds*, and those in the Charles by the *Ratcliffe* and *Poplar Members*. They are overlain by the upper Mississippian *Kibbey Formation* consisting of about 50 ft (15 m) of sandstone with anhydrite and some limestone, and by shales of the *Otter Formation*.

The Mississippian is overlain unconformably by Triassic and Jurassic strata in the Peace River region, by Jurassic sediments in most of the Williston Basin area, and by Cretaceous strata elsewhere.

In the Peace River region the Triassic is represented by the *Daiber Group* and the *Schooler Creek Group*. The Daiber Group is subdivided into the *Montney Formation*, grading from dark shale to argillaceous siltstones with a maximum thickness of 1500 ft (457 m); and the *Doig Formation*, consisting of as much as 400 ft (122 m) of basal black shale and bituminous dolomitic siltstone. Their equivalents to the north and west appear to be the *Grayling* shales, and the lower part of the siltstones and shales of the *Toad Formation*. The Schooler Creek Group is subdivided into four formations. The *Halfway Formation* consists of well-sorted, fine to medium-grained sandstone, equivalent to sandstone of the *Liard Formation* farther west. It may reach a thickness of 400 ft (122 m). The *Charlie Lake Formation*, ranging in thickness from 0 to over 1400 ft (0 – 427 m) comprises massive anhydrite, dolomitic siltstone, dolomite and minor sandstone. The *Boundary Lake Member* of this formation consists of dolomitized limestone and is a major oil producer. It is equivalent to part of the *Grey Beds* overlying the Liard Formation to the northwest. The *Baldonnel Formation* is up to 300 ft (92 m) thick, and consists of dolomitized skeletal limestone; it is a major gas reservoir, generally correlated with the upper part of the Grey Beds. The uppermost unit of the Schooler Creek Group, the *Pardonet Formation*, consists of microcrystalline limestone and siltstone.

In the Peace River portion of the Interior Plains, the Jurassic is represented by the *Fernie Formation*. It comprises 30 to 100 ft (9.2 – 30.5 m) of cherty and phosphatic dolomite or limestone, with minor siltstone and calcareous shale of the *Nordegg Member*, that grade eastward into black shales overlain by pebbly sandstone; up to 60 ft (18.3 m) of *Poker Chip* shale; glauconitic sandstone beds of the *Rock Creek Member*; shale with glauconite pellets of the *Green Beds*; and siltstone and sandstone of the *Passage Beds*. The latter grade into the quartzose marine sandstone of the *Monteith Formation*, the upper part of which is of early Cretaceous age. The sandstones grade northward into shales and siltstones similar to those of the overlying *Beattie Peaks Formation*.

In the region of the Sweetgrass Arch in southern Alberta, the Middle Jurassic is represented by up to 235 ft (72 m) of *Sawtooth Formation*, which comprises a lower and an upper quartzose sandstone member, and a middle shale-conglomerate unit. The sandstones grade eastward into limy sandstone of the Shaunavon Formation and westward into black shales of the Rock Creek Member. The overlying *Rierdon Formation*, 250 ft (76 m) of alternating calcareous shales, limestones, and siltstones, grades eastward into calcareous shales of the Lower Vanguard, and westward into the shales of the Grey Beds. The *Swift Formation*, ranging from 0 to 75 ft (0 – 22.9 m) consists of non-calcareous shale and quartzose silty sand, in part glauconitic, and overlies the Rierdon disconformably. It grades eastward into shales of the Upper Vanguard, and westward into the Green and Passage beds of the Schooler Creek Group.

In the Williston Basin the lower Jurassic red beds of the *Lower Watrous Formation* consist of siltstone, shale, and sandstone, lying unconformably on the highly irregular erosion surface of Mississippian and Devonian. Anhydrite, dolomite, and shales of the *Upper Watrous Formation* complete the 500 ft (152 m) thick sequence. In southern Manitoba it is represented by up to 300 ft (92 m) of anhydrite and dolomite of the *Amaranth Formation*. Silty and dolomitic shales of the *Gravelbourg Formation* in Saskatchewan (200 ft or 61 m) and the *Reston Formation* in Manitoba (150 ft or 46 m) overlie the Watrous and its equivalents. The succeeding *Shaunavon Formation* comprises fine-grained sandstone and oölitic limestone in the west and shale with minor sandstone in the east; it is equivalent to the lower part of the 470 ft (143 m) thick *Melita* shales in southern Manitoba. Transgressive calcareous shales of the *Lower Vanguard* are equivalent to the upper part of the Melita; sandstones of the *Middle Vanguard* and marine shales of the *Upper Vanguard* complete the sequence which reaches a total thickness of about 500 ft (152 m) in Saskatchewan. The Middle and Upper Vanguard form the equivalent of the *Swift Formation* in Southern Alberta, and of the *Waskada Formation* in Manitoba.

In the Great Slave Lake area dark grey concretionary shales of the lower Cretaceous *Fort St. John Group* overlie the Upper Devonian; in the Norman Wells area the equivalent comprises the *Sans Sault* and *Slater* shales, with a thickness of up to 1400 ft (427 m). The Fort Saint John consists of the basal *Garbutt* silty shale (about 900 ft or 275 m); *Buckinghorse* and *Lepine* shale (2000 ft or 610 m); and *Sully* shale, mudstone and silty sandstone (400 ft or 122 m). The shales are separated by sandstone units belonging to the *Scatter Formation* and the *Sikanni Formation* (up to 1000 ft or 300 m thick); the latter grade eastward into siltstone and silty shale.

In the Peace River region piedmont gravels and conglomerate of the *Cadomin Formation* (30 ft or 9.1 m) are overlain by coalbearing alluvial plain sediments of the *Gething Formation* (100 – 500 ft or 30 – 152 m). Together these form the *Bullhead Group*. The Gething grades laterally into marine sandstone and shale of the *Bluesky Formation*, which is part of the Fort St. John Group. Shales of the basal *Wilrich Member* of the overlying *Spirit River Formation* gradually replace the alluvial deltaic sandstones and shales of the *Falher Member*. The upper member of the Spirit River, the *Notikewin Member*, is a well sorted sandstone. The overlying *Peace River Formation* is subdivided into the *Harmon* shales (60 ft or 18.3 m), well-sorted *Cadotte* sandstone (70 ft or 21.3 m), and coarse-grained sandstones of the *Paddy Member*. The Fort St. John Group is completed by 400 to 900 ft (122 – 275 m) of marine shales of the *Shaftesbury Formation.*

In the central and southern Interior Plains the Lower Cretaceous comprises the *Mannville* (or *Blairmore*) *Group*, the *Joli Fou Formation*, the *Viking Formation* and an unnamed shale. The beds above the Mannville are included in the lower part of the *Colorado Group* which reaches into the Upper Cretaceous.

In central Alberta the Mannville Group is subdivided into the *McMurray* and *Fort Augustus Formations*. The McMurray comprises the *Deville Member* (50 ft or 15 m of shale, siltstone and sandstone), the *Ellerslie Member* (200 ft or 61 m of shale, siltstone and kaolinitic quartz sandstone), and an unnamed member consisting of calcareous shale and siltstone equivalent to the *Ostracode* zone farther south. The Fort Augustus Formation consists of glauconitic shale and fine-grained glauconitic sandstone of the *Wabiskaw Member* (up to 100 ft or 30 m thick), marine shale of the *Clearwater Member* (up to 170 ft or 52 m thick), grading laterally northward into sandstone of the *Grand Rapids Member.*

In east central Alberta the McMurray consists of *Deville* sandstone and shale, *Dina* sandstone (150 ft or 46 m), *Cummings* marine shale (90 ft or 27.5 m), which includes the equivalent of the Ostracode zone, and an upper sandstone sequence of 300 ft (92 m). In northeastern Alberta the McMurray sediments are impregnated with heavy oil residue (Athabasca oil sands). A thin shale, equivalent to the Ostracode zone, separates the McMurray from the glauconitic Wabiskaw member of the Fort Augustus Formation.

In southeastern Saskatchewan up to 500 ft (152 m) of nonmarine sandstone, siltstone and shale of the *Cantuar Formation* and 100 ft (30 m) of siltstone and shale of the *Pense Formation* form the equivalent of the Mannville Group. In Manitoba, the *Swan River Group* equivalent of the Mannville includes all the fine to coarse-grained quartzose sandstones in the Lower Cretaceous, as well as some clays. Shaly, glauconitic sandstone in the upper part of the Swan River appears to be equivalent to the Joli Fou and Viking Formations of southern Alberta and to part of the Ashville Formation in southern Manitoba.

The marine shales of the *Joli Fou Formation*, 60 to 110 ft (18.3 – 33.6 m) thick, are present over most of the southern Interior Plains. They are the equivalent of the Harmon shales of the Peace River Formation. The *Viking* sandstone, 50 to 100 ft (15.2 – 30.5 m) thick, grades eastward into siltstone and shale and then into marine shales of the *Ashville Formation*. It can be correlated with the *Pelican* sandstone in northeastern Alberta, and with the marine shales and sandstones of the *Bow Island Formation*, up to 400 ft (122 m) thick, in southern Alberta. Marine shales overlying this sandstone sequence belong to the *Shaftesbury Formation* in the Peace River area, to the *Lower Colorado Group* in the Western Plains in Alberta and Saskatchewan, and to the upper *Ashville Formation* in Manitoba. The boundary between Lower and Upper Cretaceous in the Interior Plains is taken at the base of the *Fish Scale Sand* in the Lower Colorado shale sequence.

Lowermost upper Cretaceous rocks are represented by the upper part of the *Shaftesbury Formation* or its equivalent, and shales of the *Lower Colorado Group*. In the northwestern part of the Interior Plains the *Shaftesbury* is overlain by up to 500 ft (152 m) of *Dunvegan* conglomerate, sandstone, and shale. Overlying shales belong to the *Labiche Formation* (1400 ft or 427 m) in northeastern Alberta, the *Colorado Group* (750 ft or 229 m) and *Lea Park Formation* (800 ft or 244 m) or their equivalents (*Milk River* sandstone and *Pakowki* shale) in central and southern Alberta and southern Saskatchewan, and to the *Favel Formation* (100 ft or 30 m), *Morden Formation* (20 – 200 ft or 6.1 – 61 m), *Boyne Formation* (30 – 140 ft or 9.2 – 42.7 m), *Pembina Formation* (50 ft or 15.2 m), and *Riding Mountain Formation* (80 – 1100 ft or 24.4 – 335 m) in southern Manitoba. Main sandstones included in the shale series are the *Cardium* (sandstone, conglomerate and minor shale) in northeastern and central Alberta, and the Milk River sandstone in southern Alberta. Sandstones that overlie the shale sequence include the *Wapiti Formation* (up to 1100 ft or 335 m) in the northwestern part of the basin; *Belly River* sandstone (up to 1100 ft or 335 m) and its *Oldman* (500 ft or 152 m) and *Foremost* equivalents in northeast, east-central and southern Alberta and southern Saskatchewan; and the *Edmonton Formation* and its equivalents in southern Alberta and Saskatchewan (*Blood Reserve, Eastend* and *Frenchman Formations)*, and in Manitoba (*Boissevain* sandstone). None of these, nor the overlying Tertiary *Paskapoo Formation* (up to 800 ft or 244 m in central Alberta), *Ravenscrag Formation* (150 ft or 45.7 in southern Alberta and Saskatchewan), and *Turtle Mountain Formation* (100 ft or 30.5 m in southern Manitoba) would qualify for waste disposal because of lack of sufficient depth, and absence of adequate confining beds.

The line marked 'A' on Figure 7 indicates the eastern boundary of the area where the sedimentary column underlying the Interior Plains generally has a thickness of 3000 ft (915 m) or more. In the area between this line and the western edge of the undisturbed portion of the basin, a number of prospective disposal formations can be identified. For additional details reference should be made to structure and isopach maps published for a number of these formations by McCrossan and Glaister (1966). A few general observations should precede this listing of the potential disposal formations.

Petroleum and natural gas are being produced from Ordovician, Devonian, Mississippian, Permian, Triassic, Jurassic and Cretaceous formations at a large number of locations throughout the Interior Plains (Geological Survey of Canada, Maps No. 1316A, 1317A, and 1318A). Locations of mining operations for coal (from Cretaceous and Tertiary formations), salt (from the Elk Point Group), and potash (from the Prairie Evaporite) are marked on Figure 7. Helium and carbon dioxide are being produced from the Cambrian and Mississippian, respectively, in Saskatchewan.

Exploration activities for these resources have provided extensive knowledge of the subsurface in Western Canada. The presence of abandoned drill holes and old wells, resulting from these activities, may create problems in some areas. More important, however, any future disposal operations would have to be undertaken in such a way that areas and formations actually or potentially productive of hydrocarbons or other economic resources are not affected.

Caution should also be exercised in regard to useable and potentially useable underground water resources. Zones where older formations contain water with low dissolved-solids concentrations (<10,000 mg/l and locally even <5000 mg/l) are found along the edges of the basin, where mixing takes place between highly concentrated but slow-moving formation brines and fresh, faster moving water from shallow flow systems. Increase of the hydraulic head in a disposal formation, as a result of waste injection in these areas, may increase the flow rate of saline water to the point where mixing at the basin edges can no longer reduce the dissolved-solids content of the mixture to an acceptable degree.

Formation waters with low dissolved-solids contents are also common in a relatively large area in southwestern Saskatchewan (van Everdingen, 1968). This fresh-water area extends all the way down into the lower Paleozoic, and it generally increases in size in successively younger formations. These waters may eventually become an important resource in this semi-arid portion of the sedimentary basin. In view of this, restrictions should be imposed on subsurface disposal of liquid wastes in this area as well as in similar areas found elsewhere in the Interior Plains.

Solution by circulating groundwater has removed appreciable quantities of soluble evaporites from the Prairie Evaporite and Muskeg Formations (Holter, 1969; Hriskevich, 1970), and it may also have affected other evaporite deposits (Lotsberg, Cold Lake, Davidson salts) to some extent. The removal of part or all of the evaporite section in a number of areas has led to subsidence of overlying strata, with accompanying fracturing and brecciation. It has also led to increased sedimentary thicknesses in subsiding areas during some periods. In addition to the difficulties in correlation caused by these phenomena, they may affect the potential confining beds in younger formations in these areas. Part of the major salt-solution area in southern Saskatchewan coincides with the area of low dissolved-solids concentrations mentioned earlier. Subsurface solution of evaporites appears to be a continuing process at least in some areas (Hitchon *et al.*, 1969; van Everdingen, 1971; Christiansen, 1971). As mentioned earlier in this report, subsidence, settlement and collapse, resulting from active subsurface solution of evaporite beds (either natural or artificial) may cause damage to surface installations and injection wells, and they may also increase opportunities for migration of injected waste to the surface. It therefore appears prudent to restrict waste injection in the salt solution areas to formations below the Prairie Evaporite.

An additional hazard may be created when waste waters are injected into formations over- or underlying mining operations, through the imposition of excessive pressures acting on the roof or floor of the mine openings and on shaft linings. To enable dealing with potential floor lifting, de Korompay (1972) introduced the concept of "bottom pressure gradient", expressed in psi/ft, which represents the ratio between the fluid pressure in the disposal formation (in psi) and the thickness of the confining beds between the mining floor and the disposal formation (in ft). Comparison between actual bottom pressure gradient and allowable bottom pressure gradient would indicate the feasibility of simultaneous injection and mining operations. The allowable bottom pressure gradient is a function of the rock mechanics characteristics of the confining beds.

Sandstones of the Cambrian *Deadwood Formation* appear to be suitable for subsurface disposal of liquid wastes in a number of places; irregular thickness and cementation may create some problems due to reservoir limitation and erratic permeability. In Saskatchewan two potash companies use this formation for the disposal of waste brine.

Sandstones of the Ordovician *Winnipeg Formation* offer similar possibilities in western Manitoba and eastern and southern Saskatchewan. Two potash companies operate three disposal wells that inject waste brine into both the Winnipeg and the Silurian Interlake Group in the Esterhazy area. One of these disposal projects, described by de Korompay (1972), deserves special mention because it undoubtedly constitutes the most thoroughly investigated, engineered, tested, and monitored disposal operation in Canada. Early signs of interference between the cones of influence of the three wells indicate the need for further study in this area.

Porous-vuggy dolomites encountered at various levels in the Silurian *Interlake Group* in southeastern Saskatchewan may have sufficiently high permeabilities to permit injection of liquids at relatively high rates with little or no well-head pressure. The distribution of the high permeability zones appears to be very irregular, and success will therefore vary from place to place. Active disposal operations injecting waste brine into the Interlake were mentioned earlier.

Limited possibilities for waste injection may exist in the clastic and carbonate (reef) facies of the Elk Point Group: *Winnipegosis Formation* in Manitoba and Saskatchewan, *Keg River, Pine Point, Sulphur Point* and *Presqu'île Formations* in Alberta, northeastern British Columbia and farther north. Restricted size of permeable zones may be a problem in all of these formations.

In the Woodbend Group and its equivalents, extensive opportunities for waste disposal by injection may exist in reefs and associated porous, vuggy and dolomitized carbonate rocks of the *Twin Falls* and *Leduc Formation* and its *Grosmont* equivalent in central Alberta. Carbonates of the *Duperow Formation* in western Saskatchewan also present a potential disposal reservoir. One disposal well is used to inject refinery wastes into the Leduc in Alberta, and one to inject cavern-washing brine into the Duperow in Saskatchewan.

Carbonates of the *Nisku Formation* of the Winterburn Group have potential for liquid waste disposal in central Alberta. A total of nine disposal wells have so far been used to inject liquid wastes from refineries and chemical plants in the Edmonton area into the Nisku. Another well is used to inject cavern washing brine. The relatively close proximity of a number of these wells to one another and to the North Saskatchewan River may eventually lead to interference of their cones of influence, accelerated buildup of pressure and, potentially, migration of the wastes in to the river valley.

Potential for disposal of liquid wastes in the Carboniferous of the Interior Plains is essentially limited to the hydrocarbon producing areas, and members of the *Souris Valley, Mission Canyon* and *Charles Formations* in Saskatchewan and Manitoba, and the *Banff, Pekisko,* and *Turner Valley-Debolt Formations* in Alberta. The Pennsylvanian *Stoddart Group* may hold some potential in the Peace River area. The *Lodgepole* (Souris Valley) is used in five cases for disposal of liquid wastes other than oil field water: two wells in Saskatchewan are used to inject cavern-washing brine; potash brine is injected into one well in Saskatchewan; and one well in Manitoba and one in Saskatchewan are used for injection of refinery waste water. The potash-brine disposal well, and the refinery-waste well are located in the main salt-removal area in southern Saskatchewan near Regina.

In the Permian *Belloy Group* in the Peace River area limited disposal potential may be available in the hydrocarbon producing sandstones. The same applies to sandstones of the Triassic *Halfway Formation* and carbonates of the *Boundary Lake Member* and the *Baldonnel Formation* in that region. Restricted size of available reservoirs will be a problem in these formations.

The *Nordegg* and *Rock Creek Members* of the Jurassic Fernie Group in the northwestern Plains, and the *Sawtooth, Shaunavon* and *Middle Vanguard Formations* in the southern plains may also have some potential. Disposal of liquid wastes in all of these post-Devonian strata should preferably be restricted to return of formation water produced with hydrocarbons.

In many of the prospective disposal formations, with the possible exception of the Interlake, the Winnipegosis-Keg River, and the Leduc, a certain amount of upward migration may well be expected to take place if wastes are injected under considerable pressure, because they are not immediately overlain by extensive shale or evaporite beds, but with a sequence of more or less slightly permeable strata.

The Lower Cretaceous offers a number of possibilities for waste injection in the northern part of the plains in the *Scatter* and *Sikanni* sandstones of the Fort St. John Group; in the Peace River region in a number of sandstones in the *Bullhead* and *Fort St. John Groups;* and in the sandstones of the *Mannville* or *Blairmore Groups* in southern Alberta and Saskatchewan, and the *Swan River Group* in southern Manitoba. Adequate confining beds should be provided by the immediately overlying *Sully, Harmon, Joli Fou* and *Ashville* shales, respectively. Disposal should not be allowed in any of these formations where depths are insufficient, where fresh water or other resources are present, or in areas immediately upstream from areas where these formations contain potentially useable water resources. Two injection wells in the Blairmore are used for disposal of brine and refinery wastes in Alberta; in Saskatchewan two wells have been used for disposal of potash brine, two are used for disposal of refinery wastes, and five for disposal of cavern-washing brine.

Similar possibilities exist in sandstones of the *Viking Formation* and its equivalents (*Bow Island Formation, Pelican, Cadotte* and *Paddy* sandstones) that are overlain by an adequate thickness of shales of the *Lower Colorado Group* and its equivalents (*Labiche* and *Shaftesbury* shales). Restrictions to be put on the use of these sandstones for waste disposal should be similar to those for the Blairmore and its equivalents. Refinery waste is being injected into the Viking near Red Deer, in the deeper portion of the basin; brines are injected into the Viking in two wells near Medicine Hat.

No subsurface disposal of liquid wastes should be allowed in any of the sandstone formations overlying the Colorado shales or their equivalents. Depths would be insufficient, confining beds inadequate, and existing or potential future water supplies would be affected adversely. In areas where hydrocarbons are produced from any of these formations, the return of produced water to the producing formation can of course be allowed if adequate precautions are taken in terms of well construction, limitation of injection pressure, etc. Safety considerations would make it desirable to inject produced water into strata below the producing horizons, if such water is not reinjected for pressure maintenance.

ARCTIC COASTAL PLAIN

The Arctic Coastal Plain encompasses three distinct units: the Yukon Coastal Plain, the Mackenzie Delta and the Island Coastal Plain (area 7 on Figure 1). They extend from the Alaska border through the Mackenzie Delta, the western portion of Banks Island, and the northwestern portions of Prince Patrick, Brock, Borden and Ellef Ringnes Islands, and include the whole of Meighen Island. Elevations range from sea level along the Arctic Ocean coastline to as much as 800 ft (244 m) on parts of Banks and Prince Patrick Islands.

The sedimentary sequence underlying the Arctic Coastal Plain includes almost undisturbed Cenozoic Strata unconformably overlying strata of Cretaceous, Jurassic and, in some cases, Triassic age. The Mesozoic formations overlap folded Devonian strata. The Arctic Coastal Plain merges, beneath sea level, with the Arctic Continental Shelf. The latter extends outward from the islands over distances varying from 80 to 120 miles (129 – 193 km) and slopes at about 12 ft per mile (2.27 m/km). Very little is known so far about the sedimentary sequence of the Arctic Shelf and of that underlying the Mackenzie Delta.

The oldest formations known to underlie the Arctic Coastal Plain belong to the late Middle Devonian and Upper Devonian *Melville Island Group*. Their presence has been ascertained only on Banks and Prince Patrick Islands. The rocks assigned to the Melville Island Group on Banks Island include some 400 ft (122 m) of marine sandstone, shale and siltstone, as well as some isolated reef limestones, the only occurrence of this type in the Arctic Islands. The *Griper Bay Formation* of equivalent age on Prince Patrick Island consists of a lower marine sequence of 1800 ft (549 m) of sandstone, siltstone and shale, and an upper non-marine sequence of 2700 ft (823 m) of sandstone, shale and coal. On Banks Island the Devonian is overlain unconformably by the Lower Cretaceous Isachsen Formation; on Prince Patrick Island by the Upper Triassic Schei Point Formation or the Jurassic Mould Bay Formation.

The early Upper Triassic *Schei Point Formation* is represented on Prince Patrick and Borden Islands by the so-called *Gryphaea Bed*, consisting of up to 100 ft (30 m) of calcareous sandstone with coquina layers. It is overlain disconformably by Borden Island strata on Borden Island, and unconformably by Wilkie Point strata on Prince Patrick Island.

The next younger formation, the *Heiberg Formation*, is not found in contact with the underlying Schei Point. It is found on Brock and Borden Islands, but it was removed on Prince Patrick Island, after uplifting, by erosion. On these islands, the Heiberg Formation consists of between 100 and 200 ft (61 m) of deltaic, partly marine sandstone.

The Lower Jurassic *Borden Island Formation* comprises up to 200 ft (61 m) of marine, glauconitic sandstone with thin beds of hard, ferruginous sandstone. Where present, the formation is overlain disconformably by Wilkie Point strata. They form the oldest known sedimentary strata on Ellef Ringnes Island.

The Middle Jurassic *Lower Wilkie Point* sandstone on Prince Patrick, Brock, and Borden Islands is quartzose or glauconitic. Hard ferruginous beds and phosphatic nodules are common. Shales of the equivalent *Savik Formation* on Ellef Ringnes Island are argillaceous and contain clay ironstone nodules. Thickness of these formations ranges from 250 ft (76 m) for the Savik to 500 ft (152 m) for the Lower Wilkie Point. The Upper Wilkie Point on Prince Patrick Island consists of non-marine quartzose sands, up to 200 ft (61 m) thick. The Savik Formation on Ellef Ringnes Island is overlain by 200 ft (61 m) of marine sandstone known as the *Jaeger Beds*.

Late Jurassic and earliest Cretaceous sedimentation is represented by the *Mould Bay Formation* on Prince Patrick, Brock, and Borden Islands and by the *Deer Bay Formation* on Ellef Ringnes Island. The Mould Bay Formation consists of 160 to 300 ft (49 – 92 m) of sands and sandstone with lower and upper shale sequences of 100 to 150 ft (30 – 46 m) thick. The latter represent interfingering with the homogeneous, up to 1000 ft (300 m) thick shale sequence of the Deer Bay Formation. The Mould Bay rests disconformably or unconformably on Wilkie Point strata or nonconformably on Devonian Griper Bay. Deer Bay shales overlie the Jaeger Beds disconformably.

The Lower Cretaceous *Isachsen Formation* overlies folded Devonian Melville Island sandstone unconformably on Banks Island; it overlies the Mould Bay disconformably on Prince Patrick, Brock, and Borden Islands; and the Deer Bay Formation conformably on Ellef Ringnes Island. The Isachsen Formation consists of mainly non-marine, quartzose sandstone, grit and conglomerate, with interbeds of siltstone, shale and coal. Crossbedding is common. Thickness ranges from 200 to 300 ft (61 – 92 m) on Banks Island, to 350 ft (107 m) on Prince Patrick Island, to 500 ft (152 m) on Borden and Brock and to more than 2000 ft (610 m) on Ellef and Amund Ringnes Islands.

The Lower Cretaceous (Albian) *Christopher Formation* overlies the Isachsen Formation, conformably in most places. On Banks Island it overlaps locally onto folded Devonian rocks. It consists mainly of grey shale, with calcareous septaria and concretions, and small amounts of siltstone and sandstone. Thickness of the Christopher ranges from 130 ft (40 m) on Prince Patrick Island to more than 1000 ft (300 m) on Banks Island, to 400 ft (122 m) on Brock and Borden Islands, and to 2000 ft (610 m) on Ellef and Amund Ringnes Islands. The Christopher is overlain by Cenomanian sandstone on Banks Island, by the Quaternary Beaufort Formation on Prince Patrick, Brock and Borden Islands, and by Upper Albian and Cenomanian Hassel sandstone on Ellef Ringnes.

The *Hassel Formation* on Ellef Ringnes Island consists of medium to fine-grained quartzose sandstone and siltstone; it is highly carbonaceous. It could represent a delta intermittently covered by the sea. The Hassel is overlain by the *Kanguk Formation* of Upper Cretaceous age, which comprises dark shale and siltstone, with minor sandstone and some local bentonitic and tuffaceous beds. On Banks Island 25 ft (7.6 m) of coal-bearing sandstone beds are overlain by up to 400 ft (122 m) of shale and fine-grained sandstone. These strata may be the equivalent of the Hassel Formation.

The Early Cenozoic *Eureka Sound Formation* consists of up to 1500 ft (457 m) of sandstone, shale and coalbeds on Banks Island; it is absent on Prince Patrick, Brock, Borden and Meighen Islands and occurs in a few places on Ellef Ringnes Island outside the Coastal Lowland area. Its equivalent to the west of the Mackenzie River is the *Moose Channel Formation*, 1200 ft (366 m) of non-marine, loosely consolidated sandstone, fine to coarse-grained, feldspathic, rippled-marked, and interbedded with silty shale, and at least one 7-foot (2.1 m) seam of coal. East of the Mackenzie River the *Reindeer Formation*, more than 700 feet (213 m) thick, contains non-marine silty shales, siltstone, sandstone, cherty conglomerate and coal.

Wood-bearing alluvial deposits of the Plio-Pleistocene *Beaufort Formation* underlie all of the Arctic Coastal Plain. They rest unconformably on Jurassic on northeast Ellef Ringnes Island; on Triassic on Borden and Brock Islands; on Lower Cretaceous, Jurassic, Triassic, and Upper Devonian on Prince Patrick Island; on the Eureka Sound Formation and Upper and Lower Cretaceous on Banks Island; and on Tertiary, Cretaceous, Mississippian, Devonian, Cambrian and Precambrian rocks in the Mackenzie Delta and Yukon Coastal Plain. The Beaufort Formation consists of cross-bedded sand, gravel and silt and is definitely preglacial. The thickness of the formation ranges up to 400 ft (122 m) on Banks Island and is at least 250 ft (76 m) on the other islands. The beds of the Beaufort are inclined slightly, seaward on Prince Patrick Island, and away from the ocean on Ellef Ringnes Island. Surface traces of faults have been identified on Prince Patrick Island; in a few places fault scarps have a relief of up to 300 ft (92 m); minor recent movements on these faults would account for the somewhat higher seismic activity centered on Prince Patrick Island.

The following can be said about the potential of the Arctic Coastal Plain for safe subsurface disposal of waste: only those areas that are underlain by a sufficient thickness (at least 2000 ft or 610 m) of undisturbed sediments which include an appreciable portion (at least 200 ft or 60 m) of the Albian to Turonian shaly sequence (Christopher Formation, Kanguk equivalent) should be regarded as holding any potential at all. The sandstones of the Isachsen and/or older formations could then be used as disposal formations; the Christopher and Kanguk equivalent shales would form the confining beds. However, very little is known regarding the extension of these older formations below the Arctic Coastal Plain (and the Arctic Continental Shelf). The Cretaceous shales appear to be absent under the Coastal Plain portions of Meighen, Ellef Ringnes, Borden and Brock Islands, and under parts of the Coastal Plain portion of Prince Patrick Island, and parts of the Mackenzie Delta and Yukon Coastal Plain.

Until more detailed knowledge has been obtained about the subsurface conditions, only *limited potential* can be assumed for parts of the Yukon Coastal Plain, the Mackenzie Delta, and the Island Coastal Plain on Banks and Prince Patrick Islands. Subsurface disposal should not be allowed anywhere in the Arctic Coastal Plain Region before detailed studies have indicated the presence of suitable disposal formations, adequate confining beds and adequate thickness of sedimentary cover. Hydrodynamic studies should be made in all cases to attempt prediction of the direction and rate of movement of injected waste. An important factor to be taken into account in such studies is the presence of a perennially frozen zone (under a very thin seasonally thawing layer) extending to depths ranging from 300 to 1500 ft (92 – 457 m).

ARCTIC LOWLANDS

The Arctic Lowlands (Area 8 on Figure 1), between the Canadian Shield and the Innuitian Region, are underlain by flat-lying to nearly flat Paleozoic and late Proterozoic sediments. They include the Victoria Lowland, the Boothia Plain, the Lancaster Plateau, and the Foxe Plain. For the purpose of this report the Sverdrup Lowland (part of the Innuitian Region) is discussed in connection with the Arctic Lowlands.

Victoria Lowland includes part of Banks Island, Victoria, Stefansson, King William, and Prince of Wales Islands, and small areas on the mainland and on Boothia Peninsula. The surface on the east side of the lowland is tilted to the southwest and south, across Prince of Wales Island. On Victoria Island the lowland reaches elevations of around 2,500 ft (762 m) in the Shaler Mountains. The latter consist of stratified Proterozoic rocks intruded by gabbro sills, and capped by flat lying volcanics.

The surface of the Lancaster Plateau, comprising parts of Ellesmere, Devon, and Somerset Islands, and the Brodeur Peninsula of Baffin Island, slopes gently southward from about 2,500 ft (762 m) on southern Ellesmere Island to average elevations between 1000 and 2000 ft (300 and 610 m) on Somerset Island and Brodeur Peninsula. It descends still further into the Boothia Plain, which comprises portions of Boothia Peninsula and Baffin Island. Foxe Plain is a shallow basin-like area, covered partly by the very shallow waters of Foxe Basin. It comprises a small portion of Melville Peninsula, all islands in Foxe Basin and a number of smaller and larger areas on Baffin Island. Maximum elevation is about 600 ft (183 m).

Sverdrup Lowland comprises a number of islands and parts of islands in the Sverdrup and Parry Groups. It is a region of generally low relief developed over a structural basin that contains soft, poorly consolidated, and little deformed Mesozoic sediments. The land surfaces are rolling and scarped, and usually less than 500 ft (152 m) above sea level; local uplands may reach 1200 ft (366 m).

About half the area of Sverdrup Lowland is covered by water up to 1500 ft (457 m) deep. The sea floor rises relatively abruptly to the island shores. This lowland was the principal site of sedimentation from the Carboniferous till late Cretaceous time.

Somewhat metamorphosed and folded Proterozoic shales, sandstones, limestone, dolomite and anhydrite are present in appreciable thickness in some of the lowlands. In most cases they are overlain by a relatively thin sequence of clastic rocks and dolomites of Cambrian age. The dolomites are best developed on Devon Island and along the east coast of Ellesmere Island.

The principal rocks of the Arctic Lowlands, are dolomites and limestones ranging in age from Middle Ordovician to Lower Devonian. The *Cornwallis* and *Allan Bay* dolomites (or equivalent) with thickness ranging to over 2000 ft (610 m) contain biostromal reefs, vuggy porosity, and bituminous residues. They are exposed in the southern regions of the Lowlands, but covered by at least 1500 ft (457 m) of the generally non-porous *Read Bay* limestone in the Victoria Strait, Jones-Lancaster, and Melville Basins. The sedimentary sequence in these basins is appreciably thicker than in the Wollaston and Foxe Basins. The Read Bay limestones are in turn locally overlain by partly crinoidal limestones, dolomite and bituminous shales of the Middle Devonian Blue Fiord Formation.

In Banks Basin the Devonian is overlain by up to 300 ft (92 m) of porous sandstones of the Lower Cretaceous *Isachsen Formation,* 1000 ft (300 m) or more of marine shales of the *Christopher Formation,* and equivalents of the *Hassel* sandstone and the *Kanguk* shale. These are in turn locally overlain by the Cenozoic *Eureka Sound* and *Beaufort Formations* and by Pleistocene and Recent deposits.

In parts of the Jones-Lancaster Basin, sandstone and coal beds of the Eureka Sound Formation and sandstone, gravel, and silt of the Beaufort Formation overlie the Devonian. On Victoria, Stefansson, Prince of Wales, King William, Somerset and Devon Islands, and in Foxe Basin, only Pleistocene and Recent deposits overlie the Devonian locally.

In the Sverdrup Lowland the Ordovician-Silurian carbonate sequence is overlain by a sequence similar to that described for the Arctic Coastal Plain: *Blue Fiord* limestone and dolomite (more than 1000 ft or 300 m); *Bird Fiord* limestone and sandstone (650 ft or 198 m); *Hecla Bay* sandstone (about 500 ft or 152 m); *Griper Bay* sandstone, siltstone, and shale (more than 1500 ft or 457 m); *Canyon Fiord* conglomerate and sandstone (up to 500 ft or 152 m); *Belcher Channel* dolomite and limestone (600 ft or 183 m); *Bjorne* sandstone and conglomerate (600 ft or 183 m); 700 ft (213 m) of *Schei Point* sandstone, siltstone, and shale; *Heiberg* sandstone; 1000 ft (300 m) of *Jaeger* sandstone and conglomerate; and *Awingak* sandstone, shale, and coal beds (100 ft or 300 m). Upper Jurassic to Lower Cretaceous *Mould Bay* sandstone and siltstone or *Deer Bay* shale and siltstone, and Cretaceous *Isachsen* sandstone, *Christopher* shale, *Hassel* sandstone and *Kanguk* shale complete the sequence on some of the Sverdrup Islands. The Eureka Sound and Beaufort Formations are present locally, as are Pleistocene and Recent deposits.

Only limited potential can be foreseen in the Arctic Lowlands as far as safe subsurface disposal of liquid wastes is concerned. Any real potential may well be restricted to areas where lower Paleozoic carbonate rocks or Devonian and younger sandstones are overlain by a sufficient thickness of shales of the Deer Bay, Christopher or Kanguk Formations (or their equivalents). An exception would be the re-injection of produced formation water into hydrocarbon-producing formations in other areas.

Detailed studies should determine in each case whether adequate confining beds overlie the available prospective disposal formations; whether depths are sufficient; and whether existing hydrodynamic gradients will allow the waste to remain confined. Special precautions will have to be taken in view of the presence of a perennially frozen zone in the subsurface in most of the Arctic Lowlands area.

Conclusions

1. The Appalachian Region (with the exception of the Maritime Plain), the Canadian Shield Region, the Cordilleran Region, and the Innuitian Region (with the possible exception of parts of the Sverdrup Basin) have no real potential for *safe* underground disposal of industrial liquid waste.

2. In the Maritime Plain the Mississippian Windsor Group may present some opportunities for *safe* disposal of liquid industrial wastes. The same could apply to some Permo-Pennsylvanian strata in deeper parts of the basin.

3. On Anticosti Island (East St. Lawrence Lowland) the Ordovician Romaine and Mingan Formations could have limited disposal potential.

4. In the Central St. Lawrence Lowland the Cambrian Nepean Formation may be suitable for disposal of limited amounts of liquid industrial wastes in the central part of the Ottawa Embayment. The Potsdam Formation in the Quebec Basin also holds potential. In the deeper part of the Quebec Basin some of the sandstones and carbonate rocks of Lower and Middle Ordovician may present additional opportunities.

5. In the West St. Lawrence Lowland the Cambrian Mount Simon and Potsdam sandstones are potential disposal formations in Lincoln and Lambton Counties, and probably also in Essex County. Further potential may locally be available in the Silurian Guelph Formation, and in caverns in the salt beds of the Silurian Salina Formation. Presence of large numbers of uncharted, unplugged old drill holes, as well as shallow depth and proximity to outcrops, make most of the Devonian Detroit River Group (used at present for waste disposal) unsuitable for *safe* underground disposal of liquid industrial wastes.

6. In the Hudson Bay Lowland limited information indicates that some potential for underground disposal of wastes may exist in the Ordovician Portage Chute sandstone and in carbonate rocks of the Silurian Attawapiskat Formation. The Lower Devonian, Sextant Formation may have some potential in the southern portion of the Moose River Basin.

7. In the Interior Plains Region potential for *safe* subsurface disposal of industrial liquid wastes exists in the sandstones of the Cambrian Deadwood and the Ordovician Winnipeg Formation; in carbonate rocks of the Silurian Interlake Group and the Devonian Nisku and Leduc Formations; in sandstones of the Cretaceous Blairmore and Viking Formations; and in the equivalents of any of these. In parts of the region the adequacy of confining beds for formations overlying the Prairie Evaporite or other evaporite beds may have been adversely affected by fracturing, brecciation, subsidence or collapse resulting from leaching of the evaporites. In such areas waste injection should be restricted to the section below the evaporite beds. Injection of liquid wastes other than formation water produced with hydrocarbons should not be permitted in Upper-Cretaceous or Tertiary formations, nor in the older formations where they contain water with less than 10,000 mg/l of total dissolved solids (e.g., in southwestern Saskatchewan).

8. In the Arctic Coastal Plain and the Sverdrup Lowland limited potential for underground disposal of liquid wastes may exist in the sandstones of the Lower Cretaceous Isachsen Formation, and in older sandstones and dolomites, wherever shales of the Savik, Deer Bay, Christopher or Kanguk Formations are present in sufficient thickness and extent to form adequate confining beds.

9. Waste injection operations should not be undertaken in any of the potential disposal regions until extensive, detailed investigation have established that *safe* subsurface disposal of industrial liquid wastes is indeed possible.

10. It should be stressed again here that greater efforts should be directed towards finding alternative methods of waste water treatment, recycling, recovery of valuable components, and changes in plant process that may reduce or even eliminate the waste disposal problem. This requirement, however, does not apply to waters produced in connection with hydrocarbon production.

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TABLE II

Eon / Era / Period / Series	Stage	Time-Rock M.Y.	Appalachian Orogenies	ST. LAWRENCE PLAT. (EAST.) — ANTICOSTI BASIN — GULF OF ST. LAWRENCE — ANTICOSTI AND MINGAN ISLANDS (30)
Phanerozoic / Cenozoic / Quaternary	RECENT			erosion / alluvium
Phanerozoic / Cenozoic / Quaternary	PLEISTOCENE	1.5 - 2		marine clay / Laurentide drift
Cenozoic / Tertiary / Neogene	PLIOCENE	7		
Cenozoic / Tertiary / Neogene	MIOCENE	26		
Cenozoic / Tertiary / Paleogene	OLIGOCENE	37-38		
Cenozoic / Tertiary / Paleogene	EOCENE	53-54		
Cenozoic / Tertiary / Paleogene	PALEOCENE	65		
Mesozoic / Cretaceous / Lower	ALBIAN	100 / 106		
Mesozoic / Cretaceous / Lower	APTIAN	112		diabase dyke cuts VAURÉAL KArR 138
Mesozoic / Cretaceous / Lower / Neocomian	BARREMIAN	118		
Mesozoic / Cretaceous / Lower / Neocomian	HAUTERIVIAN	124		
Mesozoic / Cretaceous / Lower / Neocomian	VALANGINIAN	130		
Mesozoic / Cretaceous / Lower / Neocomian	BERRIASIAN	136		
Mesozoic / Jurassic / Upper	UPPER TITHONIAN / UPPER VOLGIAN	141		uplift, erosion normal faulting during Jurassic-Cretaceous
Mesozoic / Jurassic / Upper	PORTLANDIAN / LOWER VOLGIAN	146		
Mesozoic / Jurassic / Upper	KIMMERIDGIAN	151		
Mesozoic / Jurassic / Upper	OXFORDIAN	157		
Mesozoic / Jurassic / Middle	CALLOVIAN	162		
Mesozoic / Jurassic / Middle	BATHONIAN	167		
Mesozoic / Jurassic / Middle	BAJOCIAN	172		
Mesozoic / Jurassic / Lower	TOARCIAN	178		
Mesozoic / Jurassic / Lower	PLIENSBACHIAN	183		
Mesozoic / Jurassic / Lower	SINEMURIAN	188		
Mesozoic / Jurassic / Lower	HETTANGIAN	190-195		
Paleozoic / Silurian	CAYUGAN	395		
Paleozoic / Silurian / Niagaran	LUDLOVIAN			
Paleozoic / Silurian / Niagaran	WENLOCKIAN			CHICOTTE limestone .07
Paleozoic / Silurian / Niagaran	LLANDOVERIAN			JUPITER limestone .65; GUN RIVER ls .3-.34; BECSCIE limestone .27
Paleozoic / Silurian	ALEXANDRIAN	430-440	TACONIAN OROGENY	
Paleozoic / Ordovician / Upper / Cincinnatian	RICHMONDIAN / ASHGILLIAN		TACONIAN OROGENY	ELLIS BAY ls .27; VAURÉAL
Paleozoic / Ordovician / Upper / Cincinnatian	MAYSVILLIAN		TACONIAN OROGENY	ENGLISH HEAD ls, sh 2.6
Paleozoic / Ordovician / Upper / Cincinnatian	EDENIAN		TACONIAN OROGENY	MACASTY black shale .2
Paleozoic / Ordovician / Middle / Mohawkian	BARNEVELD / CARADOCIAN		TACONIAN OROGENY	limestone
Paleozoic / Ordovician / Middle / Mohawkian	WILDERNESS		TACONIAN OROGENY	? .5+
Paleozoic / Ordovician / Middle / Mohawkian	PORTERFIELD	445	TACONIAN OROGENY	
Paleozoic / Ordovician / Middle / Chazyan	ASHBY / LLANDEILIAN			MINGAN ls, sh, cg .16-.7
Paleozoic / Ordovician / Middle / Chazyan	MARMOR, WHITEROCK / LLANVIRNIAN			gentle uplift, warping
Paleozoic / Ordovician / Lower	CANADIAN / ARENIGIAN	500±		ROMAINE dol .26-1.2
Paleozoic / Ordovician / Lower	CANADIAN / TREMADOCIAN			
Paleozoic / Cambrian / Upper	TREMPEALEAUAN			
Paleozoic / Cambrian / Upper	FRANCONIAN			
Paleozoic / Cambrian / Upper	DRESBACHIAN	515		
Paleozoic / Cambrian / Middle	ALBERTAN	540		
Paleozoic / Cambrian / Lower	WAUCOBAN	570		
Proterozoic / Hadrynian			AVALONIAN OROGENY	
Proterozoic / Helikian / Neohelikian	GRENVILLIAN	955	GRENVILLIAN OROGENY	crystalline rocks of various ages folded and metamorphosed during Grenvillian and older orogenies
Proterozoic / Helikian / Paleohelikian	ELSONIAN	1370		
Proterozoic / Aphebian	HUDSONIAN	1735		
Archean	KENORAN	2480		

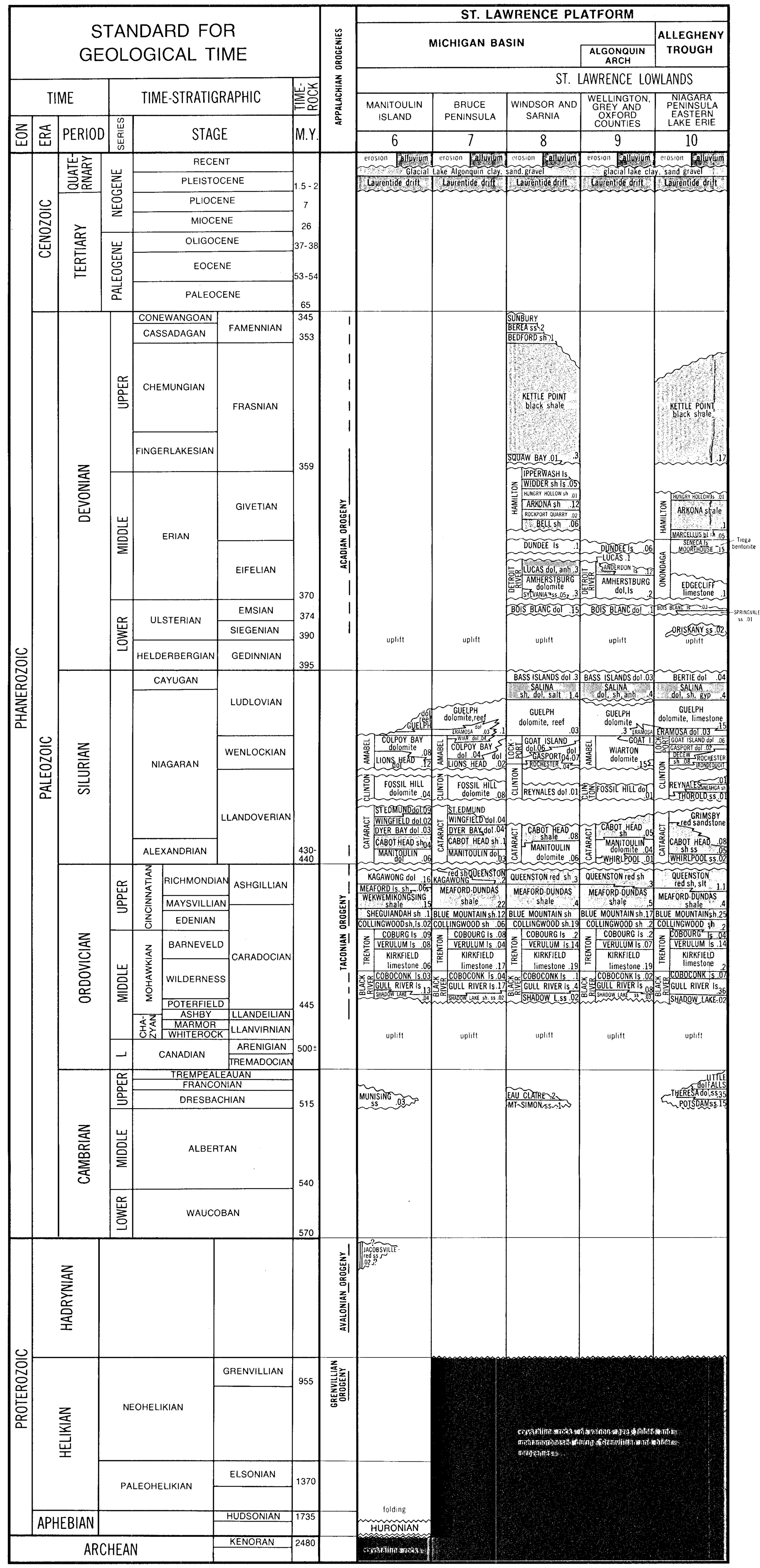
SEE LEGEND ON TABLE VI

TABLE III

Eon / Era / Period / Series	Stage	Time-Rock M.Y.	Appalachian Orogenies	ST. LAWRENCE PLAT. (CENT.) — QUEBEC BASIN — OTTAWA EMBAYMENT — ST. LAWRENCE LOWLANDS: OTTAWA (11)	MONTREAL (12)	TROIS RIVIÈRES - PORTNEUF (16)
Phanerozoic / Cenozoic / Quaternary	RECENT			alluvium	alluvium	alluvium
Phanerozoic / Cenozoic / Quaternary	PLEISTOCENE	1.5 - 2		Champlain Sea clay, sand / Laurentide drift	Champlain Sea clay, sand / Laurentide drift	marine clay / Laurentide drift
Cenozoic / Tertiary / Neogene	PLIOCENE	7				
Cenozoic / Tertiary / Neogene	MIOCENE	26				
Cenozoic / Tertiary / Paleogene	OLIGOCENE	37-38				
Cenozoic / Tertiary / Paleogene	EOCENE	53-54				
Cenozoic / Tertiary / Paleogene	PALEOCENE	65				
Mesozoic / Cretaceous / Lower	ALBIAN	100 / 106				
Mesozoic / Cretaceous / Lower	APTIAN	112			MONTEREGIAN INTRUSIONS syenite, essexite KArB110RbSrB99111	
Mesozoic / Cretaceous / Lower / Neocomian	BARREMIAN	118				
Mesozoic / Cretaceous / Lower / Neocomian	HAUTERIVIAN	124			normal faulting NE and uplift of Beauharnois Arch	
Mesozoic / Cretaceous / Lower / Neocomian	VALANGINIAN	130				
Mesozoic / Cretaceous / Lower / Neocomian	BERRIASIAN	136				
Mesozoic / Jurassic / Upper	UPPER TITHONIAN / UPPER VOLGIAN	141				uplift, erosion, normal faulting
Mesozoic / Jurassic / Upper	PORTLANDIAN / LOWER VOLGIAN	146				
Mesozoic / Jurassic / Upper	KIMMERIDGIAN	151				
Mesozoic / Jurassic / Upper	OXFORDIAN	157				
Mesozoic / Jurassic / Middle	CALLOVIAN	162				
Mesozoic / Jurassic / Middle	BATHONIAN	167				
Mesozoic / Jurassic / Middle	BAJOCIAN	172				
Mesozoic / Jurassic / Lower	TOARCIAN	178				
Mesozoic / Jurassic / Lower	PLIENSBACHIAN	183				
Mesozoic / Jurassic / Lower	SINEMURIAN	188				
Mesozoic / Jurassic / Lower	HETTANGIAN	190-195				
Paleozoic / Devonian / Lower	ULSTERIAN / EMSIAN	370 / 374				
Paleozoic / Devonian / Lower	ULSTERIAN / SIEGENIAN	390			limestone blocks in diatreme breccia	
Paleozoic / Devonian / Lower	HELDERBERGIAN / GEDINNIAN	395	TACONIAN OROGENY			
Paleozoic / Ordovician / Upper / Cincinnatian	RICHMONDIAN / ASHGILLIAN	430-440	TACONIAN OROGENY	QUEENSTON red sh .04; RUSSELL ls .04	BÉCANCOUR R. sh 2.0; PONTGRAVÉ R. ls .19	BÉCANCOUR R. sh; PONTGRAVÉ R. ls .16
Paleozoic / Ordovician / Upper / Cincinnatian	MAYSVILLIAN		TACONIAN OROGENY	CARLSBAD shale .6; BILLINGS black sh .17	NICOLET RIVER sh 2+; LACHINE sh .3	NICOLET R. sh, sl, ss 2; LOTBINIÈRE sh .26
Paleozoic / Ordovician / Upper / Cincinnatian	EDENIAN		TACONIAN OROGENY	EASTVIEW sh, ls .02	UTICA	
Paleozoic / Ordovician / Middle / Mohawkian	BARNEVELD / CARADOCIAN		TACONIAN OROGENY	TRENTON: COBOURG ls .18; SHERMAN FALL ls .05; HULL ls .18; ROCKLAND ls .06	TRENTON: TETREAUVILLE .5 sh 1; MONTREAL .04-.37; DECHAMBAULT ls .3; QUAREAU ls .02	TRENTON: NEUVILLE limestone .47; ST. CASIMIR DESCHAMBAULT ls; PONT ROUGE ls .03
Paleozoic / Ordovician / Middle / Mohawkian	WILDERNESS		TACONIAN OROGENY	BLACK RIVER: LERAY ls .07; LOWVILLE ls .16; PAMELIA ls, sh .07	BLACK RIVER: LERAY ls .02; LOWVILLE ls .04; PAMELIA	LERAY ls; LOWVILLE ls; BLACK RIVER
Paleozoic / Ordovician / Middle / Mohawkian	PORTERFIELD	445	TACONIAN OROGENY			
Paleozoic / Ordovician / Middle / Chazyan	ASHBY / LLANDEILIAN					LAVAL ss
Paleozoic / Ordovician / Middle / Chazyan	MARMOR, WHITEROCK / LLANVIRNIAN			ROCKCLIFFE ss .25; uplift	LAVAL ls, ss, sh .3; uplift	gentle uplift
Paleozoic / Ordovician / Lower	CANADIAN / ARENIGIAN	500±		OXFORD dol .41	BEAUHARNOIS dol 1	BEAUHARNOIS dolomite
Paleozoic / Ordovician / Lower	CANADIAN / TREMADOCIAN			MARCH ss, dol .03	MARCH ss, dol .25	MARCH dol, ss
Paleozoic / Cambrian / Upper	TREMPEALEAUAN			NEPEAN ss 1.1+	POTSDAM sandstone 2	POTSDAM ss .5
Paleozoic / Cambrian / Upper	FRANCONIAN					
Paleozoic / Cambrian / Upper	DRESBACHIAN	515				
Paleozoic / Cambrian / Middle	ALBERTAN	540				
Paleozoic / Cambrian / Lower	WAUCOBAN	570				
Proterozoic / Hadrynian			AVALONIAN OROGENY			
Proterozoic / Helikian / Neohelikian	GRENVILLIAN	955	GRENVILLIAN OROGENY	gneiss, gabbro, and granite of various pre-Hadrynian ages folded and metamorphosed during Grenvillian and older orogenies		
Proterozoic / Helikian / Paleohelikian	ELSONIAN	1370				
Proterozoic / Aphebian	HUDSONIAN	1735				
Archean	KENORAN	2480				

SEE LEGEND ON TABLE VI

TABLE IV



SEE LEGEND ON TABLE VI

TABLE V

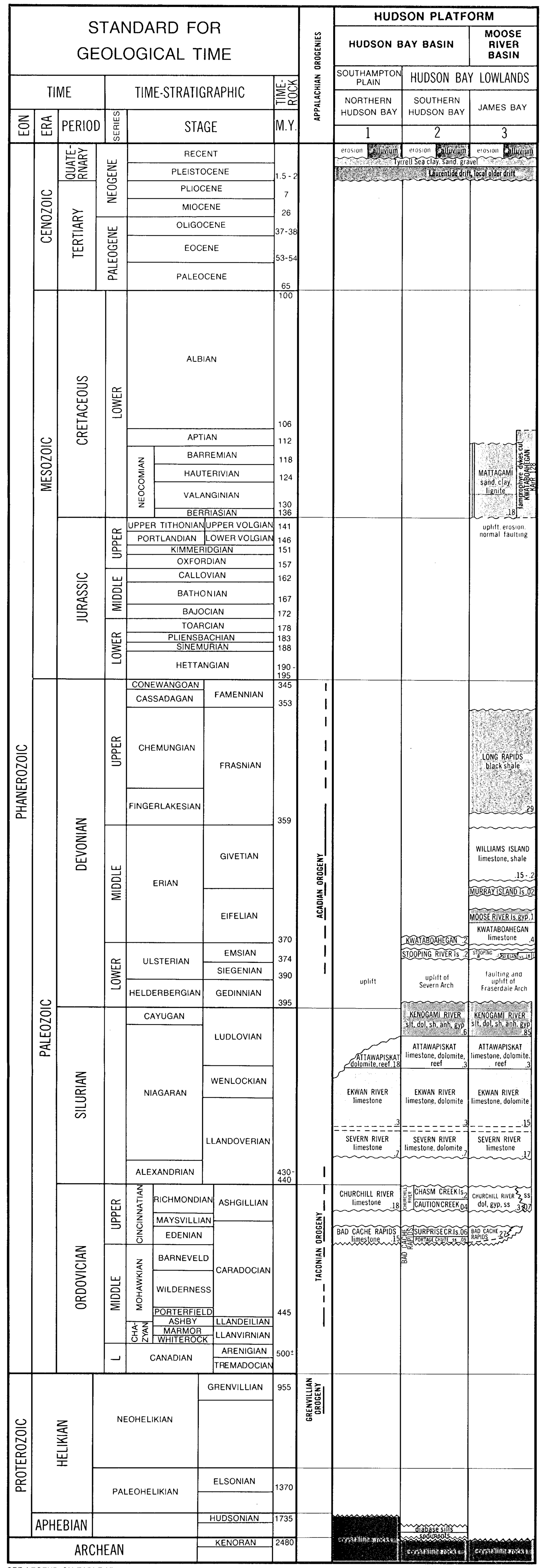


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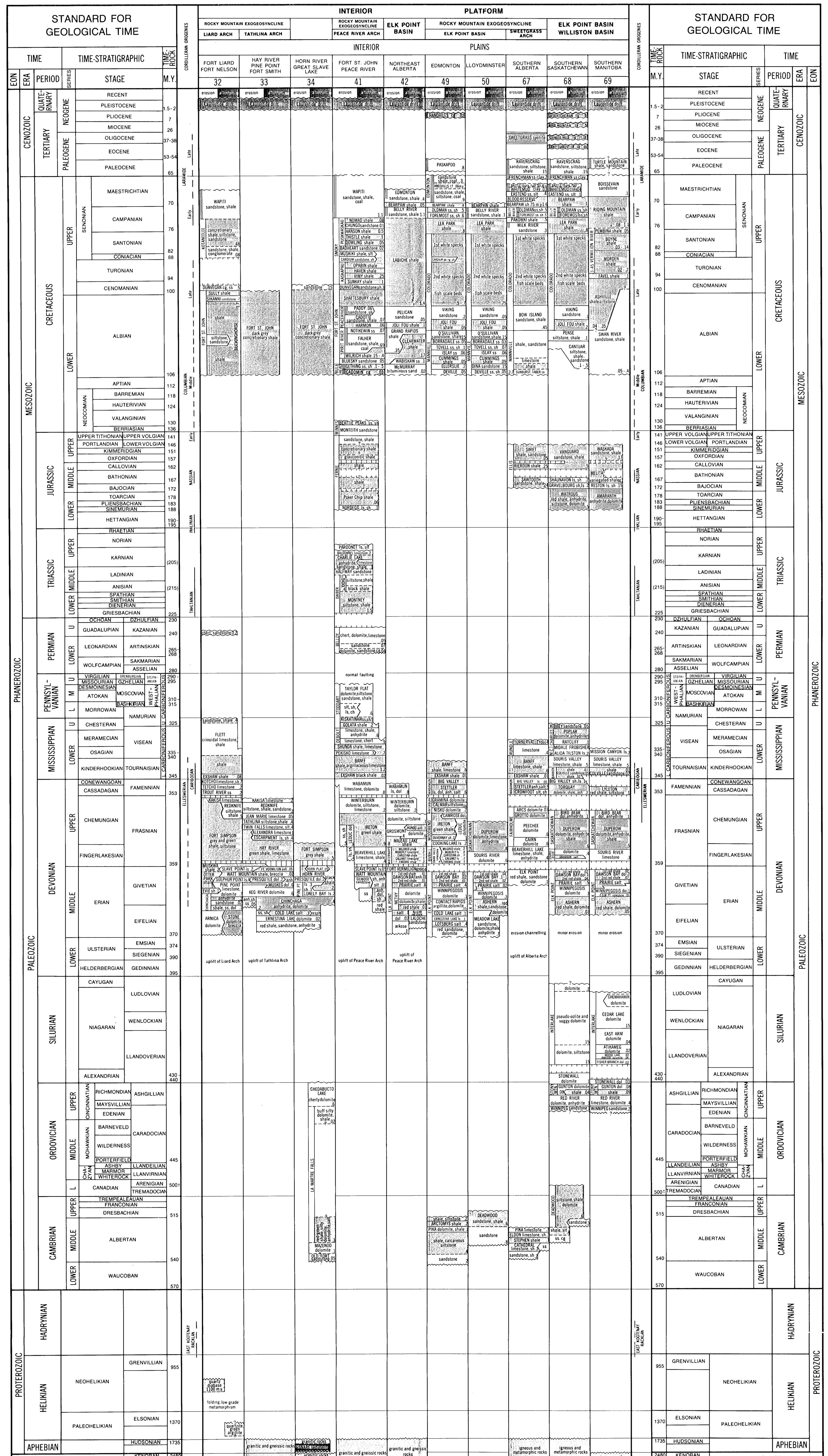
TABLE VI



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