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ONTARIO GEOLOGICAL SURVEY

Open File Report 5817

Stratigraphy and Oil Shale Resource Potential of the Upper Ordovician Collingwood Member, Lindsay Formation, Southwestern Ontario

By

P.L. Churcher, M.D. Johnson, P.G. Telford and J.F. Barker

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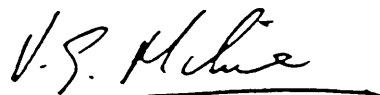
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V.G. Milne, Director
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Map 1B:	Data and subcrop map, Collingwood Member, Lindsay Fm. - Northeast sheet.
Map 1C:	Data and subcrop map, Collingwood Member, Lindsay Fm. - Southwest sheet.
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MAP SET 2

Map 2A:	Isopach map, Collingwood Member, Lindsay Fm. - Northwest sheet.
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ABSTRACT

The Upper Ordovician Collingwood Member of the Lindsay Formation is one of four potential oil shales that were studied by the Ontario Geological Survey as part of the Hydrocarbon Energy Resources Program (HERP).

This rock unit is a finely laminated, black, organic-rich marlstone which rests conformably on older limestones and dolostones of the Lindsay Formation. It is overlain by the siliceous shales of the Blue Mountain Formation. The contact between the Collingwood Member and the overlying Blue Mountain Formation is frequently marked by the presence of a phosphatic bed of variable thickness. The Collingwood Member can be easily identified in cuttings or core by its rich black colour, high calcite and bitumen content, and characteristic fauna (mainly trilobites and graptolites). The Collingwood Member can be readily identified in the subsurface using a gamma log. The increase in calcite content with depth results in a gamma log response which indicates a shale at the top of the Collingwood Member and a carbonate at the bottom.

Several organic geochemistry and petrographic analyses were performed on sample material obtained from the Collingwood Member. These analyses were performed to evaluate the economic potential of the unit, and included: Total Organic Carbon, Yield on Pyrolysis, Fisher Assay, Rock-Eval and HYTORT Pyrolysis, Elemental Analysis, and Organic Petrography. The results indicate that the kerogen within these rocks is present in sufficient quantities to yield between 14.6 to 30 L/tonne (0.08 to 0.38 barrels/ton) of shale oil. The oil shale potential of the unit appears to be greatest on Manitoulin and St. Joseph islands, and on the mainland at Collingwood.

A preliminary estimate of the total potential shale oil reserves that are contained in the Collingwood Member is approximately $8.8 \times 10^{12} \text{ m}^3$ (5.5×10^{13} barrels). This number represents an estimate of the potential shale oil reserves, and is by no means an indication of the recoverable reserves.

It is unlikely that the commercial extraction of shale oil from these rocks will be economically feasible due to current oil prices, land restrictions, and high extraction and refining costs. In addition, the unit is relatively thin and much of it lies at depths which are not amenable to either surface mining or *in situ* retorting.

The organic content and level of organic maturity make the Collingwood Member a potential source rock for oil and gas in the subsurface. Its limited areal extent and lack of known commercially viable accumulations of hydrocarbons, however, make it unlikely that it is the primary source of the hydrocarbons found within the Lindsay Formation.

**ONTARIO GEOLOGICAL SURVEY
Open File Report**

**Stratigraphy and Oil Shale Resource
Potential of the Upper Ordovician Collingwood Member,
Lindsay Formation, Southwestern Ontario**

by

P.L. Churcher¹
M.D. Johnson²
P.G. Telford³
J.F. Barker⁴

¹Geological Consultant, 51 Hawkhill Way NW, Calgary, Alberta T3G 3K1

²Supervisor, Paleozoic/Mesozoic Geology Subsection, Engineering and Terrain Geology Section, Ontario Geological Survey

³Senior Advisor, Intergovernmental Relations Office, Ministry of the Environment

⁴Department of Earth Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1

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1. INTRODUCTION

1.1 Program Review

Evaluation of the hydrocarbon resource potential of oil shales in Ontario was a project of the Hydrocarbon Energy Resources Program (HERP). This 5 year program, initiated in 1981, was funded by the Ontario Ministry of Treasury and Economics.

Development of HERP was in response to an Ontario government decision, made in 1979, that the province should endeavour to raise its energy self-sufficiency from the then current level of 23%. A target of 37.5% energy self-sufficiency by 1995 was established. As part of the 1979 decision, the Ontario Geological Survey was given the mandate to carry out an inventory of the province's hydrocarbon energy resources and to determine the contribution that these resources could make to greater energy self-sufficiency.

HERP consisted of four major components corresponding to the four types of hydrocarbon deposits known to be present in the province. The Ontario Geological Survey was responsible for conducting inventories and evaluations of peat, lignite and oil shale resources. The Petroleum Resources Section (Ontario Ministry of Natural Resources) reviewed the province's reserves and potential resources of conventional oil and natural gas.

These wide-ranging, multi-faceted activities were carried out through a combination of provincial government surveys, university-based research projects and studies contracted to private geological and engineering consulting firms. In addition, close liaison was maintained with relevant departments of the federal government, and other provincial governments, to facilitate vital information exchange and co-operative ventures. Overall management and co-ordination of the program and dissemination of results were the responsibility of the Ontario Geological Survey.

This report is one of four final reports dealing with the component of HERP that became known as the Oil Shale Assessment Project. The principal objective of this project was to determine the hydrocarbon resource potential of the oil shales in Ontario. This was the most comprehensive study of specific oil shale resources conducted to date in Canada.

1.2 Oil Shale Assessment Project

Four Paleozoic stratigraphic units in Ontario may be classified as oil shales and were investigated as part of the Oil Shale Assessment Project (Table 1). The initial phase

FORMATION	AGE	LOCATION
Collingwood Member	Upper Ordovician	South-central Ontario, Manitoulin Island and St. Joseph Island
Marcellus	Middle Devonian	Southwestern Ontario
Kettle Point	Upper Devonian	Southwestern Ontario
Long Rapids	Upper Devonian	James Bay Lowland

Table 1. Paleozoic oil shales of Ontario investigated by the Ontario Geological Survey.

of the project (1981–1982) included an intensive study of the Upper Ordovician rock unit commonly termed the Collingwood shale, but now formally defined as the Collingwood Member of the Lindsay Formation (Russell and Telford 1983). In 1982, similar investigations were undertaken on the Devonian Marcellus and Kettle Point formations of southwestern Ontario. The project was expanded, in 1984, to involve detailed stratigraphic study and assessment of the Upper Devonian Long Rapids Formation in the Moose River Basin (James Bay Lowland).

The data gathering activities for the three southern Ontario oil shales followed a similar pattern, however, geographical and logistical constraints necessitated a somewhat different approach to evaluation of the Long Rapids Formation (Russell and Telford 1984). Data for the southern Ontario units were obtained mainly through outcrop examination, considerable diamond drilling and organic geochemical analysis of selected samples. In addition, specialized sedimentological and paleontological studies of key stratigraphic intervals were undertaken (e.g., Tuffnell and Ludvigsen 1984; Harris 1985), and the inorganic geochemistry and physical properties of particular units were also considered (e.g., Delitala 1984; Dusseault and Loftsson 1985).

Outcrops of the southern Ontario oil shales are meagre; the Marcellus Formation is completely buried by Pleistocene glacial and glaciolacustrine sediments. Also, where present, outcrops of the Collingwood Member and Kettle Point Formation are of only limited lateral and vertical extent. Complete sections through these units are nowhere exposed and upper and lower contacts rarely appear in outcrop. Therefore, considerable efforts were made to obtain subsurface data to supplement the surface information. Over

60 shallow drill holes (aimed at specific stratigraphic intervals) and 12 deep drill holes (extending from surface to the Precambrian basement) were completed in southern Ontario and on Manitoulin, Cockburn, and St. Joseph islands in northern Lake Huron. All holes were fully cored and geophysically logged. Over 9000 m of core was generated. Drilling and geophysical data has been released in a series of Ontario Geological Survey Open File Reports (Johnson 1983, 1985; Johnson et al. 1983a,b, 1985).

Approximately 2000 core samples were selected from the oil shale intervals for hydrocarbon analysis. They were analyzed for Total Organic Carbon (TOC) by rapid pyrolysis methods developed at the University of Waterloo under the direction of Dr. J.F. Barker (Appendix 1). A number of the samples were also subjected to Fischer Assays, the traditional method of oil yield determination for oil shales, to establish correlation between this and the rapid pyrolysis method (Stromquist et al. 1984).

Samples from the Collingwood Member and Kettle Point Formation were supplied to the Institute of Sedimentary and Petroleum Geology (ISPG) in Calgary for appraisal by the Rock-Eval pyrolysis method (Snowdon 1984). Several samples of the Collingwood Member were given to CANMET (Ottawa) for testing in the hydrogen retorting system under development by the New Brunswick Research and Productivity Council. Several samples from the Kettle Point Formation were also analyzed by the Institute of Gas Technology (IGT) in Chicago using their patented HYTORT (R) method. A total of 50 thin sections was prepared from samples of the Lindsay Formation, Collingwood Member and Blue Mountain Formation for petrographic analysis (Appendix 2).

This report describes the stratigraphy, distribution, and hydrocarbon resource potential of the Collingwood Member of the Lindsay Formation.

1.3 Oil Shale Concepts and Definitions

An "oil shale" is not necessarily a shale and it does not contain oil in the same sense as conventional oil deposits. Because usage of the term arose long before there was understanding of the geological nature of the deposits in question, or of the character of the organic components in the rocks, "oil shale" has been one of the most loosely defined geological terms (Macauley 1984). Clarification of this situation is provided by Macauley (1984) and Macauley et al. (1985). Their definition of oil shale, which has been used in the Ontario Geological Survey investigations, is as follows:

"Oil shale is a fine grained, sedimentary rock, containing indigenous organic matter that is mainly insoluble in ordinary petroleum solvents, and from which significant amounts of shale oil can be extracted by pyrolysis (i.e., heating in a retort)."

Several of the terms in this definition require further explanation. For example, the phrase "significant amounts" is somewhat open-ended, but justification of its use is described by Macauley et al. (1985, p.2) as follows:

"The temperature of pyrolysis [of oil shales] seldom exceeds 500 to 600°C as, above these temperatures, additional yield of shale oil is low, and breakdown occurs for some of the inorganic rock constituents, especially dolomite. The energy necessary to raise the rock temperature to 500°C is approximately 150 calories/gram of rock. The heat value of the indigenous organic material is generally 10 000 calories/gram; therefore 2.5% by weight is the minimum organic content at which the amount of energy recovered as shale oil could theoretically balance the input energy. This value, then, becomes the minimum organic content needed to define an oil shale, but does not allow for other energy-equivalent input (mining, transportation, etc.). U.S. literature often quotes 10 US gallons/ton (42 litres/tonne) as a minimum shale oil yield for economic consideration, but this is an arbitrary value."

The indigenous organic matter of oil shale is mainly kerogen. This is a solid organic material, insoluble in normal organic solvents, which on heating and decomposition produces shale oil. The nature of kerogen, as determined by geochemical analysis and petrological examination, is commonly used as the basis for oil shale classification schemes (e.g., Macauley et al. 1985).

Tissot and Welte (1978) divided kerogen into three types based on atomic hydrogen/carbon ratios. Type I ($H/C > 1.4$) is derived from algae and is commonly a non-marine deposit; Type II ($H/C < 1.4$ to 1.2) is derived from phytoplankton and is marine; Type III ($H/C < 1.0$) is derived from higher land plants. Types I and II can produce oil shale while Type III produces coal. Despite these apparently simple subdivisions, kerogens can display considerable variation from deposit to deposit and between different stratigraphic levels and geographic zones in a single deposit.

Shale oil is the product of pyrolysis of oil shale and should not be confused with crude oil (petroleum) obtained from conventional sources. The character of shale oil depends on the type and composition of the kerogen from which it is derived but it will always be an undersaturated (i.e., hydrogen-depleted) hydrocarbon. Therefore, shale oil will always require further refining (i.e., hydrogenation) to produce a petroleum equivalent to that from conventional oil reservoirs (Macauley 1984).

There is some confusion in the literature with regard to descriptive terms commonly applied to shales and other rocks with an organic constituent. The terms,

bituminous, petroliferous, kerogenous and carbonaceous, are often used incorrectly. The following guidelines should be noted:

- **Petroliferous** rocks are those containing a liquid petroleum phase;
- **Bituminous** rocks contain soluble solid hydrocarbon;
- **Kerogenous** rocks contain insoluble organic material (i.e. kerogen); and
- **Carbonaceous** rocks contain organic carbon and minimal hydrogen content denoting the presence of higher plant remains.

2. PALEOZOIC GEOLOGY OF SOUTHERN ONTARIO

2.1 Structural and Paleogeographic Setting

Paleozoic strata form the bedrock of two discrete parts of southern Ontario, each of which has its own distinctive structural style and paleogeographic history. In southeastern Ontario, east of the Frontenac Axis, Lower to Middle Ordovician sandstones, shales and carbonate rocks underlie the physiographic region known as the Ottawa–St. Lawrence Lowland (Figure 1). West of the Frontenac Axis and south of the Precambrian Shield, in south-central and southwestern Ontario, Upper Cambrian to Upper Devonian strata underlie an area of approximately 70 000 km² forming part of the Great Lakes–St. Lawrence Lowland. Manitoulin, Cockburn, and St. Joseph islands in

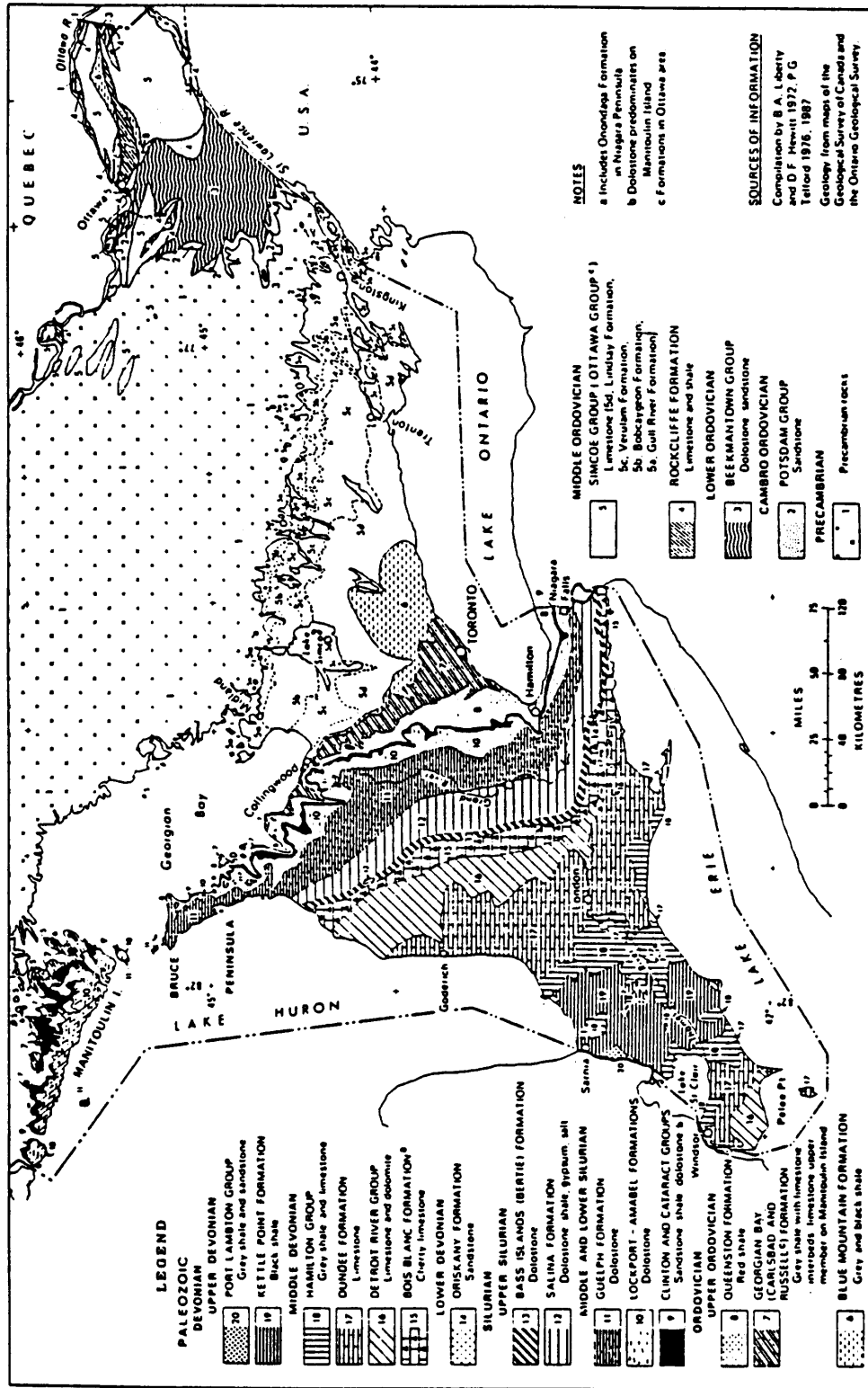


Figure 1. Paleozoic geology of southern Ontario. The Niagara Escarpment is delineated by the Clinton and Cataract Groups (black pattern, No. 9).

northern Lake Huron, which are underlain by Ordovician and Silurian strata, are also included in this geological-physiographic unit (Figure 1).

Ottawa–St. Lawrence Lowland

The Ordovician sediments of the Ottawa–St. Lawrence Lowland were deposited in a relatively narrow embayment extending northwestward from the northern Appalachian Basin. Unlike the strongly folded, lithologically diverse strata of the Appalachian Basin which were formed in a tectonically active continental margin environment, the strata in the Ottawa–St. Lawrence Lowland are generally flat-lying and of comparatively uniform composition. They were formed in a stable shallow shelf environment mainly unaffected by Paleozoic orogenic episodes. However, during the Late Mesozoic, tectonic activity associated with the opening of the Atlantic Ocean produced block faulting along a structure termed the Ottawa–Bonnechere Graben. The trend of this feature essentially paralleled the original depositional embayment although the block faulting of the Ordovician strata was most severe in the northern part of the Ottawa–St. Lawrence Lowland, along the present valley of the Ottawa River.

Mapping by the Ontario Geological Survey in this area has provided a clearer picture of the stratigraphic sequence and structural patterns (Williams and Wolf 1982; Williams and Rae 1983; Williams 1991). Ordovician strata up to 1130 m thick is present. Steeply dipping normal faults and fault zones are common and some have up to 900 m of vertical displacement. Bedding is normally close to horizontal and steep dips only occur in close proximity to faults and within fault zones.

Limited attention was given to the oil shale resource potential of this region. The Eastview Member (Lindsay Formation) and Billings Formation are Upper Ordovician black shales which outcrop and subcrop beneath surficial deposits in several small areas east of Ottawa (Williams et al. 1984). Initially, the Eastview Member was of particular interest to the Oil Shale Assessment Project as the unit is correlative with, and lithologically similar to the Collingwood Member (Lindsay Formation) of southwestern Ontario (Russell and Telford 1983). However, preliminary organic geochemical analyses of core samples from the Eastview and Billings were discouraging. The apparently rich organic content of the shales was over-mature and potential oil yields correspondingly low (Johnson 1982). This was probably the result of the intense Late Mesozoic igneous intrusion and tectonism in the region.

Great Lakes–St. Lawrence Lowland

The Upper Cambrian to Upper Devonian stratigraphic succession of south-central and southwestern Ontario contains a variety of platform deposits formed in a shallow epi-continental sea. The geology appears to be simple: apparently flat-lying carbonate, clastic and evaporitic units displaying little evidence of severe structural disturbances. However, deposition of these units took place in and around three major paleogeographic elements (Figure 2):

- (a) Appalachian Basin, an elongate, northeast-trending, clastic-dominated foreland basin centred primarily in the northeastern part of the United States, extending some 1400 km from Alabama to the Niagara Peninsula in Ontario;

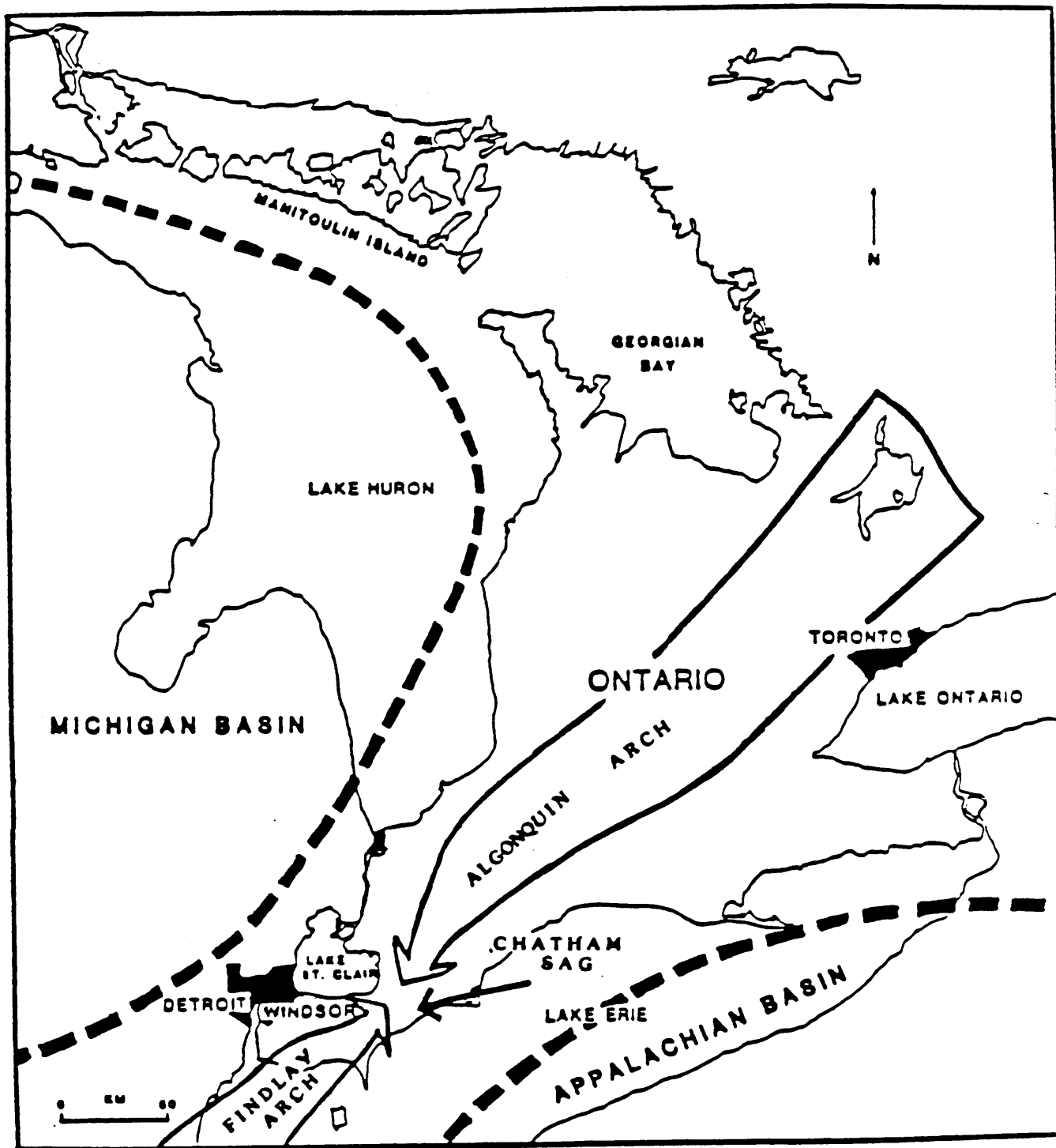


Figure 2. Major structural and paleogeographic elements in southern Ontario.

- (b) Algonquin Arch, a broad basement ridge forming the spine of the southwestern Ontario peninsula. The arch is a northeastern extension of the Findlay Arch and, throughout the Paleozoic, acted as a hinge line between the Appalachian and Michigan basins;
- (c) Michigan Basin, a roughly circular, carbonate-dominated intracratonic basin (roughly 650 km in diameter) centred on the peninsula of Michigan and whose eastern rim approximates the axis of the Algonquin Arch.

The Algonquin Arch trends in a southwest direction across southern Ontario, forming a broad positive lineament from which the overlying Paleozoic strata dip westward into the Michigan Basin or southward into that part of the Appalachian Basin which is commonly termed the Allegheny Trough (Winder and Sanford 1972). Within the central Michigan Basin the Paleozoic strata reach a maximum thickness of about 4300 m. Within the Appalachian Basin, in Pennsylvania and West Virginia, the Paleozoic sequence is up to 6700 m in thickness. In contrast, the maximum thickness of Paleozoic strata in southwestern Ontario (at the southern end of Lake Huron) is about 1525 m (Winder and Sanford 1972).

The Findlay Arch (Figure 2) trends obliquely to the Algonquin Arch, extending through western Ohio, southeastern Indiana, and into the extreme western part of southern Ontario. The two arches are separated by the Chatham Sag (Figure 2), which is a locally developed broad depression within which the Paleozoic strata are generally horizontal. Away from the Chatham Sag and the crests of the two arches, Paleozoic

strata have a consistent regional dip of 5.5 to 8.5 m/km into the Michigan Basin or Appalachian Basin (Winder and Sanford 1972).

Upper Cambrian and Lower Ordovician strata of the initial Paleozoic marine transgression in the southern Ontario region terminate along the southeastern flank of the Algonquin Arch. This, together with the onlap and overlap of subsequent Middle Ordovician carbonates over the arch, confirms that the arch was a positive topographic feature in early Paleozoic time. The arch apparently maintained its positive nature, to varying degrees, throughout much of Paleozoic time and had considerable influence, in particular, on deposition of the Devonian units of southwestern Ontario. Consequently, the Paleozoic sequence is complicated by major facies changes as strata typical of the Appalachian Basin interfinger with strata typical of the Michigan Basin in complex onlap-offlap patterns over the Algonquin Arch and through the Chatham Sag.

Recently, a more complicated picture of the structural geology of the Paleozoic strata of southwestern Ontario has emerged. This region has long been considered to be tectonically inactive and to have undergone very little structural disturbance during its geological history. Thus, very little attention has been given to the occurrence or significance of faults and fracture systems within the Paleozoic strata. However, using modern Landsat imagery, data on major and minor earthquake distribution and conventional subsurface information (which is abundant for many areas in southwestern Ontario), combined with current theories of plate tectonics, Sanford et al. (1985) have developed a new interpretation for the structural geology of the Paleozoic sequence in the region. They suggest that broad segments of the craton, underlying such areas as the

Michigan Basin, were in intermittent motion through most of the Paleozoic and that some segments (e.g., Algonquin Arch region) are still mildly tectonically active. They further suggest that basement arch movements and basin development in southwestern Ontario and adjacent areas may have been influenced by crustal plate motions and associated orogenic activity centred at or beyond the actual margins of the craton.

In the light of these interpretations, re-examination of surface and subsurface stratigraphic data from southwestern Ontario has led to a new detailed picture of probable faults and fracture systems within the Paleozoic succession (Sanford et al. 1985). Southwestern Ontario is considered to occupy parts of two fault blocks: the Bruce and Niagara megablocks (Figure 3). The boundary between the blocks is approximately coincident with the Algonquin Arch. The Bruce megablock was interpreted by Sanford et al. (1985) to have been less active and was described as having a relatively simple system of east trending fractures within the Paleozoic strata. The more active Niagara megablock was described as having a correspondingly more complex system of three fracture sets.

Although additional study and testing of this model is needed, it presents numerous implications with respect to the occurrence of hydrocarbon resources in southwestern Ontario. The model also has significance to stratigraphic problems previously thought to be the result of depositional or facies variations caused by the alignment of the major paleogeographic elements of the region.

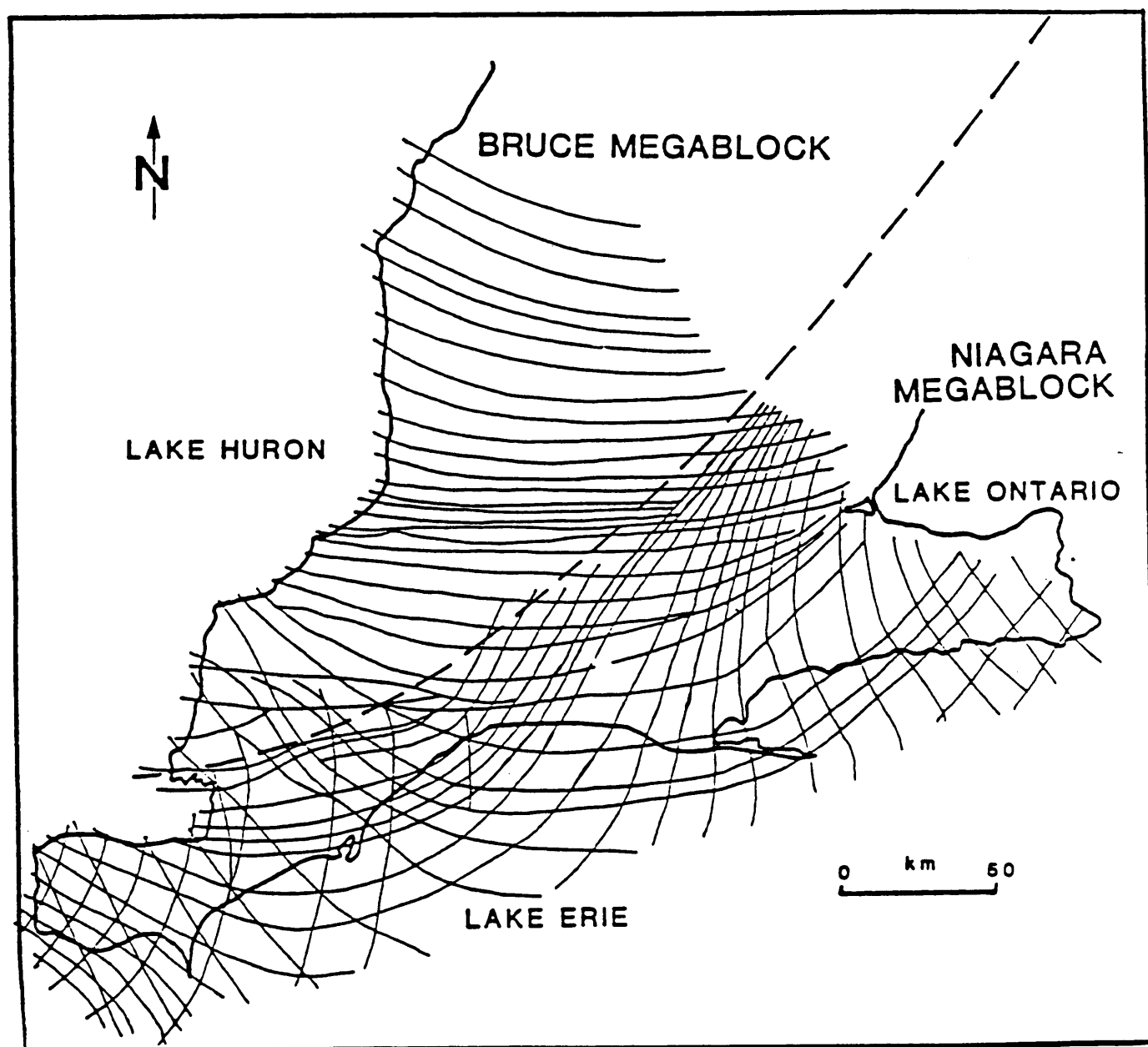


Figure 3. Major fracture system in the Paleozoic rocks of southwestern Ontario (after Sanford et al. 1985).

2.2 Stratigraphy of Southwestern Ontario

The relatively complex paleogeography and patterns of major and minor structural elements, which have controlled, to varying degrees, the sediment types and their distribution throughout the Paleozoic, have led to a variety of stratigraphic terminology among the neighbouring jurisdictions of Ontario, New York, Ohio and Michigan. The problem is most acute in southwestern Ontario which is geologically and geographically central, lying partly along the boundary between the Michigan and Appalachian basins. In addition, the poor exposure of all Paleozoic units in southwestern Ontario compared with the reasonably good exposure of Middle Ordovician strata in south-central Ontario bordering the Precambrian Shield, and of Silurian strata of the Niagara Escarpment, has resulted in the establishment of two stratigraphic schemes based on subsurface and surface data, respectively.

As part of the Oil Shale Assessment Project and other projects in southern Ontario, the OGS has acquired 12 complete cores and downhole geophysical logs through the Paleozoic sequence (Figure 4). This has provided an important supplement to the OGS program of modern surface geological mapping of southern Ontario begun in the early 1970s. Thus, as reported by Telford et al. (1984), the OGS is now attempting to rationalize the conflicting surface and subsurface terminology in Ontario as a contribution to standardizing the Paleozoic stratigraphic nomenclature of the Great Lakes region. The work is far from complete. The stratigraphic terminology used below and elsewhere in this report reflects the most current usage by the OGS (Figure 5).



Figure 4. Location of deep (regional) and shallow drill holes used in the Oil Shale Assessment Project. Only those shallow holes containing the Collingwood Member are shown.

Upper Cambrian/Lower Ordovician

The timing and character of the earliest Paleozoic marine transgression into the southern Ontario region are not well understood. Except for sporadic outcrops of clastic rocks on the eastern and western flanks of the Frontenac Arch (Figure 1), Upper Cambrian or Lower Ordovician strata are restricted to the subsurface. In southwestern Ontario, these basal units pinch out on the flanks of the Algonquin Arch and are overlapped unconformably by Middle Ordovician carbonate units.

From the southeastern side of the Algonquin Arch, the Cambro-Ordovician units increase in thickness to about 155 m beneath the Ontario portion of Lake Erie and reach a maximum thickness of about 2200 m in the central Appalachian Basin. On the northwestern side of the Algonquin Arch in Ontario, they have a thickness of about 77 m and reach a maximum thickness of 620 m in the south-central Michigan Basin (Sanford and Quillian 1959; Winder and Sanford 1972). On both sides of the Arch a similar sequence of rock types occurs: basal conglomerates and sandstones grading upward to interbedded sandstones and grey shaly dolostones, which are in turn overlain by brown dolostones. Drilling by the OGS on Cockburn Island, on the extreme northern rim of the Michigan Basin, encountered a similar lithological pattern (Wolf 1985). Appalachian Basin stratigraphic terminology (in ascending order, Potsdam, Theresa, and Little Falls formations) and Michigan Basin terminology (in ascending order, Mount Simon, Eau Claire, and Trempealeau formations) have been applied to this basal succession on the southeastern and northwestern sides, respectively, of the Algonquin Arch.

There is little doubt that these basal units are markedly diachronous, but, because of a lack of paleontological evidence, their age in southern Ontario is uncertain. On the basis of subsurface continuity with rocks of known Cambrian age in Wisconsin and New York State, Winder and Sanford (1972) favoured an Upper Cambrian age. Because of the marked diachroneity and the Middle Ordovician age of overlying strata, other workers have proposed a Lower Ordovician age.

Recently, there has been increased interest in the basal Cambro-Ordovician sandstones for their potential oil and gas resources. Previous hydrocarbon discoveries were reviewed by Winder and Sanford (1972). An OGS deep drill hole near Port Stanley (Figure 4), completed in 1983 as part of the Oil Shale Assessment Project (OGS 82-3; Johnson et al. 1985), penetrated 36.8 m of Cambro-Ordovician strata, within which was encountered a good show of oil in the depth interval 1125 to 1135 m. This stimulated considerable interest from the petroleum exploration community.

Middle Ordovician

Following an Early Ordovician erosional interval, the Middle Ordovician marine transgression of southwestern Ontario was very extensive and the entire region was blanketed by a comparatively thick succession of shallow-water shelf carbonate deposits. The facies variations inherent in such a depositional system have produced a complex stratigraphy with lithological changes occurring both along strike and down-dip into the Appalachian and Michigan basins. The Middle Ordovician units are exposed only along a narrow zone, bordering the Precambrian shield, extending from eastern Lake Ontario to Georgian Bay and thence along the northern edges of the islands in northern Lake

Huron (Figure 1). Only the shallower water, basin margin carbonate deposits can be examined in outcrop, while the deeper water facies, and those closer to sources of terrigenous sediments from the eastern side of the Appalachian Basin can be examined only with subsurface data. Consequently, at least three stratigraphic nomenclature schemes (covering the south-central Ontario outcrop belt, northern Lake Huron outcrop belt, and southwestern Ontario subsurface, respectively) have evolved to describe the Middle Ordovician carbonate sequence.

In describing the Middle Ordovician portions of the cores obtained during the Oil Shale Assessment Project, terminology proposed by Liberty (1969) was used for drill holes at Wiarton (OGS 82-4; Johnson et al. 1985), Corbetton (Johnson et al. 1983b) and in the Toronto region (OGS 83-1 to 83-3; Johnson 1983), all of which lie within or close to the south-central Ontario outcrop belt (Figure 4). Subsurface terminology proposed by Sanford (1961) and Beards (1967) for the subsurface of southwestern Ontario was used for drill holes near Sarnia (OGS 82-1), Chatham (OGS 82-2), and Port Stanley (OGS 82-3) (Johnson et al. 1985). This subsurface terminology which is largely biostratigraphically-based, includes the following: the Coboconk, Kirkfield, Sherman Falls, and Cobourg formations (Figure 5, Table 2). These formations together with the Shadow Lake and Gull River formations, are grouped into the Trenton and Black River groups. Middle Ordovician carbonates were left undifferentiated in the lithological logs for drill holes on Manitoulin and St. Joseph islands (OGS 83-5 and 83-6, respectively; Johnson et al. 1985) and on Cockburn Island (OGS 85-7; Wolf 1985).

Drill Hole Unit	Southwestern Ontario				Central Ontario				Northern Lake Huron	
	OGS-82-1 Lambton	OGS-82-2 Chatham	OGS-82-3 Port Stanley	DH-1 Corbetton	OGS-82-4 Wiarton	OGS-83-1 Milton	OGS-83-2 Clarkson	OGS-83-3 Pickering	OGS-83-5 Little Current	OGS-83-6 St. Joseph Is.
Upper contact elev. m.	Cobourg 1050.95	Cobourg 899.46	Cobourg 860.00	Lindsay 485.76	Lindsay 292.76	Lindsay 436.46	Lindsay 275.46	Lindsay 48.20	Lindsay 109.70	Lindsay 158.45
Lower contact elev. m.	1096.35	934.28	905.00	494.94	327.70	503.64	340.61	81.46	115.35	169.00
Upper contact elev. m.	Sherman Falls 1096.35	Sherman Falls 934.28	Sherman Falls 905.00	Verulam 494.94	Verulam 327.70	Verulam 503.64	Verulam 340.61	Verulam 81.46	Undifferentiated 115.35	Undifferentiated 169.00
Lower contact elev. m.	1129.28	978.10	933.90	539.47	382.98	549.89	433.09	147.80	208.38	328.96
Upper contact elev. m.	Kirkfield 1129.28	Kirkfield 978.10	Kirkfield 933.90							
Lower contact elev. m.	1189.60	1028.92	992.73							
Upper contact elev. m.	Coboconk 1189.60	Coboconk 1028.92	Coboconk 992.73	Bobcaygeon 539.47	Bobcaygeon 382.98	Bobcaygeon 549.89	Bobcaygeon 433.09	Bobcaygeon 147.80		
Lower contact elev. m.	1199.85	1060.09	1028.15	566.72	396.24	595.98	440.43	198.35		
Upper contact elev. m.	Gull River 1199.85	Gull River 1060.09	Gull River 1028.15	566.72	396.24	595.98	440.43	198.35		
Lower contact elev. m.	1336.25	1169.63	1098.80	597.72	416.66	630.17	473.44	227.19		
Upper contact elev. m.	Shadow Lake 1336.25	Shadow Lake 1169.63	Shadow Lake 1098.80	Shadow Lake 597.72	Shadow Lake 416.66	Shadow Lake 630.17	Shadow Lake 473.44	Shadow Lake 227.19	Undifferentiated (Shadow Lake) 208.38	
Lower contact elev. m.	1340.53	1175.00	1107.47	602.79	422.72	637.45	484.78	236.54	213.30	

Table 2. Middle Ordovician carbonate units intersected in deep drill holes of the Oil

Shale Assessment Project.

Table 2 summarizes the stratigraphic thickness and terminology of Middle Ordovician carbonate units penetrated in the southern Ontario drill holes. The thickest section of Middle Ordovician carbonates encountered (289.58 m in OGS 82-1 near Sarnia) is close to the maximum thickness of 304 m reported by Winder and Sanford (1972). The Middle Ordovician units include a full spectrum of shallow water carbonate rock types representing supratidal, intertidal and shallow subtidal environments. The Shadow Lake Formation or equivalent (Table 2) is a distinctly diachronous basal clastic unit of shales, siltstones and argillaceous dolostone. It is succeeded gradationally by a sequence of fine-grained to lithographic limestones and minor dolostones (Gull River Formation). The middle part of the Middle Ordovician succession is generally dominated by bioclastic limestone or calcarenite, commonly interbedded with calcareous shales. The upper part of the succession is mainly fine-grained argillaceous limestone. All units except the clastic Shadow Lake Formation are richly fossiliferous.

The Gull River, Bobcaygeon and Verulam formations (or their equivalents, Table 2) span most of the Blackriveran and Trentonian Stages of the Middle Ordovician (Barnes et al. 1981). The uppermost carbonate unit in the succession (Lindsay Formation or equivalent, Table 2) actually straddles the Middle-Upper Ordovician boundary, ranging in age from upper Trentonian to Maysvillian (Barnes et al. 1981). These rocks of the Gull River to Lindsay formations form the Simcoe Group, which is equivalent to the Ottawa Group in eastern Ontario (Williams 1991).

The Collingwood Member of the Lindsay Formation (Russell and Telford 1983) is one of the three southern Ontario oil shales investigated in the Oil Shale Assessment

Project (Table 1). It is composed of interbedded organic-rich limestone and highly calcareous shale and forms the upper part of the Lindsay Formation. This unit represents the final phase of the Upper Ordovician carbonate depositional sequence in southern Ontario. The Collingwood Member, as defined by Russell and Telford (1983), is not equivalent to the Collingwood Formation of Sanford (1961) identified in the subsurface of southwestern Ontario (Figure 5). The latter should probably be termed the Blue Mountain Formation. The Collingwood Member is essentially a facies within the upper part of the Lindsay Formation and is restricted in lateral distribution. The distribution of this unit will be discussed in more detail later in this report.

Upper Ordovician Shales and Carbonates

A major change in sedimentation patterns took place during the Late Ordovician. The Taconic Orogeny of eastern North America, coupled with a eustatic sea level drop caused by continental glaciation on the north African craton (Dennison 1976), had a profound effect on the character and distribution of sediments in the Appalachian and Michigan basins. Erosion of the newly created highlands encroaching into the eastern side of the Appalachian Basin shed large volumes of terrigenous material into the now shallower epicontinental seas. This is clearly illustrated in southern Ontario where the Middle (to Upper) Ordovician carbonate sequence is followed by a thick succession of shales and related terrigenous clastic units.

The Lindsay Formation is overlain disconformably by blue-grey and brown, predominantly noncalcareous shales of the Blue Mountain Formation. Thicknesses of 40

to 60 m of Blue Mountain Formation were recorded during the deep drilling program of the Oil Shale Assessment Project in southwestern Ontario (Johnson et al. 1985).

The overlying Georgian Bay Formation is a thick sequence of grey-green shales, siltstones, and minor limestones. The abundance of carbonate horizons increases to the north (i.e., away from the southeastern source of terrigenous sediments), and on Manitoulin Island, the upper (Kagawong) Member of the Georgian Bay Formation is dominantly bioclastic and argillaceous limestones and dolostones (Johnson and Telford 1985a-f). The Georgian Bay Formation is over 250 m thick in the Toronto region (Johnson 1983), but thins to less than 100 m in southwestern Ontario and northern Lake Huron (Johnson et al. 1985).

The uppermost Ordovician unit in southern Ontario is the Queenston Formation. This unit is a thick sequence of red and maroon siltstones and shales that was deposited as the distal fine-grained facies of a major deltaic complex extending from the eastern margin of the Appalachian Basin. The unit reaches a maximum thickness in Ontario (under eastern Lake Erie) of 341 m (Winder and Sanford 1972). Northwestwards, the red clastic unit thins and grades laterally into the grey shales and carbonates of the upper part of the Georgian Bay Formation.

The Blue Mountain–Georgian Bay–Queenston sequence is upper Maysvillian to Richmondian in age (Barnes et al. 1981). Strata representing the youngest Ordovician Gamachian Stage are not present in southwestern Ontario or adjacent areas, indicating

that the Late Ordovician global sea level drop was sufficient to produce a significant hiatus in the region before a marine transgression again took place in the Early Silurian.

Lower-Middle Silurian

The Silurian strata of southwestern Ontario constitute the most intensely studied and best understood sequence in the region. This is due in part to the excellent exposures of Lower and Middle Silurian rocks along the Niagara Escarpment (Figure 1), and to the exploration and development of oil and gas resources from several of the stratigraphic units.

The Niagara Escarpment is a prominent cuesta which separates lowlands, underlain by Ordovician strata to the east, from uplands of Silurian, and eventually Devonian, rocks in the west. It first appears as a distinct geological and topographical feature near Rochester, New York State. Paralleling the south shore of Lake Ontario, the Escarpment enters Ontario at Queenston Heights and extends westward to Hamilton. It swings to the north, extending to the Blue Mountain area near Collingwood on southern Georgian Bay, and then continues in a serrated fashion northwestwards to Wiarton. North of Wiarton, it forms the spectacular eastern shore of the Bruce Peninsula as far as Tobermory where it dips beneath the waters of Lake Huron. Reappearing on the north side of Manitoulin Island, the Escarpment continues northwestward as a more subdued topographic feature and eventually passes into the northern peninsula of the State of Michigan.

The Escarpment extends from the Appalachian Basin, over the Algonquin Arch, and into the Michigan Basin, exposing a variety of rock types and facies associations within the Lower and middle Silurian. During the Silurian the Michigan Basin was mainly a carbonate and evaporite basin whereas sediments in the adjacent Appalachian Basin were largely clastics with less abundant carbonates.

Bolton (1957) provided the first fully comprehensive account of the stratigraphy of the Niagara Escarpment in southern Ontario. Martini (1971) examined the Lower Silurian part of the sequence (the Medina Group) in the Niagara Peninsula and western New York State, showing that this dominantly clastic sequence was formed in deltaic and prodeltaic environments. Lower and Middle Silurian strata (in ascending order, the Cataract and Clinton groups, and Lockport/Amabel and Guelph formations) in the subsurface of southwestern Ontario were described by Sanford (1969), who interpreted the Middle Silurian strata as consisting of complex carbonate shelf, bank, and reefal lithofacies. A more recent summary of the Niagara Escarpment succession in southern Ontario was provided by Telford (1978). New maps of the Silurian geology on Manitoulin Island have been released by the Ontario Geological Survey (Johnson and Telford 1985a-f). The recent application of new depositional models to detailed outcrop and cores studies has led to proposed stratigraphic revisions for part of the Silurian sequence in the Niagara Peninsula and New York (Brett et al. 1990; Duke 1991; Duke et al. 1991).

Because of the diverse facies associations, total thicknesses of the Lower-Middle Silurian strata in southwestern Ontario are variable, ranging from almost 300 m beneath

eastern Lake Erie and northern Lake Huron to less than 100 m in the Sarnia area (OGS 82-1; Johnson et al. 1985) and the Niagara Peninsula. The thickest sequences occur in former shelf areas around the rim of the Michigan Basin where there was major carbonate bank and reefal development (Sanford 1969). The classic section in the Niagara Gorge, extending from the basal Silurian Whirlpool Formation to the Middle Silurian Lockport Formation, is about 85 m in thickness (Telford 1978).

More than 90% of the gas production and about half of the oil production to date in Ontario has come from Silurian rocks. Most of the oil has been extracted from Middle Silurian reefal carbonates of the Guelph Formation and overlying carbonates of the Upper Silurian Salina Formation (Rybansky and Trevail 1983). Powell et al. (1984) suggest that the principal source of these hydrocarbons was the Middle Silurian Eramosa Member of the Amabel Formation (Figure 5). The dark laminated dolostones of the Eramosa Member were formed in restricted inter-reefal zones and, with organic carbon contents ranging to about 3% (Powell et al. 1984), the unit could be classified as a potential "oil shale". It was not investigated in the Oil Shale Assessment Project due to its relatively low organic content.

Upper Silurian

The Late Silurian was, again, a time of contraction of the epicontinental seas in eastern North America, and evaporitic conditions were strongly developed in the Michigan Basin and adjacent areas. In southwestern Ontario, the Upper Silurian Salina Formation consists of salt (halite), gypsum and anhydrite units alternating with dolostone, limestone and shale. Near the southern end of Lake Huron, salt beds in the

Salina Formation have a composite thickness of over 200 m (Winder and Sanford 1972). The current subsurface distribution of the salt beds is considered to be greatly reduced from their original depositional extent (Sanford 1969). This is the result of gradual dissolution of the salt which began in the Late Silurian along the margins of the Michigan Basin and continued basinward through successive periods of geological time. Sanford et al. (1985) have demonstrated a close relationship between the salt dissolution patterns and major fracture systems in southwestern Ontario.

The Salina Formation is conformably overlain by dolostones of the Bass Islands Formation (called the Bertie Formation on the Niagara Peninsula). This is the youngest Silurian unit in southern Ontario and its top is an erosional surface signifying a major hiatus and period of subaerial exposure. Sand and other sediments from overlying Devonian formations are often present in cracks and joints extending for several metres into the upper part of this unit (Telford and Johnson 1984).

The maximum combined thickness of the Salina and Bass Islands formations is 518 m near southern Lake Huron, but the sequence thins to only 105 m over the Algonquin Arch (Winder and Sanford 1972). In OGS drill hole 82-1 near Sarnia (Figure 4), the Salina Formation is 330 m thick and the Bass Islands Formation is 24 m thick (Johnson et al. 1985).

Age determinations and regional correlations of the Lower to Middle Silurian and especially the Upper Silurian formations are not as precise as the underlying Ordovician and overlying Devonian units. For example, correlation of the mainly unfossiliferous

Salina and Bass Islands formations is based solely on the stratigraphic positions of these units. For further information, the reader should refer to Telford (1978) and Winder et al. (1975).

Lower Devonian

In southwestern Ontario, the Early Devonian was mainly a time of emergence and erosion. The oldest Devonian strata of the region are quartzose sandstones of the Oriskany Formation which occur as erosional remnants in depressions on the irregular Upper Silurian surface. The formation has been positively identified at only one locality in Ontario, outcropping in an approximately 600 hectare area, 10 km east of Hagersville (Winder and Sanford 1972; Uyeno et al. 1982; Telford and Johnson 1984). Sanford (1968) suggested that the formation may be present elsewhere in the subsurface of southwestern Ontario. Sandstones of the Oriskany Formation have a wide distribution in the Appalachian Basin and the Ontario occurrences are probably close to the northern depositional edge of the unit.

The Oriskany Formation was deposited during the middle Early Devonian (Pragian) and was, in turn, subjected to erosion before deposition of the overlying Bois Blanc Formation during the late Early Devonian. The Bois Blanc Formation is an eastward thinning carbonate wedge, having a maximum thickness of 50 m in southwestern Ontario; however, it is only 3 to 15 m thick on the Niagara Peninsula (Uyeno et al. 1982). It is essentially a Michigan Basin rock unit which spilled over the Algonquin Arch and overlapped and intertongued with clastic and carbonate units of the Appalachian Basin. The Bois Blanc Formation consists of argillaceous fossiliferous

limestone, dolomitic limestone, abundant chert and a glauconitic sandy facies sporadically developed in its basal part.

Lower-Middle Devonian Carbonates

Overlying the Bois Blanc Formation is a variable sequence of limestones and dolostones of upper Early to lower Middle Devonian age. On the Niagara Peninsula, the Bois Blanc Formation is overlain with possible disconformity by coral-rich biostromal limestones of the Edgecliff Member of the Onondaga Formation (Telford and Tarrant 1975b). In western New York State, the Onondaga Formation has been divided into four limestone members (in ascending order: Edgecliff, Clarence, Moorehouse and Seneca; Oliver 1976) and the lower three can be traced into the Niagara Peninsula of Ontario, as far west as Port Dover (Telford and Tarrant 1975a,b; Telford and Hamblin 1980). Farther west, the Appalachian Basin Onondaga limestones grade laterally into limestones and dolostones of the Michigan Basin Detroit River Group.

The lower unit of the Detroit River Group is the Amherstburg Formation which consists of bituminous, chert-rich, bioclastic limestone. Its lateral relationships with the Onondaga Formation are not clear because of a lack of outcrops and subsurface data in key areas. Its contact relationships with the underlying Bois Blanc Formation are poorly understood because the lithological similarities between the units preclude accurate discrimination in subsurface records (Beards 1967). Around the southern part of the Michigan Basin, in Ontario (Windsor-Essex area) and Michigan, the carbonates of the lower Amherstburg intertongue with strand-line and eolian quartzose sandstones of the Sylvania Member. To the north, in Bruce and Huron counties, the Amherstburg

Formation contains extensive reefal deposits (Sanford 1968). Termed the Formosa Reef Limestone, these reefs and bioherms were part of a large platform reef development which characterized the southeastern rim of the Michigan Basin during the time of Amherstburg deposition. Toward the centre of the Michigan Basin the Amherstburg is largely a dolomitic unit.

Conformably overlying the Amherstburg Formation is the Lucas Formation, a complex unit with a variety of rock types. In the central Michigan Basin it is basically an evaporite, made up of salt and anhydrite interbedded with anhydritic dolostones and limestones (Sanford 1968). Around the margins of the basin, such as the Algonquin Arch region of southwestern Ontario, the formation consists of shallow shelf carbonate deposits of dolostones and high purity limestones. The latter are quarried extensively in the Woodstock–Ingersoll and Amherstburg areas for use in the cement, steel and chemical industries. The high purity limestone facies is often termed the Anderdon Member (Uyeno et al. 1982). Near Ingersoll the upper part of the Anderdon Member is characterized by a distinctive sandy limestone facies.

The Lucas Formation pinches out rapidly to the east and, in the Simcoe area, the Dundee Formation directly overlies the older Amherstburg or Onondaga formations (Telford and Hamblin 1980). In Ontario, near the southern end of Lake Huron, thicknesses of 62 m and 93 m have been recorded for the Amherstburg and Lucas formations, respectively (Winder and Sanford 1972). In OGS drill hole 82-1 near Sarnia (Figure 4), the total thickness of the Detroit River Group is 120.65 m (Johnson et al. 1985).

Overlying the units of the Detroit River Group, with probable slight disconformity, are richly fossiliferous micritic limestones of the Dundee Formation. This unit forms the bedrock of a broad belt extending across southwestern Ontario from central Lake Erie to Lake Huron; it also underlies part of the Windsor–Essex area and Pelee Island in Lake Erie (Figure 1). The Dundee is correlative, in part, with the Delaware Formation of Ohio and the upper part of the Onondaga Formation in New York (Uyeno et al. 1982). The Tioga Ash Bed, which separates the Moorehouse and Seneca members of the Onondaga Formation in New York and is a widely used marker horizon in the Appalachian Basin, may be present in the lower part of the Dundee Formation, but positive confirmation is still required (Sanford 1968; Uyeno et al. 1982).

The Dundee Formation has a maximum thickness of 120 m in the Saginaw Bay area of Michigan, but is considerably thinner in southwestern Ontario (Sanford 1968). Thicknesses of 35 to 45 m were recorded during the deep drilling phase of the Oil Shale Assessment Project (Johnson et al. 1985).

Formations of the Detroit River Group are considered to be of uppermost Early Devonian (Emsian) age while the overlying Dundee Formation is of lower Middle Devonian (Eifelian) age. The Dundee Formation has yielded the richest and most diverse conodont fauna of any Devonian unit in southwestern Ontario (Uyeno et al. 1982). Preservation of the conodonts is extremely good and collections from the Dundee have been used in a number of important taxonomic and paleoecological studies (e.g., Ferrigno 1971; Klapper and Philip 1971).

The first recorded occurrences of oil in southern Ontario, in the early 1800s, were seeps from shallow reservoirs of Devonian age. The first oil well in North America was dug and drilled in 1858 at Oil Springs in southwestern Ontario, discovering crude oil in the Dundee Formation. Since then, almost 40% of Ontario's oil production has come from dolomitized zones within the Dundee or underlying Lucas Formation (Rybansky and Trevail 1983). The shallow oil pools of the Dundee continue to attract considerable interest from the petroleum exploration industry.

Middle Devonian Shales

The late Middle Devonian Acadian Orogeny in eastern North America produced significant changes to the sedimentation patterns of the Appalachian and Michigan Basins. Deposition of fine marine clastics derived from eastern land areas succeeded the widespread early Middle Devonian carbonate deposition. In southwestern Ontario, the limestones of the Dundee Formation are overlain by either black shales of the Appalachian Basin Marcellus Formation, or grey shales of the Michigan Basin Bell Formation.

The Marcellus Formation is a potential oil shale which forms the bedrock of a restricted area along the north shore of Lake Erie near Port Stanley. Refer to Johnson et al. (1989) for stratigraphic details.

The Bell Formation is the lowermost unit of the Hamilton Group which overlies the Marcellus Formation in southwestern Ontario. Overlying units within the Hamilton Group include, in ascending order, the Rockport Quarry (limestone), Arkona (shale),

Hungry Hollow (limestone), Widder (shale, siltstone, limestone), and Ipperwash (limestone) formations. The Hamilton Group of Ontario correlates with the middle part of the Hamilton Group in New York State and with the Traverse Group of Michigan. The Ontario rock units actually lie in a transition zone between the largely clastic units of the New York (Appalachian Basin) sequence and the largely carbonate sequence in the Michigan Basin.

Maximum total thickness of the Hamilton Group in Ontario is about 93 m (Winder and Sanford 1972). The following formation thicknesses were measured in OGS drill hole 82-1 (Johnson et al. 1985):

Ipperwash Formation -	1.99 m
Widder Formation -	21.44 m
Hungry Hollow Formation -	2.00 m
Arkona Formation -	32.10 m
Rockport Quarry Formation -	5.76 m
Bell Formation -	14.57 m
Total -	77.86 m

The Ipperwash Formation is actually quite variable in thickness (0 to 13 m) because of irregular erosion of these limestones during the hiatus which preceded deposition of the overlying Kettle Point Formation.

The Rockport Quarry Formation is much thicker in Michigan (averaging about 20 m) and the Ontario occurrences are close to the eastern depositional edge of the unit. The richly fossiliferous Hungry Hollow Formation is noteworthy in that it maintains its low thickness over a large area and can be traced accurately in the subsurface using geophysical logs from oil and gas exploration wells (Beards 1967; Telford 1976).

The Hamilton Group in southwestern Ontario is considered to be of early Givetian age (Uyeno et al. 1982). However, paleontological data are poor for the lower units (lower Arkona to Bell), which occur only in the subsurface, and they may range as old as late Eifelian.

Upper Devonian

The change from carbonate-dominated to clastic-dominated deposition, which began during the Middle Devonian, culminated in the Upper Devonian with deposition of noncalcareous black shales throughout the sedimentary basins of eastern North America. In southwestern Ontario this depositional episode is represented by the Kettle Point Formation, a potential oil shale and one of the principal targets of the Oil Shale Assessment Project. The Kettle Point and its equivalents in the Michigan, Appalachian, Illinois and Moose River basins are known collectively as the Eastern Gas Shales. The older Marcellus Formation and correlative black shales also are considered to be part of the Eastern Gas Shales sequence (Johnson et al. 1989).

Conodont studies suggest that the Kettle Point Formation, where it is fully preserved, may span almost the entire Upper Devonian, ranging from early Frasnian to late Famennian age (Uyeno et al. 1982).

The youngest Devonian, indeed the youngest Paleozoic units in southwestern Ontario, are the formations of the Port Lambton Group. In ascending order, they consist of the Bedford (grey shale), Berea (sandstone), and Sunbury (black shale) formations, which have a combined maximum thickness in Ontario of about 62 m (Winder and Sanford 1972). They occur in the subsurface of a small area south of Sarnia bordering the St. Clair River (Figure 1). In OGS drill hole 82-1 (Johnson et al. 1985), 33.4 m of dark grey shale referable to the Bedford Formation was present, overlying the Kettle Point Formation with probable disconformity. The age of the Port Lambton Group has been a matter of debate, with some workers assigning it to the Upper Devonian and others to the Lower Mississippian. A late Devonian age is now generally accepted (Uyeno et al. 1982).

3. LITHOSTRATIGRAPHY, GEOLOGY AND GEOPHYSICS OF THE MIDDLE-UPPER ORDOVICIAN

3.1 Lithostratigraphy and Geology

Evolution of the stratigraphic nomenclature

The lithostratigraphic nomenclature for the Middle to Upper Ordovician rocks has been the subject of considerable debate for over 70 years (Russell and Telford 1983; Harris 1984). The main difficulties in concisely defining the stratigraphy of this age in southwestern Ontario were outlined by Russell and Telford (1983). These authors noted

that many of the differences in the proposed nomenclature stemmed from the lack of good outcrop and core, and poor geophysical well log signatures. The nomenclature was further muddled by lithostratigraphic classifications based essentially on paleontological evidence.

The regional and shallow drilling program completed as part of the Oil Shale Assessment Project provided a considerable amount of valuable subcrop and subsurface data (including several drill cores) on which detailed lithological, sedimentological, geochemical and geophysical studies could be based. As a result of this multidisciplinary approach, revisions have been made to the stratigraphic nomenclature currently in use at the Ontario Geological Survey (Figure 5). The following paragraphs contain a review of the evolution of the Middle to Upper Ordovician stratigraphic nomenclature. For further details the reader should refer to Russell and Telford (1983).

Raymond (1912) first proposed the name Collingwood Formation to describe "a thin formation consisting of layers of fine-grained rather pure blue limestone alternating with thick beds of soft brown shale." These interbedded shales and limestones were said to overlay the limestones of the Trenton Formation.

Parks (1928) redefined the Collingwood Formation based on faunal content, and split the unit into three parts. The uppermost part he called the Blue Mountain shales; this was underlain by the Upper Collingwood (a black shale unit containing the trilobite species *Pseudogygites canadensis*) and a Lower Collingwood unit consisting of "ninety feet

of limestones." This unit would later be variably referred to as the Lindsay (Liberty 1969), Trenton (USA terminology), or Cobourg (Beards 1967) formations.

The most recent classifications of these strata, including the one used in this study, are summarized in Figures 5 and 6. Prior to Russell and Telford (1983), the OGS used the stratigraphic nomenclature proposed by Liberty (1969). He grouped the black "Collingwood shales" with the overlying grey shales and called the unit the Whitby Formation. The black shales were renamed the Craigleith Member. The Whitby Formation is underlain by the Middle Ordovician nodular limestones and dolostones of the Lindsay Formation (formerly the Trenton Formation). The subsurface terminology, which is still in use today, was reviewed by Beards (1967). He called the Middle Ordovician carbonates the Cobourg Formation.

Russell and Telford (1983) developed the stratigraphic nomenclature which is used in this report (Figure 6). They proposed that the black shales of the Craigleith Member (Whitby Formation) are actually an areally restricted anoxic facies of the underlying carbonate package, and renamed the unit the Collingwood Member of the Lindsay Formation. The Collingwood Member is most commonly overlain by the blue-grey shales of the Blue Mountain Formation; however, in the Pickering area, it is overlain by brown shales containing thin, calcareous, organic interbeds. These localized shales are generally referred to as the Rouge River Member of the Blue Mountain Formation (Russell and Telford 1983). Because these shales also contain calcareous, organic interbeds, the Rouge River–Collingwood contact is sometimes difficult to determine. The relationship of the Rouge River Member with the blue-grey shales of the Blue Mountain Formation (strata

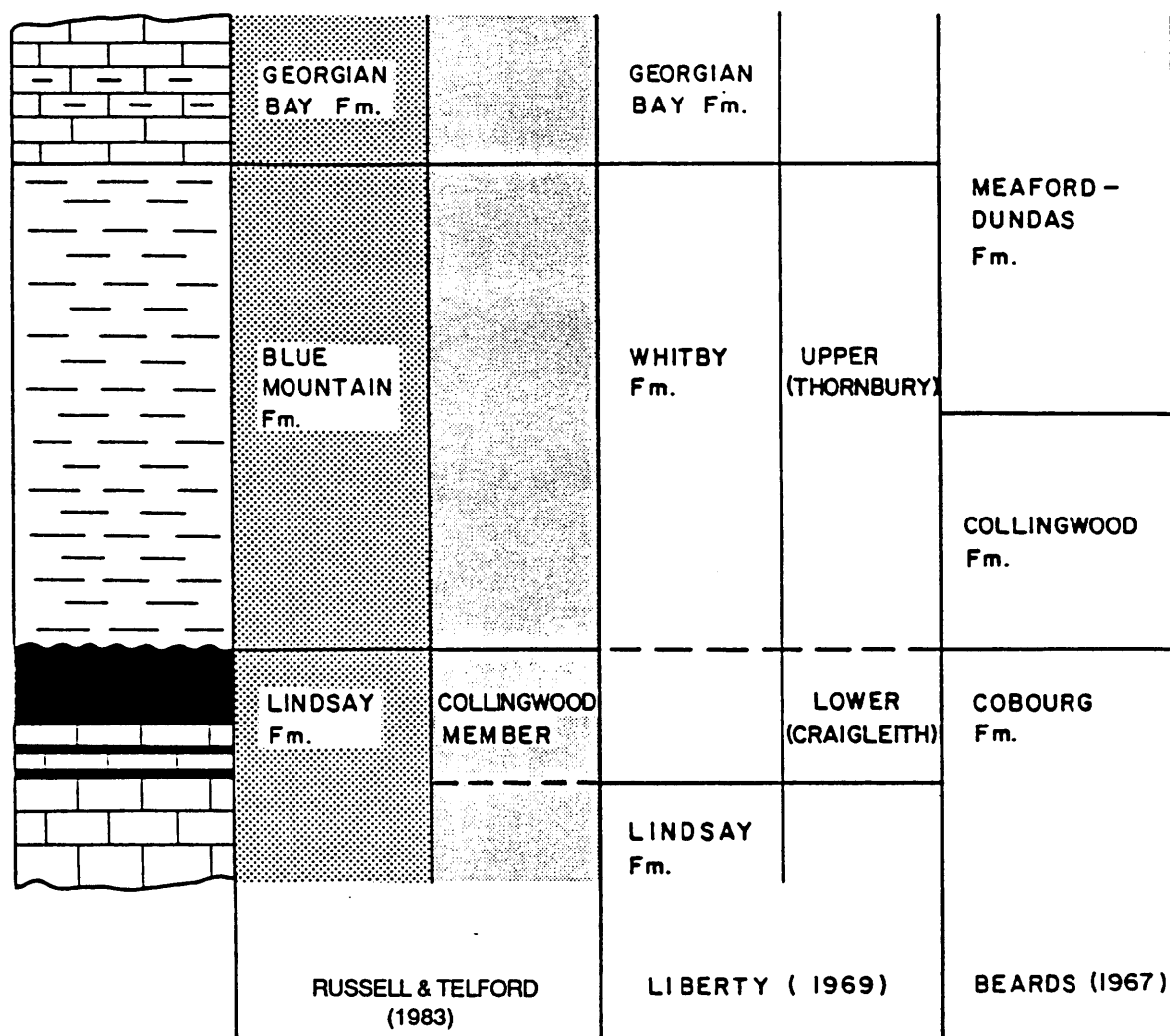


Figure 6. Historical review of Middle-Upper Ordovician stratigraphic nomenclature (*after* Russell and Telford 1983).

equivalent to Liberty's, 1969, Thornbury Member of the Whitby Formation) is uncertain. The Rouge River Member may have had a greater distribution but was eroded away in areas north and west of Toronto prior to the deposition of the blue-grey shales. The brown shales of the Rouge River Member most likely represent a restricted facies variation of the Blue Mountain blue-grey shales (Russell and Telford 1983). Russell and Telford's reclassification of the "Collingwood shales" was based on the: "1) lack of a distinct lithological break between the Collingwood shales and the nodular limestones of the Lindsay Formation; 2) the sharp drop in carbonate content at the top of the Collingwood shales; and 3) the concomitant drop in organic carbon content." They also concluded the current use of the term Collingwood Formation in the subsurface nomenclature does not contain any of the strata originally defined as the Collingwood Formation, and recommended that the Blue Mountain Formation be used instead.

General Description, Mineralogy and Age of the Collingwood Member

The Collingwood Member of the Lindsay Formation, as defined by Russell and Telford (1983), is a finely laminated, black organic-rich, marlstone or impure limestone, which when cleaved, produces a strong petroliferous odour. It can be easily identified in cuttings (or core) by its deep black-brown colour and by its high calcite content (fizzes in dilute HCl acid). The unit also gives a distinctive response on the downhole gamma logs. At the top of the unit the response of this log is that of a pure shale and is very similar to the overlying siliceous shales of the Blue Mountain Formation. This response gradually trails over to an almost pure carbonate response. This and other geophysical well log responses will be discussed in more detail later in this report.

The upper contact of the Collingwood Member is regionally very sharp and is, for the most part, marked by the presence of a phosphatic bed. The Toronto-Pickering area is an exception, however, as here the Collingwood Member is gradationally overlain by the interbedded calcareous and siliceous shales of the Rouge River Member, of the Blue Mountain Formation (Russell and Telford 1983).

The lower contact with the nodular limestones of the Lindsay Formation is gradational and consists of interbedded black marlstone, marlstone and nodular limestone. In the Manitoulin-St. Joseph Island area and on the mainland in Michigan, this contact is locally erosional. The localized nature of these two lower contact types was demonstrated by Hiatt (1985). She noted that the contact in the Taratuta 1-13 core from Presque Isle Co. in northern Michigan is sharp and erosional, whereas in the State Albert 1-10 core, just one county to the south, the contact shows well developed interbedding. The present authors also noted three contact types in closely-spaced cores from St. Joseph Island. These three contact types were sharp/erosional, gradational with no interbedded black marlstones and nodular limestones, and gradational with interbedded black marlstones and nodular limestones. These cores can be examined along with lithological descriptions prepared by D.P. Rogers at the Ministry of Northern Development and Mines core storage facility in Sault Ste. Marie.

X-ray diffraction and Total Inorganic Carbon (T.I.C.) analyses performed by Hiatt (1985) and Churcher (1984) on samples taken from the nodular limestones and dolostones of the Lindsay Formation, the Collingwood Member, and the overlying blue-

grey shales of the Blue Mountain Formation indicate that these units are made up of the following minerals:

Nodular Limestone, Lindsay Formation — calcite, with trace amounts of quartz, pyrite, clay, and locally, dolomite;

Collingwood Member, Lindsay Formation — calcite (up to, or greater than 50%), quartz, clays (illite and iron chlorite), pyrite, phosphate, and locally, dolomite;

Blue Mountain Formation — quartz, illite and iron chlorite, with trace amounts of calcite, and feldspar.

The age of the Collingwood Member has been previously estimated to be either late Middle Ordovician, or early Late Ordovician depending on the lithostratigraphic association. Many of the problems encountered in the relative dating of this unit in the past lay in the facies changes which limited the use of zone fossils, such as graptolites. A detailed paleontological study performed by Barnes (1985) using conodonts revealed that the unit is Late Ordovician in age. Conodonts extracted from the nodular limestones of the Lindsay Formation were found to be Trentonian to Edenian (Middle to Late Ordovician), whereas those extracted from the Blue Mountain shales were found to be Maysvillian (Late Ordovician) in age.

Depositional Environment

It is generally accepted that the Collingwood Member was deposited in shallow water conditions at the peak of a major marine regression, and that the overlying shales of the Blue Mountain Formation represent the beginning of a marine transgression triggered by the global rise in sea level and the Taconic Orogeny (Harris 1984; Hiatt 1985; Macauley et al. 1990). The numerous shell beds (coquinas) within the Collingwood Member attest to the fact that this unit was frequently exposed to storms and, therefore, must have been deposited at, or near, the fairweather wave base. Harris (1985) concluded, based on faunal evidence, that the Collingwood Member was deposited in relatively shallow water that deepened from northwest to southeast. This deepening trend continues into the Appalachian Basin, southeast of Toronto.

Thick organic-rich horizons in proximity to the margins of sedimentary basins are not uncommon in the rock record and may result from the development of a restricted basin (Hiatt 1985), or from the development of a stratified water column (Harris 1984). Hiatt (1985) proposed that the Collingwood Member was deposited in a lagoonal-type environment. She suggested that this lagoon may have been formed as a result of uplift of the carbonate platform to the south and a drop in sea level to the north.

Harris (1984) proposed that the continental sea in this region was stratified with respect to oxygen content at the time of the deposition of the Collingwood Member, and that this region of the craton was close to the equator. This stratified water column is believed to have had an oxygen-rich layer on top and an oxygen depleted (anoxic) layer on the bottom. These environmental conditions are ideal for the development and

preservation of black shale sequences (Demaision and Moore 1980). Nutrient upwelling (mostly phosphatic material) is frequently associated with these depositional environments and promotes the production of organic matter in the oxygen-rich zones (Harris 1984). Using faunal evidence, Harris supported the existence of a stratified water column. He noted that there is a lack of infaunal/sessile and epifaunal organisms present in these rocks, and that the assemblage is dominated by nectoplanktonic and poorly developed benthic communities consisting of trilobites, graptolites, cephalopods, inarticulate brachiopods and ostracodes. These observations are consistent with a poorly oxygenated sea floor environment. His theory is supported by the significantly higher P_2O_5 concentrations that were detected in the Collingwood Member compared to the underlying Lindsay limestones, or overlying Blue Mountain Formation shales. Similar concentrations of phosphate were noted by Hiatt (1985).

Present Distribution

The isopach maps presented in this report (Appendix 3, back pocket) were generated from core, cuttings and well log data obtained from boreholes on both sides of the international border. These maps represent the total thickness of the Collingwood Member, and include the interbedded black marlstones and limestones at the base of the unit. The maps show that the present distribution of the Collingwood Member is thickest towards the margins of the two sedimentary basins that it occupies. This wedge of sediment, which thins basinward, may have been formed as a result of combined upwelling and high organic productivity in shallow waters. A similar isopach map was generated by Hiatt (1985) for the northern part of Michigan state. She noted that the basinward thinning of the Collingwood Member is completely different from the pattern

of sedimentation observed for the underlying carbonates of the Lindsay (Trenton) Formation and overlying siliciclastic shales of the Blue Mountain (Utica) Formation. Both of these rock units show classical basinward thickening of the sedimentary package. As a result of these observations, an alternate model to explain the present distribution of the Collingwood Member in the subsurface is presented below.

The present distribution of the Collingwood Member appears to be controlled by two erosional events. The first event occurred at the peak of the marine regression (upper Middle Ordovician) and has been called the Trenton unconformity (Rooney 1966). The second period of erosion is associated with the modern unconformity surface.

The existence of an unconformity surface at the top of the Trenton–Black River Group carbonate sequence has been the subject of considerable debate (Churcher 1986). Some authors claim that there was widespread subaerial exposure and erosion of the unit (Rooney 1966; Churcher 1986), while others believe that the features of the contact surface between the Lindsay (Trenton) Formation and the Blue Mountain Formation shales represents a submarine corrosion surface or hardground (Gutstadt 1958; Keith, personal communication, 1986).

The strongest evidence for the presence of a regional unconformity surface at the top of the Collingwood Member is that this surface can be mapped over an area spanning several states and one province, and that it appears to cut across and remove several facies (Rooney 1966). A phosphatic bed defines the distribution of this unconformity surface throughout the Michigan and Illinois basins (Figures 7 and 8). This

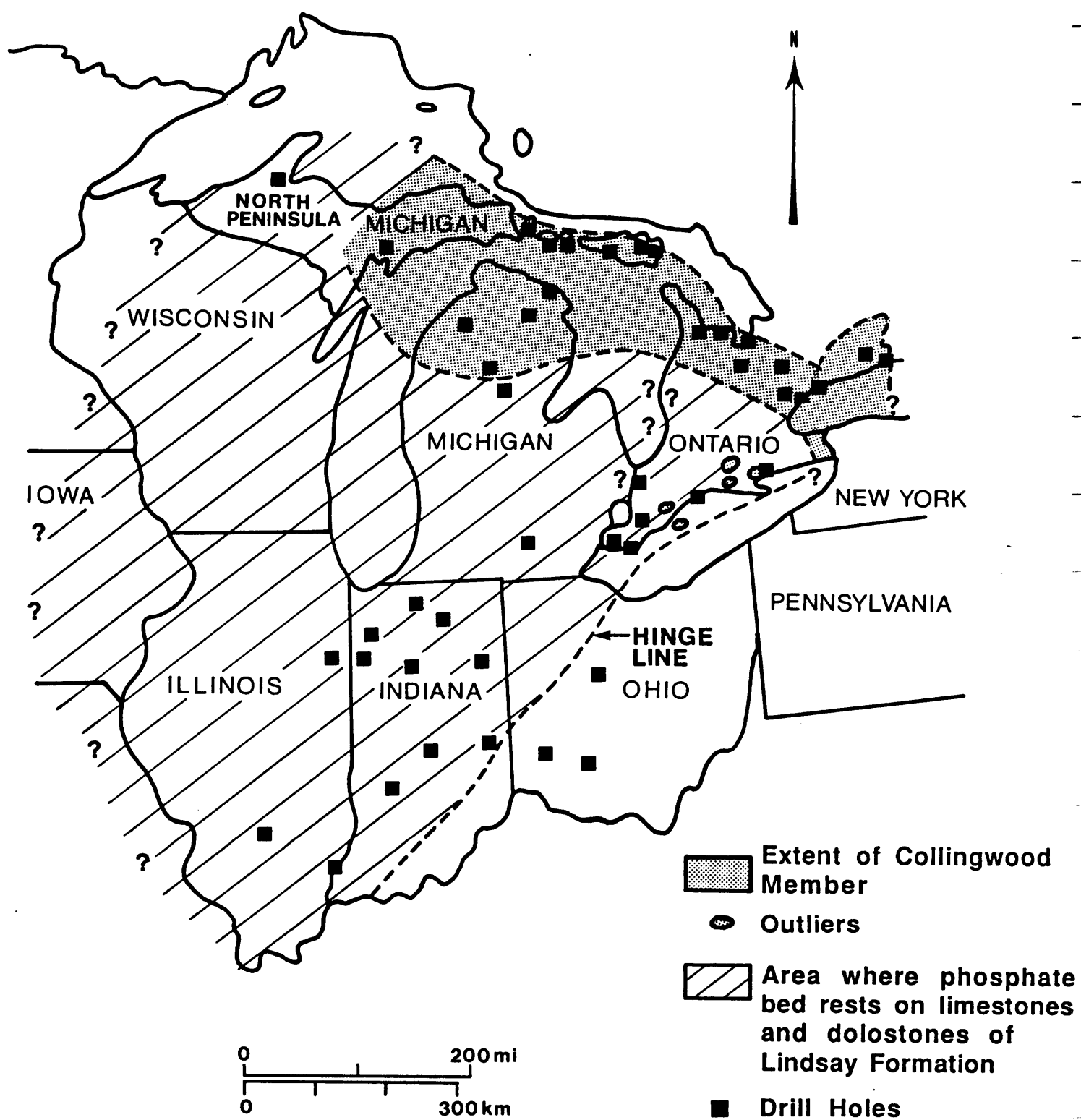
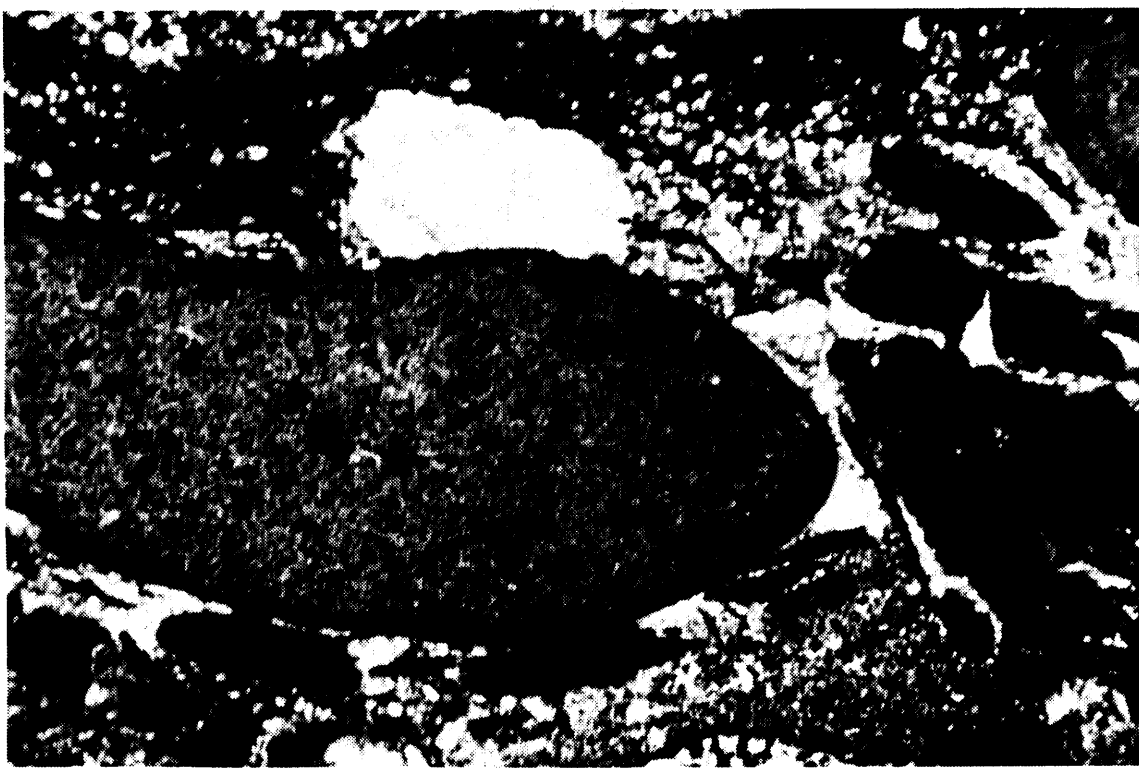


Figure 7. Regional study of the Trenton disconformity surface and distribution of the phosphate bed.



a.



b.

Figure 8. Thin section photomicrographs of the phosphatic bed found at the top of the Collingwood Member and Lindsay nodular limestone/dolomite, a) Top of Collingwood Member, well c-12 Robinson Township, Manitoulin Island, b) Top of nodular lindsay Formation limestone (no Collingwood Member present) well c-47, Milton.

phosphatic unit is well developed on the upper contact surface of the Collingwood Member. Where the Collingwood is absent, the phosphate bed rests on top of the carbonates of the Lindsay Formation. The beds range in thickness from a few to several centimetres, and are made up of phosphate nodules, phosphatized shell fragments (trilobites, brachiopods and molluscs), and pyrite, all suspended in a sparry calcite or dolomite cement (Figure 8). These beds have been previously interpreted as a debris flow (Harris 1984) and as a weathered zone (Hiatt 1985). The disappearance of these beds coincides with the appearance of the Rouge River Member in the Toronto area.

Exposure and erosion of the carbonate platform during the marine regression in the Upper Ordovician time may have resulted in the removal of the thin basinward portion of the Collingwood Member. The existence of outliers of this unit in the subsurface supports the theory that the Collingwood Member was, at one time, more widely distributed than it is today. One such outlier has been cored (C-51, U.S. Steel DDH No. 1, Norfolk Co., Charlottesville Twp. 21-I; Churcher 1984). The location of these outliers (Appendix 3, back pocket) coincides with many of the downthrown fault blocks proposed by Sanford et al. (1985). Cambrian sandstones are also preserved on the downthrown side of many of these faults.

The Rouge River Member of the Blue Mountain Formation is a stratigraphic problem in the Toronto area. The contact of this unit with the underlying Collingwood Member is frequently described as being gradational, and consists of siliceous shales with interbeds of calcareous, fossiliferous shales. Macauley et al. (1990) pointed out that this contact relationship indicates that sedimentation was continuous across the Colling-

wood–Blue Mountain contact. A similar continuation of sedimentation across this contact was reported in Ohio by Rooney (1966). He noted that the Trenton limestones are almost entirely removed north and west of a northeast-trending zone he termed the "Hinge Line" (Figure 7). To the south and east of this zone, in the Appalachian Basin, the sedimentary record is continuous across the Trenton–Upper Ordovician shale boundary and there is no indication of an unconformity surface. He proposed that this hinge zone represents an area of structural weakness, which would be defined in modern terms as the boundary between the platform and the foredeep.

Similar structurally controlled sedimentation may have occurred in the Toronto area during Rouge River time. Russell and Telford (1983) proposed that the restricted areal distribution of the Rouge River Member may have been the result of either erosion prior to the deposition of the blue-grey shales the Thornbury Member (Russell and Telford 1983) of the Blue Mountain Formation, or a facies change. Subsequent drilling has revealed the presence of blue-grey Thornbury Member shales overlying interbedded grey and black shales of the Rouge River Member in drill holes S.I.S. No. 1 and Nobleton 1 (Johnson et al. 1983a). Like the Collingwood Member, this unit thins and disappears to the west near Milton, suggesting that the distribution is controlled more by erosion than by a facies change. Possible erosional remnants of the Rouge River Member were also noted in the Milton and Clarkson holes (Johnson 1983). A phosphatic bed was found to be developed on the top of the remnant in the Milton core. Additional drilling in this region, however, would be required to fully test this hypothesis.

The isopach and subcrop pattern maps (Appendix 3, back pocket) also show that the Collingwood Member tends to thin to the north and northeast, with local thickening in the Collingwood and Manitoulin–St. Joseph island areas, possibly associated with structural features or pre-existing local topographic lows. This thinning of the unit to the north cannot entirely be attributed to the modern unconformity surface as some of the thinned unit lies in the subsurface. This may indicate that the Collingwood Member was eroded in these regions prior to the deposition of the Blue Mountain Formation. This is evident in the increased thickness of the phosphatic bed on Manitoulin and St. Joseph islands. As hypothesized by Hiatt (1985), a withdrawal of the sea to the north during this time could have resulted in periods of erosion and possible submarine corrosion in these areas.

In summary, the distribution and thickness variability of the Collingwood Member in the subsurface may be a function of post-depositional erosion. The eastern limit of the unit is controlled by the modern erosional surface. Local faulting, or paleotopographical lows could have resulted in greater thicknesses and the selective preservation of the Collingwood Member in some areas. Detailed paleontological work and further drilling on a regional scale would be required, however, to fully test these hypotheses.

3.2 Characteristic Geophysical Well Log Responses

Downhole geophysical data (primarily the natural gamma logs) were used to assist in the delineation of the Collingwood Member in the subsurface. The following section contains a summary of the geophysical log responses that have been used to

evaluate the Collingwood Member in the subcrop and subsurface. A more detailed description of the characteristic log responses is provided by Russell and Telford (1983).

The upper contact of the Collingwood Member is marked by a decrease in the natural gamma intensity (Russell and Telford 1983; Churcher 1984). This drop in gamma intensity becomes more pronounced with depth and gradually trails over to the response that would be obtained from a limestone (Figures 9 and 10). This response results from an increase in the carbonate content and a corresponding decrease in the clay within the Collingwood Member with depth. Figure 11 shows typical gamma log responses where the Collingwood Member is absent.

The upper contact can also be determined from the response of the focussed electric or resistivity log (Figure 12). Russell and Telford (1983) noted that an increase in the resistivity (up to 5000 ohm-metres) also occurred at the upper contact. This increased resistivity was attributed to the presence of an increased amount of highly resistive organic material within the Collingwood Member, but may also be due to the presence of bitumen (10 to 50%). Passey et al. (1990) stated that increased resistivity of organic-rich horizons is directly proportional to their level of organic maturation (i.e., the presence of bitumens resulting from catagenesis).

4. ORGANIC GEOCHEMISTRY

4.1 Kerogen Richness and Type

Over 1000 samples were selected for Total Organic Carbon (TOC) content from over 90 regional boreholes. These samples included cuttings from over 70 oil exploration

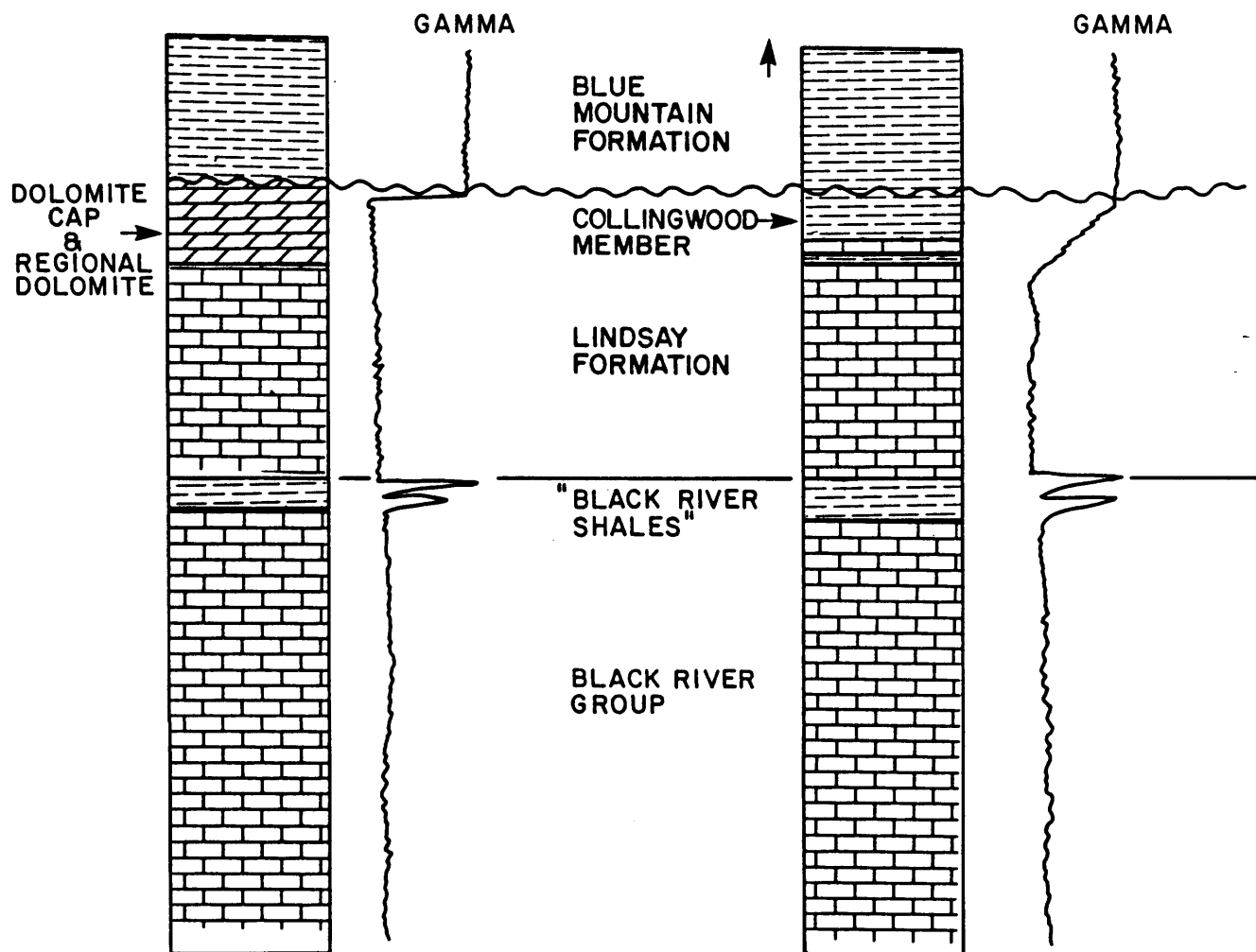


Figure 9. Schematic stratigraphic section and gamma log responses.

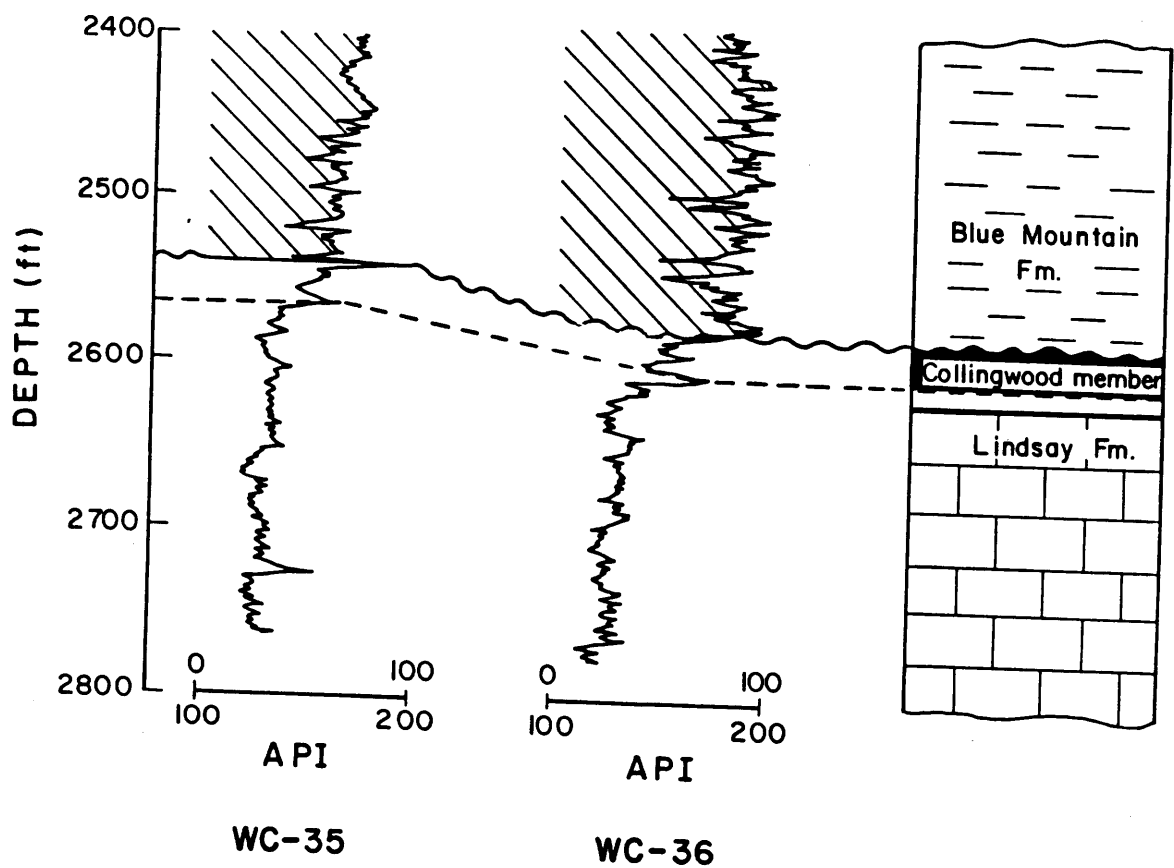


Figure 10. Actual gamma log responses - Collingwood Member present. The cross-hatched pattern indicates use of the lower (100 to 200 API) scale. Borehole locations are given in Appendix 3.

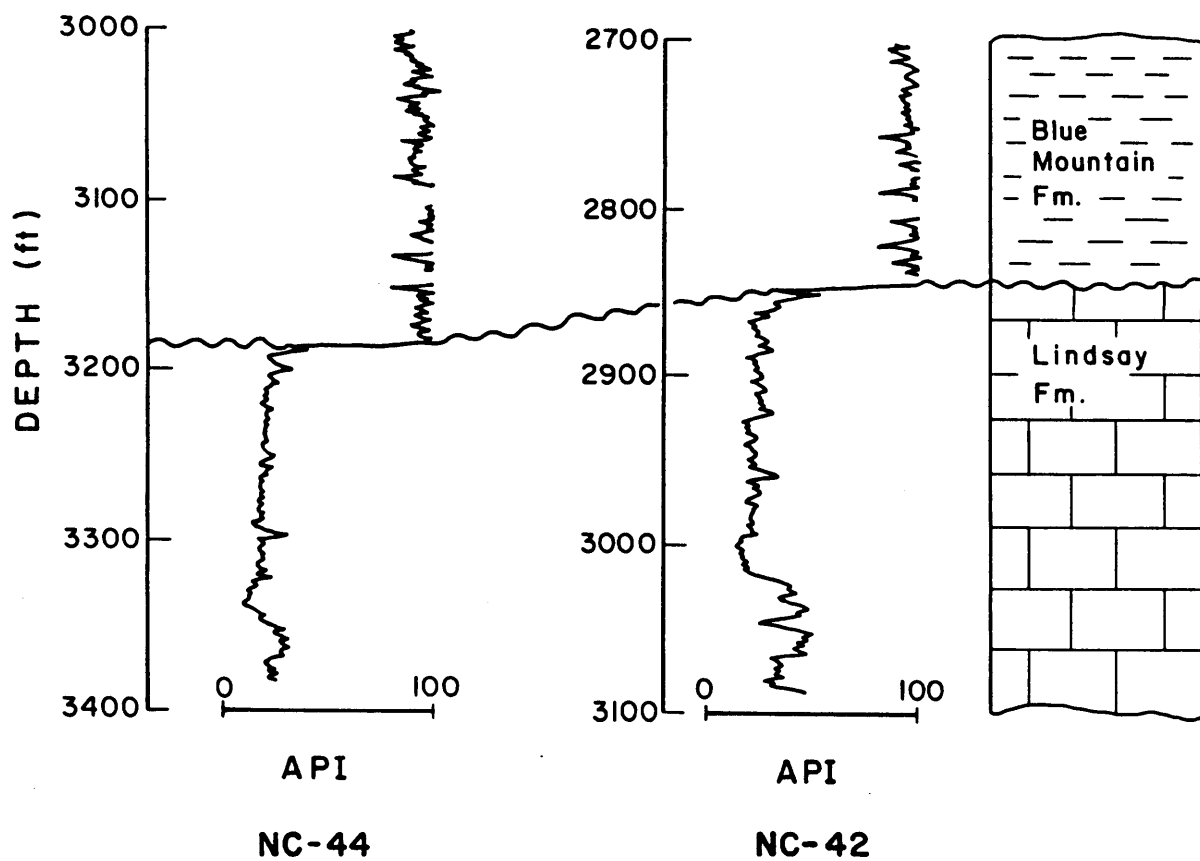


Figure 11. Actual gamma log response - Collingwood Member absent. Borehole locations are given in Appendix 3.

DOWNTOWN TORONTO BOREHOLE

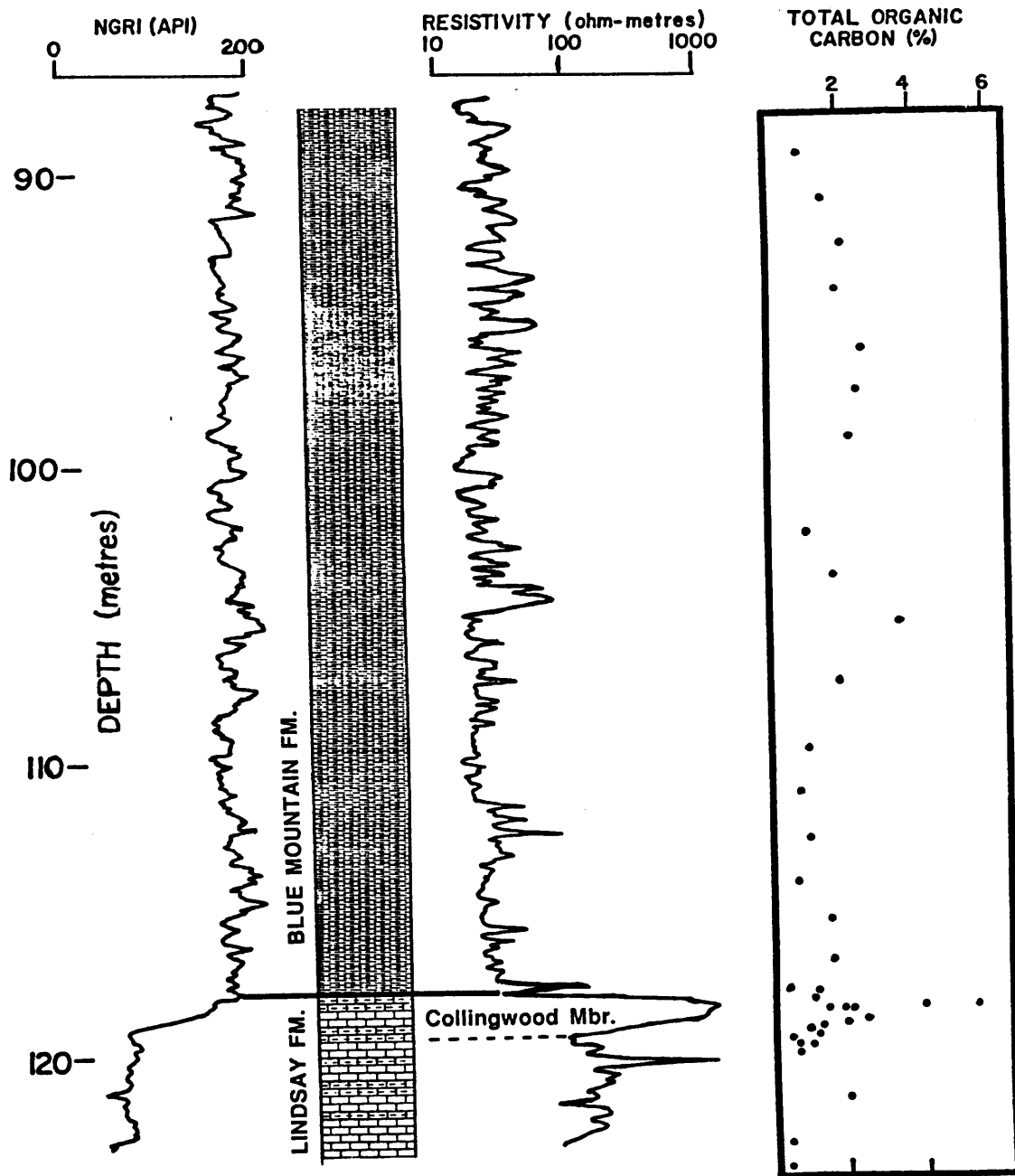


Figure 12. Typical gamma and focused electric log response - Toronto area (from Russell and Telford 1983).

and development wells and core from 24 other holes (Appendix 3). These samples, straddling the Lindsay–Blue Mountain contact, were analyzed using equipment developed at the University of Waterloo. An outline of the methodology can be found in Appendix 1. For a more detailed description, the reader should refer to Churcher and Dickhout (1987).

Total Organic Carbon analysis provides a basis for evaluating the oil shale (kerogen) richness on a regional scale. Measured values for the Collingwood Member range from 0.9 to 11.2% by weight and averaged 4.3% based on the data contained in Barker (1985) and Churcher (1984). The bulk of the data used in this report was obtained from TOC analyses performed on sample material obtained from the regional and shallow OGS cored holes, and is summarized in Table 3.

The TOC data indicates an overall increase in the average amount of organic matter within the Collingwood Member from the Toronto–Pickering area to the Manitoulin–St. Joseph island area. This trend corresponds to the direction of shallower water conditions as proposed from faunal evidence presented in Harris (1984). Shallower water on platform edges tends to have higher organic productivity. Average values from each of the regions within the study area were 3.5% in the Toronto–Pickering, 3.9% in the Collingwood, and 5.5% in the Manitoulin–St. Joseph island areas. These trends in the TOC data were first described by Barker et al. (1983) and Macauley and Snowdon (1984) using smaller databases. These authors also noted that the trend towards a reduction in the amount of organic matter continued to the east. In the Ottawa area,

LOCATION	NUMBER OF SAMPLES	AVERAGE TOC (%)	RANGE TOC (%)	ESTIMATED OIL YIELD (l/tonne)	THICKNESS (m)	AVERAGE BULK DENSITY (kg/m3)
=====						
A. Toronto-Pickering						
SIS 01	33	3.70	1.0-6.0	16.10	4.65	2500.00
02	5	3.80	1.8-5.2	16.90	4.70	2450.00
03	5	4.60	3.7-6.8	23.20	6.19	2450.00
04	3	1.70	1.5-1.9	1.10	1.46	-
04a	12	2.60	0.9-5.3	8.20	-	-
OGS 83-2	no data	-	-	-	-	-
3	no data	-	-	-	-	-
Nobleton-1	7	2.90	1.6-3.7	10.10	9.44	-
TOTAL	65 samples					
AVERAGE		3.5%		14.6 l/t (0.08 bbl/ton)		
RANGE				0-39.4 l/t (0.21 bbl/ton)		

B. Collingwood-Bruce Peninsula						
Clgd-1	30	4.10	0.9-8.6	19.10	9.58	2500.00
2	5	2.10	0.5-4.8	4.10	10.16	2450.00
3	2	5.60	4.3-6.9	30.40	4.80	-
4	no data	-	-	-	-	2200.00
4b	30	4.70	1.1-9.4	23.60	10.04	-
6a	3	3.00	0.6-4.7	10.90	6.29	2400.00
7a	2	3.90	3.8-4.0	17.60	7.32	2400.00
16	21	5.00	1.5-9.6	25.90	10.06	2400.00
17	no data	-	-	-	-	-
OGS 83-4	no data	-	-	-	-	-
82-4	8	2.50	1.1-3.7	7.10	1.75	-
TOTAL	101 samples					
AVERAGE		3.9%		17.6 l/t (0.09 bbl/ton)		
RANGE				0-60.5 l/t (0.32 bbl/ton)		

C. St. Joseph-Manitoulin Islands						
SIS 05	21	6.20	2.3-10.5	34.92	6.45	-
06	24	5.20	1.9-9.0	28.20	5.97	-
07	19	5.90	3.9-9.1	32.70	4.83	-
OGS 83-5	no data	-	-	-	-	-
85-7	no data	-	-	-	-	-
83-6	20	4.80	1.0-11.2	24.40	10.55	-
TOTAL	84 samples					
AVERAGE		5.5%		30.0 l/t (0.16 bbl/ton)		
RANGE				0-72.5 l/t (0.38 bbl/ton)		

Table 3. Summary of Total Organic Carbon and Oil Yield Data.

TOC values obtained from the Billings shale (Collingwood Member equivalent) averaged 2.6%.

In addition to TOC analysis, a select group of samples was submitted to the Institute of Sedimentary and Petroleum Geology (ISPG) in Calgary, Alberta, for Rock-Eval analysis, and to the Department of Chemical Engineering at the University of Waterloo for elemental analysis (C, H, O, ash content). Both of these analytical techniques have been used to determine the indices which are plotted on van Krevelen-type diagrams. These indices are termed Hydrogen Index (HI) and Oxygen Index (OI) in the Rock-Eval process, and H/C and O/C ratios in the elemental analysis process. Van Krevelen-type diagrams are used to determine the type of organic matter and the level of organic metamorphism (LOM). The latter parameter will be discussed later in this report.

From these van Krevelen-type diagrams Macauley and Snowdon (1984) and Barker et al. (1983) determined that the kerogen found within the Collingwood Member was a mixture of Types I and II. These types of kerogen are commonly found in oil shales and are known to produce primarily liquid hydrocarbons upon pyrolysis.

A visual assessment of samples of acid-extracted kerogens from the Collingwood Member was reported in Barker et al. (1983). Their findings indicate that these kerogens are made up of a mixture of marine-derived (algal/bacterial matter) amorphous and terrestrial-derived (spores and pollen) exinous material. This marine-terrestrial mixture, deposited in a shallow marine environment, would generally indicate that the kerogen

would be classified as Type II (Tissot and Welte 1978). Barker et al. (1983) also reported that the oil shales in the Collingwood area appear to contain significantly more amorphous material than do those from the Manitoulin Island and Toronto areas. This may reflect differences in the paleo-water depths, distance from the shoreline, and prevailing wind direction between the two areas at the time of deposition.

4.2 Level of Organic Maturation (LOM)

Several techniques have been used to determine the level of organic maturation for each of the subcrop areas. These techniques include: Rock-Eval pyrolysis, vitrinite reflectance, thermal alteration index (T.A.I.), conodont alteration index (C.A.I.) and percentage of hydrocarbon in bitumen.

Level of organic maturation data obtained using these techniques are reported in Macauley and Snowdon (1984), Barker et al. (1983) and Legall et al. (1981). In general, these authors noted that the Collingwood Member along the subcrop edge in southwestern Ontario is mature to marginally mature (i.e., it has produced a small amount of liquid hydrocarbons). In the Ottawa area, the Billings shale (Collingwood Member equivalent) is mature to overmature (i.e., it has generated all of the liquid hydrocarbons that it is capable of producing). Macauley and Snowdon (1984) also noted that the LOM values for the Collingwood and Manitoulin Island areas within the subcrop belt were very similar, with samples from Manitoulin Island indicating slightly higher maturation levels. Samples from the subcrop belt near Toronto (Whitby) area were found to be significantly more mature than those samples taken further to the northwest (Macauley and Snowdon 1984, Figure 3). These samples indicated a low to

moderately mature maturation level which is reflected in both the Tmax (temperature of maximum hydrocarbon generation) and Production Index (PI) data. A summary table of these data is contained in Appendix 2.

Potential oil shales, by definition, contain kerogen that is immature to marginally mature. The overmature LOM values obtained for the Billings Formation shale in the Ottawa area, therefore, eliminate it as a potential oil shale. The low to moderate LOM values in the Toronto-Pickering area limit the oil shale potential of the Collingwood Member in this area.

4.3 Estimation of Shale Oil Yield

Four pyrolysis techniques were used to evaluate the potential shale oil yields from the Collingwood Member. These techniques include:

- 1) **Hytort Pyrolysis.** A technique in which the sample is retorted in a hydrogen-rich atmosphere;
- 2) **Rock-Eval Pyrolysis.** A technique where 100 mg of sample material is pyrolysed in an inert atmosphere by increasing the temperature slowly to less than 550°C;
- 3) **Yield On Pyrolysis.** A technique where 5 to 20 mg of sample material is pyrolysed in an inert atmosphere and resultant liquids and gases are measured using a flame ionization detector (FID); and

- 4) **Modified Fischer Assay Pyrolysis.** This is the ASTM standard shale oil retorting technique in which 200 g of sample are pyrolysed and the volumes of liquid hydrocarbons evolved are measured.

Details of each of these methods are described in Appendix 1 and in Johnson et al. (1989), Barker et al. (1983) and Macauley and Snowdon (1984).

For the purposes of this report the linear relationship between Total Organic Carbon and Fischer Assay (FA) Pyrolysis Yield was used. A preliminary plot showing the linearity of the relationship between these two parameters was published by Barker et al. (1983). The equation used to obtain the shale oil yields found in Table 3 is as follows:

$$\text{Fischer Assay Yield (l/tonne)} = (\% \text{TOC} \times 7.52) - 11.7$$

The shale oil yield values found in Table 3 are slightly lower than those that would have been obtained using similar relationships derived from the Rock-Eval or Hytort pyrolysis techniques. This indicates that shale oil yields could be increased using a different retorting technique. A linear relationship between Yield on Pyrolysis values and Fischer Assay Pyrolysis yields was reported by Barker et al. (1983).

The data presented by Barker et al. (1983) and Macauley and Snowdon (1984) for the Collingwood Member indicate that the potential shale oil yields from the Manitoulin–St Joseph island and Collingwood areas are very similar and are significantly higher than those obtained from sample material analyzed from the Toronto-Pickering area. As discussed earlier in this chapter, these differences in shale oil yields are likely

related to the observed differences in organic matter type and level of thermal maturation.

The average shale oil yields, calculated using the FA/TOC relationship for the data published by Barker (1985), increased from 14.6 L/t in the Toronto–Pickering area to 17.6 L/t in the Collingwood area and finally to 30 L/t on Manitoulin and St. Joseph islands. Shale oil yields from individual organic-rich beds, however, range from a maximum of 39.4 L/t (0.21 barrels/ton) in the Toronto area to 72.5 L/t (0.36 barrels/ton) on the northern islands. An average shale oil yield of 21 L/t was selected for use in the resource evaluation calculations.

5. RESOURCE EVALUATION

5.1 Total Resource Estimates

A volumetric reserves calculation was performed using all available data in order to estimate the total shale oil potential of the Collingwood Member in southwestern Ontario. The potential reserves from the Billings shale near Ottawa were purposely left out of these calculations because of the thermal maturation problems (i.e., high LOM values) discussed earlier in this report. The values presented in this chapter are by no means an indication of the recoverable reserves, and are only provided to serve as a general guide.

The volumetric estimates were subdivided into two parts; a Land Accessible Resource Estimate and an Offshore Resource Estimate. These two estimates, when combined, yield the Total Canadian Formation Estimate for this rock unit. Each estimate

was further subdivided into subcrop/outcrop and subsurface resource potential, reflecting the vastly different set of economics and extraction techniques involved in recovering the shale oil from each of these regions.

All of the resource estimates were calculated using the following equation:

$$\text{Shale Oil Reserves} = \text{Rock Volume (m}^3\text{)} \times \text{Bulk Density (kg/m}^3\text{)} \times \text{Shale Oil Yield (L/t)/1000}$$

The rock volume used in this equation is obtained by multiplying the planimeted surface area (m²) by the thickness of the rock unit (m). This data was provided by Sproule Associates Limited in Calgary, Alberta, using a digitized version of the isopach and subcrop maps found in the back of this report. There are several limitations involved in using the rock volume numbers in the calculations of the shale oil reserves. Firstly, the isopach thickness of the rock unit is a combination of both the organic-rich upper portion of the unit and the organic-poor lower interbedded portion. The inclusion of these beds in the isopach thickness was unavoidable in order to make use of all of the available subsurface data (cuttings and geophysical well logs). Secondly, the location of the isopach contours themselves is somewhat arbitrary due to a limited data set. Their location will affect the surface area measured for a given thickness. Finally, the subcrop pattern used in the estimate of the subcrop/outcrop reserves is poorly defined due to limited borehole and outcrop control.

The surface areas and rock volumes used in the reserves estimate calculations are as follows:

Land Accessible (onshore)

• Subcrop/Outcrop	- surface area	-	2082 km ²
	- rock volume	-	2.97 x 10 ⁹ m ³
• Subsurface	- surface area	-	24375 km ²
	- rock volume	-	10.8 x 10 ¹⁰ m ³

Offshore

• Subcrop/Outcrop	- surface area	-	1347 km ²
	- rock volume	-	3.84 x 10 ⁹ m ³
• Subsurface	- surface area	-	16164 km ²
	- rock volume	-	5.7 x 10 ¹⁰ m ³

The bulk density value used in the calculations is 2450 kg/m³. This value represents an average bulk density for the unit and was obtained from corrected downhole density logs. The rock volumes calculated from the isopach map are converted to a weight (in kilograms) by multiplying by the bulk density. Unfortunately, no laboratory density measurements could be found for this rock unit.

The shale oil yield value used in the reserves calculations was 21 L/t. This value represents an average shale oil yield from each of the three areas studied and was calculated using the linear relationship that exists between TOC and FA yield. This oil yield value does not, however, take into account the differences in oil yield that may occur from one region to the next as a result of differences in organic matter type, richness, and maturity.

The following values were obtained for each of the reserve estimates:

Land Accessible Resource Estimate

Subcrop/Outcrop - $1.5 \times 10^{11} \text{ m}^3$ or 9.6×10^{11} barrels/ton

Subsurface - $5.5 \times 10^{12} \text{ m}^3$ or 3.5×10^{13} barrels/ton

Offshore Resource Estimate

Subcrop/Outcrop - $2.0 \times 10^{11} \text{ m}^3$ or 1.2×10^{12} barrels/ton

Subsurface - $2.9 \times 10^{12} \text{ m}^3$ or 1.8×10^{13} barrels/ton

Total Canadian Formation Estimate

$8.8 \times 10^{12} \text{ m}^3$ or 5.5×10^{13} barrels/ton

5.2 Exploitation/Development Considerations

The potential for economically recovering shale oil from the Collingwood Member is limited due to a combination of market price, high extraction, processing and transportation costs, limited unit thickness/oil yield, land availability (leasing) and present land use and environmental constraints.

In a surface mining and retorting operation the overburden must first be removed. In this case, the overburden consists of between 0 to 200 m of glacial sediments and, in some areas, between 10 to 20 m of Blue Mountain Formation shales. Stripping ratios are therefore greater than 50:1. The oil shale would have to be crushed and retorted to produce the shale oil, and the shale oil would then have to be further refined to produce usable end products.

The limited thickness (maximum 12 m) and potential oil yield of the unit would prohibit the viability of underground mining. Mining, described in Dusseault et al. (1983), would also entail crushing, retorting, and refining costs.

The use of *in situ* retorting techniques is also limited by the thickness of the unit in the subsurface. It would be very difficult and costly to drill horizontal wells into the Collingwood Member. These wells would be required to obtain sufficient surface area for an introduced heat source within the oil shales.

Transportation costs must also be considered in any economic evaluation. Shale oil produced on Manitoulin Island could be shipped to market via tanker on the Great Lakes, truck, rail or pipeline. Any route taken would require ground transportation and there is the added risk of damaging an environmentally sensitive area. In the Collingwood area, the shale oil would have to be trucked to the nearest refinery. In the Pickering-Toronto area there would be a ready market for the shale oil and transportation costs would be minimal. The Collingwood Member in this area, however, is leaner and yields less shale oil than in the other two areas.

Land availability and current land use in southwestern Ontario present another problem in the development of the Collingwood Member oil shale resources. Much of the oil shale outcrop lies either in, or near, boundaries of major population centres, where land costs are high and accessibility limited, Provincial Parks or Indian Reservations.

Other constraints on the development of the Collingwood Member shale oil reserves are the environmental dangers. Surface mining of oil shale would require that vast areas be strip mined. The retorting process produces harmful ammonium sulphate which must be removed from the flue gases before discharging them to the atmosphere. The extremely heavy sludge resulting from the shale oil refining process, however, may be used for paving, and the spent oil shale residue may be used as a low-grade aggregate.

Although its potential as an economically viable oil shale is presently limited, the Collingwood Member does represent a potential oil and gas source rock in the subsurface. The level of organic maturity determined from sample material obtained from the subcrop belt in the Manitoulin-St. Joseph island and the Pickering-Toronto areas is sufficient to have produced oil. In fact some samples have been found to contain between 10 to 50% bitumen (Barker et al. 1983). Although the distribution of the main part of the Collingwood Member is limited, it may still represent the source of the oil showings and seeps found on Manitoulin and St. Joseph islands. If fractured, dolomitized reservoirs, similar to those found in the Windsor-Leamington area of southwestern Ontario, exist in the Middle Ordovician carbonates of the Lindsay Formation to the north, there may be the potential for some conventional oil and gas reserves. To date, however, the known reservoirs are subeconomic.

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APPENDIX 1: Outline Of Organic Geochemical Techniques Used In This Study.

INTRODUCTION

Geochemical analysis of the Collingwood oil shales was undertaken to evaluate their potential as a source of petroleum products and to assist in the geological studies of the factors controlling their potential. The term "oil shales" is rather misleading (Tissot and Welte 1978; Macauley et al. 1985). Oil shales do not contain oil nor are they necessarily shales. They are fine-grained sedimentary rocks (limestones, dolostones, shales, argillites) which contain organic matter sufficient to produce petroleum products in economic amounts when heated in an oxygen-depleted atmosphere. This heating or retorting without oxygen is a form of pyrolysis. Organic-rich sedimentary rocks may be combusted in oxygen, or air, to yield heat and may have value for other processing, but these aspects are beyond the scope of this geochemical study.

The petroleum product yield, both specific products and amounts, depends upon the commercial process used. It also depends upon the 'richness' of the rock, which is controlled by the organic matter content and type of organic matter present. For this study, richness and the geological/geochemical control of richness was evaluated by geochemical analyses of rock samples; these analyses can be grouped into three categories:

- 1) *Pyrolysis yield.* The standard assay for yield upon retorting pyrolysis is the Fischer Assay (FA). This analysis requires large (200 g) samples and is relatively expensive. However, a large Fischer Assay data base exists for many oil shales. Retorting with a hydrogen atmosphere can enhance yields and this possibly was evaluated by HYTORT (R) retorting.
- 2) *Organic matter content.* The organic matter content of Collingwood oil shale samples was assessed by measurement of their total organic carbon (TOC) content. Carbon generally makes up from 60 to 90% by weight of sedimentary organic matter. For formations of limited depth and areal extent containing a similar type of organic matter, such as is the case for Ontario's potential oil shales, the weight percent carbon is much more limited and TOC accurately assesses the organic matter content.
- 3) *Organic matter geochemistry.* The pyrolysis yield of oil shales also depends upon the chemistry of the organic matter. Hydrogen-rich organic matter yields more petroleum-like pyrolysis products, termed pyrolysates, than hydrogen-poor organic matter. Pyrolysis yields seem to be limited more by organic hydrogen than by organic carbon content. Thus, the nature of the organic matter must be assessed in the evaluation of this resource. Such studies also assist in the determination of geological controls of oil shale richness. Organic matter in sedimentary rocks is operationally divided into solvent-soluble bitumen and solvent-insoluble kerogen. The former more closely approaches the composition of crude oils, being relatively enriched in hydrogen, and it is generally considered to be derived from the thermal maturation of kerogen. The amount of bitumen generated is directly proportional to the hydrogen-richness of the initially-deposited organic matter. Similarly, the relative proportion of bitumen to kerogen increases with maturation level. By definition, all oil shales contain indigenous organic matter (kerogen) at low to intermediate thermal maturation levels.

The organic matter geochemistry is assessed by a number of techniques. Temperature-programmed pyrolysis, including Rock-Eval analysis, permits estimates of the bitumen/kerogen proportion, and gas chromatography/mass spectrometry of the pyrolysates helps characterize the chemistry of the bitumen and kerogen. The origin and thermal maturation level of kerogen is assessed by elemental analysis, infrared spectroscopy and stable carbon isotopic (C^{13}/C^{12}) analyses.

The depositional environment of organic-rich rocks can be partially assessed by geochemical analyses. Parameters used include carbonate content (as total inorganic carbon, or

TIC), total sulphur content, phosphorous content (as P_2O_5), and stable carbonate isotopes of the carbonate minerals.

This comprehensive suite of geochemical analyses provided the geochemical basis for the evaluation of the Collingwood's oil shale as a resource. Complete evaluation, however, requires the integration of this data with geological, engineering and economic studies.

TOTAL ORGANIC CARBON (TOC)

The method used for determining the total organic carbon content of the Collingwood Member rock samples follows that outlined in Churcher (1984) and Churcher and Dickhout (1987). A sample weight of 0.2 to 0.5 g of finely crushed (<200 mesh) rock was weighed onto a glass microfibre filter paper. The filter paper was placed on a Hirsch funnel and the sample acidified with warm 30% HCl and then thoroughly washed with deionized water. Bituminous samples were wetted with a drop of methanol prior to acidification. The inorganic-carbon-free sample contained inside the filter paper was dried and then combusted at about 800°C in a Lindburg tube furnace. The combustion products were swept with CO_2 -free oxygen through a water sorban 1 (Drierite) and then into a Beckman non-dispersive infrared detector, where the CO_2 from combustion of organic matter was detected. Quantification was accomplished by comparing the area of the CO_2 peak from sample combustion to that of gravimetrically prepared charcoal-pumice standards. This calibration of the detector response was made daily. In addition, two homogeneous "in house" standards prepared from the Kettle Point Formation material were analyzed frequently to confirm reproducibility. These and other standards were analyzed by other laboratories and the agreement was very good.

Churcher (1984) evaluated the major sources of bias in this analysis, especially the potential loss of organic matter during acidification and methanol addition, as well as the potential addition of carbon via the methanol. No significant bias was documented. For the major "in house" standards, analyzed from 8 to 39 times, the relative standard deviation was less than 5.5%. The mean differed from the average value reported by all other labs by less than 5.4%, except for CLGD-Composite, where a difference of about 12% was found. Therefore, the TOC analyses are generally accurate and reproducible to within about 5% over the TOC concentration range of 4 to 15%. Poorer accuracy and precision may occur at lower concentrations, but accuracy at these lower concentrations is of less significance in evaluating these potential oil shales.

FISCHER ASSAY (FA)

The standard method for evaluating the oil yield upon retorting oil shales is the Fischer Assay. The technique is described by Hubbard (1965). All Fischer Assay analyses were performed by the Analytical Services Laboratory, Colorado School of Mines Research Institute. One hundred grams of less than 8 mesh shale chips were added to the retort in five layers to promote effective pyrolysis. The retort was heated without air entry to 500°C over a period of 40 minutes and held at 500°C for 20 minutes. The pyrolysate was collected in an attached receiver held between 0° and 37.8°C. The volume and weight of condensate (oil plus water) were determined and, if sufficient oil was present, its specific gravity was determined. The volumes of oil and water produced were converted to units of US gallons per ton or litres per metric ton. Unaccounted sample weight loss (or gain) was also reported and the difference, if a loss, was usually attributed to the generation of uncondensed gases. Hubbard (1965) reported that oil yields for an oil shale with a mean oil yield of 39.5 gallons per ton had a range from 38.3 to 40.2, or within 3% for 12 replicate analyses. Water and oil specific gravity showed a similar small range of values.

BITUMEN AND KEROGEN ISOLATION

Solvent Extraction for Bitumen Isolation

After experimenting unsuccessfully with a rapid chloroform extraction of bitumen, a regular soxhlet extraction procedure was employed. This involved the continuous extraction of rock by chloroform over a 12 to 14 hour period. The chloroform reservoir was heated, the chloroform vapours condensed and recirculated through the rock powder (greater than 200 mesh). The chloroform was then concentrated to about 1 cm³ by evaporation in a modified Kuderna-Danish concentrator. This procedure extracts the chloroform-soluble organics (bitumen) and retains those less volatile than chloroform, which has a boiling point of about 62°C.

Kerogen Isolation

Powdered (less than 100 mesh) rock samples were alternately digested in 50% HCl and 50% HF to remove inorganic mineral matter. The kerogen was further purified from inorganically contaminated kerogen by density difference in a ZnCl₂ solution in which the purest kerogen rose to near the top of the solution. This procedure was found to leave up to 37% inorganic material in the kerogen. Subsequent kerogen isolations involved initial soxhlet extraction with chloroform to remove bitumen, followed by leaching with concentrated HCl and HF to remove inorganic minerals. The acid-leaching was repeated once. The kerogen concentrate was repeatedly rinsed with deionized water, separated by centrifugation with the final wet isolate allowed to dry at room temperature before storage over a desiccant (Drierite). Generally, the kerogen was found to contain less than 20% inorganic impurities.

This kerogen was then subjected to various geochemical analyses including ash content, elemental carbon and hydrogen analysis, pyrolysis and infrared absorption studies.

ASH CONTENT OF KEROGEN

The kerogen extract was heated to about 80°C and cooled in a water vapour-free container. An aliquot of about 0.1 g was then weighed, combusted at 600°C for 1 hour, cooled and reweighed. The residual material was taken as inorganic ash.

WHOLE ROCK ANALYSIS

Approximately 10 mg of pulverized whole rock powder was placed in the quartz tube of an Envirochem model 787 high temperature furnace. The sample was purged with helium for a few minutes, then heated from ambient temperature to 300°C at 40°C/min. and held at the final temperature until the signal from the FID monitoring the evolution of hydrocarbons had returned to the baseline. At this point the hot zone was removed from the sample, the pyrolysis products having been collected on a tenax trap.

With the completion of the cycle, the tenax was thermally desorbed, and a small fraction of the products split to a flame ionization detector to produce a "bitumen, total hydrocarbon" peak. The rest was transferred onto a narrower bore trap for subsequent desorption onto a 60 m DB5 quartz capillary column for chromatography. Here the individual hydrocarbon components were resolved before detection by an FID. Pyrolysis components were identified on the basis of retention time determined with pure standards.

The hot zone of the high temperature furnace was then repositioned over the sample and heating was resumed at the previous rate until a temperature of 700°C was reached. This resulted in the thermal breakdown of kerogen, the products of which were handled in the same way as those of bitumen. The initial split to the FID generated a "kerogen, total hydrocarbon" peak and the kerogen pyrolysate chromatography was carried out as with the bitumen pyrolysate.

The chromatograph uses, in both of the above cases, a 60 m DB5 column, heated from 35° to 280°C at a rate of 8°C/min. and held at 280°C for 10 minutes.

The following parameters are determined from the chromatograms:

- 1) **Transformation Ratio.** The transformation ratio is defined as bitumen/bitumen+kerogen and is obtained from the total hydrocarbon responses (bitumen, total hydrocarbon/(bitumen, total hydrocarbon plus kerogen, total hydrocarbon)). It is an indicator of thermal maturation; that is, maturity is greater with increasing value.
- 2) **Pristane/phytane Ratio (PR/PH).** The peak areas of these two isoprenoid compounds are obtained from the bitumen pyrochromatogram. The pristane/phytane ratio is commonly used to indicate the lacustrine/terrestrial nature of the original organic material. Generally, ratios lower than 1.5 indicate a marine shale-carbonate sequence while ratios greater than 3.0 indicate a significant amount of terrestrial source material. This ratio can also be affected by depositional environment conditions (i.e., whether the environment was oxidizing or reducing) and by maturation.
- 3) **Odd-even Preference (OEP).** The predominance of odd or even n-alkanes is determined by summing the peak areas on odd and even n-alkanes in the bitumen pyrochromatogram. The C₁₆ to C₂₀ n-alkanes are examined and the ratio established according to the method of Scalan and Smith (1970).
- 4) **p+m-xylene/n-octene Ratio.** This ratio is calculated from the areas of the appropriate compound peaks on the kerogen pyrochromatogram. It defines the aromaticity of the kerogen and serves as an indicator of source material type according to the classification scheme of Larter and Douglas (1978). The scheme is defined as follows:

<i>Kerogen Type</i>		<i>Ratio Value</i>
Type I: alignites		R < 0.4
Type II: sporinites		0.4 < R < 1.3
Type III: vitrinites		R > 1.3

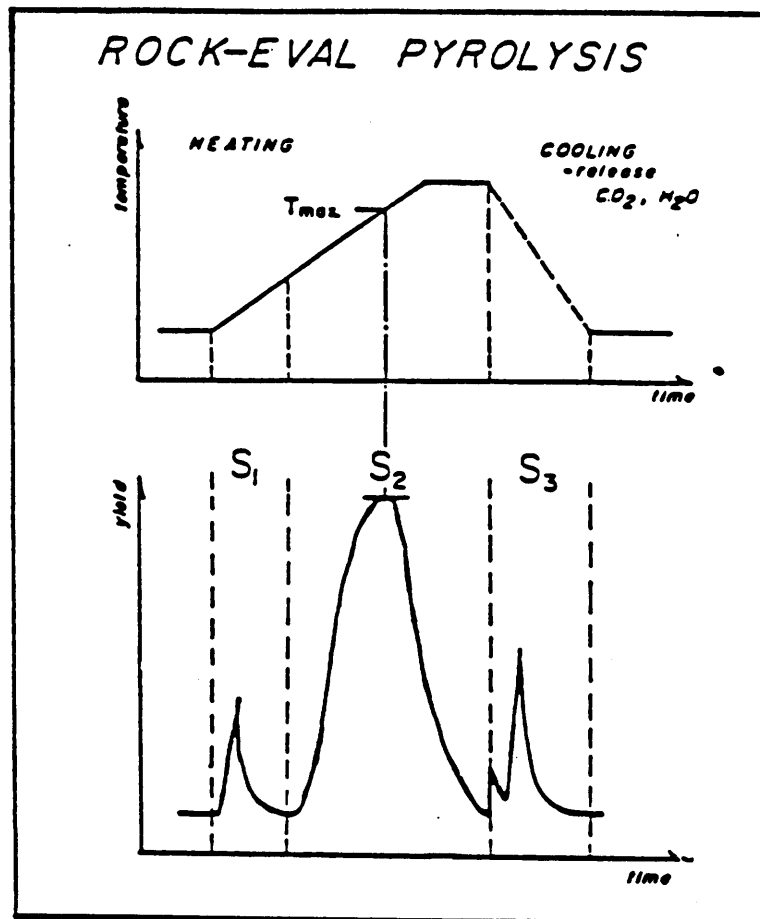
For quality control purposes, four samples of the Collingwood Member from borehole CLGD-4, at a depth of 70.31 to 70.41 m, were pyrolyzed (room temperature to 300°C) and the bitumen pyrolysate analyzed by gas chromatography. The values of various geochemical parameters calculated from the chromatogram are shown in Appendix 2. Interpretation of the results must consider the 9 to 24% standard deviations observed for these replicate analyses.

ROCK-EVAL ANALYSIS

Rock-Eval whole-rock pyrolysis was conducted by the Institute of Sedimentary and Petroleum Geology (I.S.P.G.), Calgary. The technique, developed by Espatalie et al. (1977), is described in Tissot and Welte (1978). It involves heating a finely crushed rock powder progressively to 500°C and measuring evolved hydrocarbons. An example of the output parameters and typical pyrolysis curves obtained from this method is shown in Figure 13.

Hydrocarbons evolve in two stages. Those already present in the rock in a free state, or bitumen components, evolve at 200° to 250°C and are defined as S1 yield. The pyrolysis of kerogen occurs at higher temperatures (400° to 500°C) and generates second stage hydrocarbons, termed S2 yield. Oxygen-containing volatiles, namely CO₂ and water, derived from oxygen-containing kerogen structures evolve at high temperatures and are known as S3 yield. Figure 11 depicts a recorded pyrolysis sequence and additional information that can be obtained from the pyrolysis.

In viewing information obtained from the pyrolysis, it is useful to consider that bitumen is a product of thermally matured kerogen. Therefore, the amount of bitumen (S1) can be considered the



Information obtained for this study:

- S₁- oil or gas show (kg./ton rock)
- S₁/S₁+S₂- transformation ratio
- T_{max}.- temperature of maximum hydrocarbon generation (°C)
- S₁+S₂- petroleum potential (kg./ton rock)
- S₂/TOC- hydrogen index (mg. yield/g. TOC)
- S₃/TOC- oxygen index (mg. yield/g. TOC)

Figure 13. Rock-Eval pyrolysis curves (from Sacheli 1985).

"bitumen show" of the rock. The ratio of bitumen to bitumen plus kerogen represents the amount of thermal maturation endured, and a transformation ratio, $S1/(S1+S2)$, can therefore be used as a maturation indicator. Tmax, the temperature of maximum hydrocarbon generation, is also indicative of thermal maturation.

Tissot and Welte (1978) indicate that the Tmax increases progressively with maturation, but numerical scaling is dependent on the rate of pyrolysis heating. Tmax can be correlated with other maturation indicators such as vitrinite reflectance (Tissot and Welte 1978). The petroleum potential ($S1+S2$) reflects the overall organic richness of the shale. Samples with high petroleum potential are rich in bitumen and/or kerogen or both.

Kerogen typing can also be performed by Rock-Eval pyrolysis using hydrogen and oxygen indices, which are calculated by $S2/TOC$ and $S3/TOC$, respectively. A modified Van Krevelen diagram can be constructed to determine organic matter type. Espatalie et al.(1977) discusses the correlation between Rock-Eval calculated indices and elemental concentration in kerogens. Major limitations of Rock-Eval kerogen typing are discussed by Snowdon (1984).

APPENDIX 2 Catalogue of Thin Sections Cut For the Ontario Geological Survey-Collingwood Member.

<u>Slide No.</u>	<u>Location</u>	<u>Depth (m)</u>	<u>Comments</u>
OGS-01	Norfolk, Charlottesville	898.26	U.S. Steel #1, Clgd.
OGS-02	OGS Chatham	899.46	top contact Clgd.
OGS-03	Norfolk, Charlottesville	898.56	U.S. Steel #1, Clgd.
OGS-04	OGS Clarkson	67.65	top contact lost in cutting
OGS-05	OGS Lambton	1050.82	Blue Mtn-Lindsay Fm.
OGS-06	OGS Milton	435.35	Micrite/phosphorite bed
OGS-07	OGS Milton	435.35	" "
OGS-08	OGS Milton	435.35	" "
OGS-09	OGS Milton	435.57	Micrite-Nodular Lindsay
OGS-10	OGS St. Joseph	158.45	Blue Mountain Fm.
OGS-11	OGS St. Joseph	158.45	Phosphorite Bed
OGS-12	OGS St. Joseph	158.45	Gypsum Nodules
OGS-13	OGS St. Joseph	158.45	Phosphorite Bed/Clgd.
OGS-14	OGS St. Joseph	168.95	Clgd.-Nodular Lindsay Fm.
OGS-15	OGS Little Current	109.10	Clgd.
OGS-16	OGS Little Current	109.10	Clgd.
OGS-17	OGS Little Current	109.10	Clgd.
OGS-18	OGS Little Current	112.41	Clgd.
OGS-19	OGS Little Current	112.38	Clgd.
OGS-20	OGS Little Current	112.87	Clgd.-Lindsay Nod. Limestone
OGS-21	OGS Little Current	113.58	Lindsay Nodular Limestone/Dol.
OGS-22	OGS Little Current	107.65	Blue Mountain Fm.??
OGS-23	OGS Little Current	107.23	Blue Mountain Fm.
OGS-24	OGS Little Current	107.00	Blue Mountain Fm.
OGS-25	OGS Wiarton	290.93	Blue Mountain Fm.
OGS-26	OGS Wiarton	291.24	Clgd.
OGS-27	OGS Wiarton	294.74	Clgd.
OGS-28	OGS Nobleton	219.73	Blue Mountain Fm.
OGS-29	OGS Nobleton	220.86	" "
OGS-30	OGS Nobleton	224.33	Phosphorite Bed
OGS-31	OGS Nobleton	224.79	Clgd.
OGS-32	OGS Pickering	42.67	Clgd.
OGS-33	OGS Pickering	46.76	Clgd.
OGS-34	OGS Pickering	46.76	Clgd.
OGS-35	Drummond Island WB-1	125.53	Top Clgd.
OGS-36	Drummond Island WB-2	229.21	Alternating shale & Phosphorite beds
OGS-37	Drummond Island WB-2	231.21	" "
OGS-38 - OGS-43	Detailed examination of the Phosphorite beds as above.		
OGS-44	Drummond Island WB-2	236.98	Bottom Clgd.-Lindsay
OGS-45	St. Joseph Island J-10	91.89	Top Collingwood
OGS-46	St. Joseph Island J-10	102.34	Clgd.-Lindsay
OGS-47	St. Joseph Island J-08	33.22	Clgd.-Lindsay
OGS-48	Shequiandah, Outcrop Manitoulin Island		Green Limestone below Clgd.
OGS-49	" "	"	Contact-Clgd.-Lindsay
OGS-50	" "	"	Clgd.

APPENDIX 3 Subcrop, Isopach and Data Maps (8 Maps) of the Collingwood Member

The back pocket of this report contains eight maps. The first four maps--Data and Subcrop Maps, show 1) the well identification numbers (listed in full in Appendix 3); 2) the structural top (depth measured from kelly bushing) of the Collingwood Member (or nodular limestone of the Lindsay Formation where the Collingwood Member is absent); 3) the thickness of the Collingwood Member (as measured from logs, cuttings, or core); and 4) the distribution of the subcrop pattern. Cored holes are represented by a solid circle, and are assigned a number from 1 to 55, prefixed by the letter "C". Holes of which cuttings provide the only sample material, or where only old descriptive geologic logs were available, are designated by an open circle. These holes are grouped together according to the presence or absence of the Collingwood Member. Holes containing the Collingwood Member are numbered from 1 to 43, and are prefixed by the letters "WC". Holes not containing the Collingwood Member are numbered from 1 to 53, are prefixed by the letters "NC", and do not have a thickness (i.e., 0.0 m) recorded next to the well location.

The second set of four maps, Isopach Maps, show the distribution of the Collingwood Member and isopach thicknesses. These maps are preliminary in nature and should be upgraded as more subsurface data becomes available.

Picking the tops and measuring the thickness of the Collingwood Member in cores presented no difficulty; however, with the well cuttings, geologic logs, and geophysical logs, considerably more interpretation was required. The age of the data available ranged from before the turn of the century to the present. Thus, interpretation regarding the contacts and the thickness of the oil shale take into account the type of drill used to obtain the cuttings (cable-tool, rotary, or air), the quality of the geophysical well logs (gamma logs prior to standardization in API units are not as useful as those after), and the reliability of the driller's/geologist's logs (where only geological logs were available). In almost all cases when the gamma logs were used, there was no difficulty in determining the top contact of the Collingwood Member. The problem arose in picking the bottom contact. This was due to the highly calcareous nature of the unit towards its base and to the fact that in the northern areas, the limestone of the underlying Lindsay Formation is very argillaceous, making the contact between the two units difficult to pick on the logs. In these situations, an attempt was made to define the thickness on the basis of both cuttings and logs.

APPENDIX 4 Catalogue Of Surface Outcrop And Subsurface Boreholes Used In This Study.

Part A: Diamond Drill Core Crossing Interval of Interest

Ontario Geological Survey Core

<u>Map Number</u>	<u>Hole Name</u>	<u>Borehole Location</u>	<u>Top(m)</u>	<u>Thickness (m)</u>
C-39	SIS 01	Municipality of Metro Toronto, City of Scarborough, Rouge Ck. Park	42.67	4.65
C-41	SIS 02	Regional Municipality of Durham, Town of Ajax, 16-II	21.16	4.70
C-38	SIS 03	Regional Municipality of Durham, Town of Ajax, 32-II	30.97	6.19
C-45	SIS 04	Municipality of Metro Toronto, City of Toronto, Don Valley Brickyard	118.66	1.46
C-14 ³	SIS 05	District of Manitoulin, Howland Twp., 16-VI	15.93	6.45
C-17	SIS 06	District of Manitoulin, Sheguiandah Twp., 27-X	41.53	5.97
C-13 ³	SIS 07	District of Manitoulin, Howland Twp., 23-VI	19.25	4.83
C-22	CLGD 01	Grey Co., Collingwood Twp., 27-VII	52.52	9.58
C-23	CLGD 02	Grey Co., Collingwood Twp., 24-VIII	106.84	10.16
C-24	CLGD 03	Grey Co., Collingwood Twp., 26-VII	52.82	4.80 ?
C-25	CLGD 04	Grey Co., Collingwood Twp., 25-IV	5.48	7.42
C-26	CLGD 04b	Grey Co., Collingwood Twp., 25-VI	45.86	10.04
C-27	CLGD 06a	Grey Co., Collingwood Twp., 16-II	43.99	6.29 ?
C-28	CLGD 07a	Grey Co., Collingwood Twp., 10-I	72.69	7.32 ?
C-21	CLGD 16	Grey Co., Collingwood Twp.	69.34	10.06
C-20	CLGD 17	Grey Co., St. Vincent Twp., Town of Meaford	51.95	1.75
C-40	OGS 83-3	Durham Co., Pickering Twp., 18-R III BT.	43.65	4.55
C-47	OGS 83-1	Halton Co., Nassagaweya Twp., 9-VII	437.69	0.00
C-48	OGS 83-2	Peel Co., Mississauga Twp., 23-III	275.36	0.10
C-36	Nobleton-1	Regional Municipality of York, King Twp., 20-21-V	224.49	9.44
C-35	OGS 82-0	Dufferin Co., Melancthon Twp., 251-II	414.34	11.49
C-29	OGS 83-4	Grey Co., Collingwood Twp., 67-A	67.65	9.70
C-19	OGS 82-4	Bruce Co., Albemarle Twp., 25-I W.B.R.	292.76	6.24
C-15	OGS 83-5	District of Manitoulin, Howland Twp., 6-V	109.70	3.25
C-11	OGS 85-7	District of Manitoulin, Cockburn Island, 15-16-13	25.00	6.7
C-7	OGS 83-6	District of Algoma, St. Joseph Island, Jocelyn Twp., 67-A	158.45	10.55
C-52	OGS 82-2	Kent Co., Harwich Twp., 25-I E.C.R.	899.46 ¹	0.00
C-49	OGS 82-1	Lambton Co., Moore Twp., 18-Front	1050.95 ¹	0.00
C-50	OGS 82-3	Elgin Co., Yarmouth Twp.	860.02 ¹	0.00

¹Where no Collingwood Member is present in the core, the depth indicates top of the nodular limestone of the Lindsay Fm.

³Used to define subcrop pattern.

Petroleum Resources Laboratory Core

<u>Map Number</u>	<u>Hole Name</u>	<u>Borehole Location</u>	<u>Top (m)</u>	<u>Thickness (m)</u>
C-16	Imp. Oil Ltd. 644	Manitoulin Dist. Bidwell	114.30	6.55
	J.H. Bayer No.1	Twp., 3-IX		
C-18 ²	Great Lakes Carbon (G. Skakel) #3	Manitoulin Dist. Indian Reservation No.26	251.46	4.57
C-37	Murray Little #1	York Co., Markham Twp.,	144.17	0.61
	28-VII	C-53		
	Imp. Oil Ltd. 646	Kent Co., Romney Twp.,	822.96 ¹	0.00
	Imperial-Union	A-Gore		
	Dom "A" Gore			
	A.D. Howard No.1			
C-51	U.S Steel DDH No. 1, J.H. Lawrence No.1	Norfolk Co., Charlottes-ville, 21-I	815.80	0.46
C-54	Place G&O No.5	Lake Erie, 302-D	627.89 ¹	0.00
C-55	Imperial et al.	Essex Co., Gosfield S.,	732.40 ¹	0.00
C-12	Union Carbide Corp. DDH	Manitoulin Dist. Robin-Lots 1-2, Conc. V, VI	192.12	4.78

Ministry of Transportation and Communication (MTC) - GEOCRESS SYSTEM

<u>Map Number</u>	<u>Hole Name</u>	
<u>GEOCRESS REFERENCE NUMBER</u>		
C-42-43	Wilmot Ck. Bridge, Hwy.2 Boreholes 1 and 4	ONLY WP NO. AVAILABLE W P . 1 8 7 - 7 9 -
03	Lindsay only	
C-34	WOH'S Bridge, Mariposa Ck.	31 - D - 163 Lindsay only
C-32	Pesserlan Bridge, Hwy. 48	31 - D - 202 Lindsay only
C-33	CNR Overhead Hwy. 48	31 - D - 213 Lindsay only
C-30	Hwy. 26 Batteaux River	41 - D - 33 Lindsay only
C-31	Hwy. 26 Pretty River	41 - A - 41 Lindsay only
C-01	St. Joseph Island Bridge	41 - J - 18 Lindsay only

¹Where no Collingwood Member is present in the core, the depth indicates top of the nodular Lindsay Fm. or lower Trenton units.

²This hole had only chips taken from a core. The original core has long since vanished on the Indian Reservation.

Ontario Hydro Core

<u>Map Number</u>	<u>Hole Name</u>	<u>Borehole Location</u>	<u>Top(m)</u>	<u>Thickness (m)</u>
C-44	Darlington Nuclear Power Plant Site Investigation boreholes		Outcrop	9.00-nil
C-46	OHD-1 Lakeview	Lakeview Coal Plant	185.48	0.05

Core Drilled by D.P. Rogers Ltd. (Stored in Sault Ste. Marie, MNR Core Library)

C-09	W.B.-80-1	USA, Drummond Island, Twp. 42 N-R 7 E-Sec.6	116.73	8.83
C-10	W.B.-80-2	USA, Drummond Island, Twp. 42 N-R 7 E-Sec. 33	229.21	7.77
C-03	J - 80 - 7	Algoma Dist., St. Joseph Twp., 10-K	43.89 ¹	0.00
C-04 ³	J - 80 - 8	Algoma Dist., St. Joseph Twp., 27-A	31.69	1.67
C-08	J - 80 - 9	Algoma Dist., Jocelyn Twp., A-VII	138.68	10.36
C-06	J - 80 - 10	Algoma Dist., Jocelyn Twp., 4-VII	91.89	10.45
C-05 ³	J - 80 - 2	Algoma Dist., St. Joseph Twp., 22-A	15.42	3.23
C-02	J - 80 - 1	Algoma Dist., St. Joseph Twp., 9-F	18.44 ¹	0.00

Outcrops

Manitoulin Island³ - Near Sheguiandah, Road cut and quarry, Hwy. 6 South, and on NE Peninsula, Indian Reservation

Bowmanville - St. Mary's Cement Quarry

Ontario Hydro's Darlington Nuclear Power Plant Site - good cut in Forebay zone

¹Where no Collingwood Member is present in the core, the depth indicates top of the nodular limestone of the Lindsay Fm. or Trenton-Black River units.

³Used to define subcrop pattern.

Part B: HOLES WITH WELL CUTTINGS, AND/OR LOGS CONTAINING COLLINGWOOD MEMBER

<u>Map Number</u>	<u>Borehole Name</u>	<u>Borehole Location</u>	<u>Top(m)</u>	<u>Thickness (m)</u>	<u>Criteria</u>
WC-1	F.D. Barton et al.	Chippewa Co. Drummond Twp. 17-41N-6E USA	304.19	10.06	cuttings
WC-2	DPR-79-2	Chippewa Co. Drummond Twp. 25-43N-6E, USA	85.65	10.67	cuttings
WC-3	Cockburn Is. Syndicate-Bay City Bank #1	Manitoulin Dist. Cockburn Is. 11-VIII	297.18	6.10	cuttings
WC-4	Imperial Oil 528, W.J. Watson #1	Bruce Co., Edmund Twp., 44-I EBR	320.04	6.40	cuttings/ old log
WC-5	Imp. Oil 532 Lindsay 36-IV E	Bruce Co., Lindsay Twp., 36-IV E	304.19	4.57	cuttings
WC-6	Imp. Oil 536 Taylor et al. #1	Bruce Co., Amabel Twp., 52-II NCD	316.99	6.00	cuttings
WC-7	Ben Allen Cement Co., Chambers & Dewus-McMillan #1	Grey Co., Keppel Twp., 30-VIII	274.32	6.10	gamma only
WC-8 ³	Collingwood Explor. No.1	Simcoe Co., Notta- wasaga Twp., 43-XII	28.35	7.62	cuttings
WC-9	W.R McMaster & Sons #1 E. Morrison No.1	Simcoe Co., Notta- wasaga Twp., 15-VII	143.26	9.14	cuttings
WC-10	Arnora Sulphur Mining Corp. #1	Grey Co., Proton Twp. 10-XIX	445.00	6.10	gamma only
WC-11	Carmac No.1 Mulmur 18-IV	Dufferin Co., Mulmur Twp., 18-IV	175.26	4.57	cuttings only
WC-12	Monray No.2	Grey Co., Egremont Twp., 11-VIII	472.44	3.05	logs/cuttings
WC-13	Cressing No.2	Grey Co., Egremont Twp., 8-IX	467.26	3.05	logs/cuttings
WC-14	Monray No.1	Grey Co., Egremont Twp.	471.53	3.05	logs/cuttings
WC-15 ³	Wellington Indust. Securities Ltd. A.B. Breedon No.1	Simcoe Co., Adjula Twp., 21-III	115.82	1.52	cuttings
WC-16	Wellington Indust. Securities Co. E. Skule No.1	Simcoe Co., Adjula Twp., 20-III	110.64	6.10	cuttings
WC-17	Eugene Boileau #1 Elwood Nichol #1	Simcoe Co., Tecumseth Twp., 12-IX	??	??	old drillers log

WC-18	Village of Tottenham	Simcoe Co., Tecumseth Twp., 5-IV	??	??	old drillers log
WC-19	Kenartha No.6 Arthur 8-23-VI	Wellington Co., Arthur Twp., 8-23-VI	513.89	3.05	gamma log only
WC-20	Buxton No.2 Maryborough 1-12-XVI	Wellington Co., Maryborough Twp., 1-12-XVI	525.78	6.10	gamma & cuttings
WC-21	Sir Donald Mann-John Ash Farm Consumers 1630	York Co., Vaughan Twp., 11-III	154.83	4.88	old gamma
WC-22	Page Oil and Gas Page Farm	York Co., Vaughan Twp. 33-I	195.37	5.79	cuttings
WC-23 ³	John H.C. Durham No.1	York Co., White- church Twp., 64-I	201.17	6.10	old drillers log
WC-24 ³	Sunderland Oils Ltd. H. Hird #1	Ontario Co., Scott Twp., 3-IV	12.19	??	old drillers log
WC-25	No name	Ontario Co., Brock Twp., 24-X	??	??	old drillers log
WC-26	Pacific Elma 2-13-XI	Perth Co., Elma Twp., 2-13-XI	642.21	3.05	gamma & cuttings
WC-27	Petromark et al. Elma 2-36-XIV	Perth Co., Elma Twp., 2-36-XIV	637.64	5.00	gamma & cuttings
WC-28	Tony Seynuck #2, Anthony Gas & Oil Expl. No.1	Halton Co., Nassagaweya Twp.	417.27	6.10	cuttings
WC-29	Anthony Gas & Oil Expl. No.20, A. McDonald #3	Halton Co., Esquesing Twp., 15-V	377.65	3.05	cuttings
WC-30	Anthony Gas & Oil Expl. #9 Acton #7 W.S. McDonald #1	Halton Co., Esquesing Twp., 12-IV	360.88	3.05	cuttings
WC-31	Anthony Gas & Oil Acton #7-W.S. McDonald #29	Halton Co., Esquesing Twp.	356.00	1.83	cuttings/ old gamma
WC-32	Imperial Grantham 3-3	Lincoln Co., Grantham Twp., 3-III	445.00	6.10	cuttings/ gamma
WC-33	Imperial Enterprises Niagara 148(878)	Lincoln Co., Niagara Twp., 148-VII	477.01	6.70 gamma	cuttings/ gamma
WC-34	Crowland Gas- Effingham #1 J. Abbott	Welland Co., Pelham Twp., 3-III	524.25	3.05	cuttings/ gamma
WC-35	Imperial Dereham 23-5(897)	Oxford Co., Dereham Twp., 23-V	774.19	7.62	cuttings/ gamma
WC-36	Imperial Enter. Dereham 24-6	Oxford Co., Dereham Twp., 24-VI	786.38	9.14	cuttings/ gamma
WC-37	Sidasa Canborough	Haldimand Co., Canborough Twp.,	652.27	6.10	cuttings/ gamma

WC-38	No.2-16-1 Bowman Dev. Wainfleet 7-4-III	16-I Welland Co., Wainfleet Twp., 7-4-III	752.24	3.05	cuttings/ gamma
WC-39	Bluewater et al. Malahide 28-V	Elgin Co., Malahide Twp., 28-V	845.82	7.62	cuttings/ gamma
WC-40	C.P.O.G. Welland No.2a.	Welland Co. Lake Erie	881.48	2.44	cuttings/ gamma
WC-41	Allegany- Bartok No.1	Kent Co., Orford Twp., 4-VII	951.58	3.05	cuttings/ gamma
WC-42	Consumers 13176 Lake Erie 222-V	Kent Co., Lake Erie 222-V	1051.56	3.05	cuttings
WC-43	W.P. Bullard No.9	Manitoulin Indian Reserve Cape Smith	??	??	old drillers log

³Used to define subcrop pattern.

Part C - BOREHOLE CONTAINING NO COLLINGWOOD MEMBER

Map Number	Well Name	Borehole Location	Top of Lindsay Fm. Limestone(m)
NC-1	Home-C.D.R Saugeen 12-1-C	Bruce Co., Saugeen Twp., 12-I	573.00
NC-2	B.P Triad Saugeen 29-II (A)	Bruce Co., Saugeen Twp., 29-II	522.70
NC-3	J.A. Currie No.2 Twp., 34-XII	Simcoe Co., Nottawasaga	88.39
NC-4	Robert Cherry No.4	Simcoe Co., Nottawasaga Twp., 28 & 29V	???
NC-5	Robert Cherry No.3	Simcoe Co., Nottawasaga Twp., 39-VI	6.10 ?
NC-6	no name	Simcoe Co., Nottawasaga Twp., 31-II	38.71
NC-7	B.P Triad Kincardine 17-VIII	Bruce Co., Kincardine Twp., 17-VIII	704.10
NC-8	Amoco A-1 Kincardine 2-31-V	Bruce Co., Kincardine Twp., 2-31-V	696.70
NC-9	G. Heroux-B. Smith No.1	Simcoe Co., Essa Twp. 22-III	121.92
NC-10	M. Stobie No.4 - J.F.Hambly No.1	Simcoe Co., Gwillimbury W. Twp., 19-XI	48.77
NC-11	M. Stobie - Wm. Nelson No.1	York Co., E. Gwillimbury Twp., 29-VII	35.05
NC-12	M. Stobie No.1 G.H. Dean No.1	York Co., E. Gwillimbury Twp., 113-I E	61.57
NC-13	Sunderland Oils - J.Sedore No.1	York Co., N. Gwillimbury Twp., 11-VIII	60.56
NC-14	Sunderland Oils Ltd. W.J. Bradshaw No.1	Ontario Co., Brock Twp.,	???
NC-15	Total et al. Ashfield 1-12-IX	Huron Co., Ashfield Twp., 1-12-IX	810.50
NC-16	Pacific Culross 4-25-V	Bruce Co., Culross Twp., 4-25-V	659.00
NC-17	Imperial Oil #600 Ashfield 8-III ED. GV. Black No.1	Huron Co., Ashfield Twp., 8-III ED	850.00
NC-18	Pacific Turnberry 1-1-II	Huron Co., Turnberry Twp., 1-1-II	640.00
NC-19	Imp. Oil 563 Colborne 12 LRE W.W. Hill No.1	Huron Co., Colborne Twp., 12-LRE	872.00
NC-20	Buxton-Bozian Arthur No.1 8-25-V	Wellington Co., Arthur Twp., 8-25-V	505.36
NC-21	Tipperary #4 Goderich 2-37-IX	Huron Co., Goderich Twp., 2-37-IX	885.40
NC-22	K.R. Hay 2-26-XV	Huron Co., Hay Twp., 26-XV	862.60
NC-23	Birchfield No.1	Wellington Co., Puslinch Twp., 30-VII	501.10
NC-24	Joseph's Well 1 Puslinch 1-8-III	Wellington Co., Puslinch Twp., 1-8-III	505.35
NC-25	Canadian Essex Oil No.1	Wentworth Co., E. Flamborough Twp., 2-X	461.8 ?
NC-26	K.R. Stephen 4-4-B	Huron Co., Stephen Twp., 4-BIRC	874.80
NC-27	Baslen-Dover Blenheim 13-XI	Oxford Co., Blenheim Twp., 13-XI	621.80
NC-28	W.P.Carr (#6) Ancaster 29-III	Wentworth Co., Ancaster Twp., 29-III	555.30

NC-29	Imperial Saltfleet 12-4 (910)	Wentworth Co., Saltfleet Twp., 12-IV	523.00
NC-30	King Resource Bosanquet 3-9-XI	Lambton Co., Bosanquet Twp., 3-9-XI	1004.30
NC-31	B.P. Triad Brantford 41-Burtch	Brant Co., Brantford Twp., 41-Range II-Burtch	639.80
NC-32	Coppingen Burford 10-XI-7-1	Brant Co., Burford Twp., 20-XI	705.90
NC-33	Smyth-Barchild Plympton 18-VII	Lambton Co., Plympton Twp. 18-VII	1027.20
NC-34	Imp. 582 BRN 1 Moore 2-19-VIII	Lambton Co., Moore Twp., 2-19-VIII	1025.70
NC-35	I.O.E Bluewater et al. Delaware 15-III (873)	Middlesex Co., Delaware Twp., 15-III	829.10
NC-36	I.O.E. Barnett N. Dorchester 14-4	Middlesex Co., N. Dorchester Twp., 14-IV S	808.30
NC-37	Carl Roberts No.3	Norfolk Co., Middleton Twp., 23-II STR	801.60
NC-38	Lloyd Vanderburg No.6-E. Barnard No.2	Norfolk Co., Windham Twp., 1-XIII	768.10
NC-39	ERCO No.2	Haldimand Co., Sherbrooke Twp., 3-II	768.10
NC-40	Texaco 1 Walpole Island 2-19 BLKA	Lambton Co., Walpole Island 2-19-BLKA	921.40
NC-41	Mills 2 Dunwich 5-23-I	Elgin Co., Dunwich Twp., 5-23-I	831.50
NC-42	Baslen-Yarmouth 14-5	Elgin Co., Yarmouth Twp., 14-V	867.20
NC-43	Pinetree-Whitty Dover 3-9-VI	Kent Co., Dover Twp., 9-VI	867.50
NC-44	Canadian Essex-Jensen No.1 (103)	Kent Co., Oxford Twp., 3-NMR	971.40
NC-45	Brett et al. Rochester 8-16-VI	Essex Co., Rochester Twp., 8-16-VI	802.80
NC-46	Palomino-Buxton 1 Raleigh 1-3-X	Kent Co., Raleigh Twp., 1-3-X	861.70
NC-47	Imperial 773 et al.-Brunner Mond No.1	Essex Co., Anderdon Twp., 3-X	738.20
NC-48	Canadian Delhi McGregor No.1a	Essex Co., Anderdon Twp., 9-VIII	737.00
NC-49	Imperial Oil 772 Clifford Shepley No.1	Essex Co., Colchester N. Twp., 14-C.S.M.R.	727.60
NC-50	Pembina et al. Mersea	Essex Co., Mersea Twp., 7-19-VI	765.00
NC-51	Imperial Oil 736 Imp. Harvest Submarine Colch. S. No.21 Bondy No.1	Essex Co., Colchester S. 83-Front	635.20
NC-52	Consumers 13730 Lake Erie 284-U	Essex Co., Lake Erie 284-U	973.50
NC-53	Amerada Hess 2 Lake Erie 359-F	Essex Co., Lake Erie 359-F	572.20

APPENDIX 5 Organic Geochemistry Data

The following abbreviations are used in the tables below: TOC, total organic carbon; YP, yield upon pyrolysis; Tmax, temperature (in °C) of maximum hydrocarbon generation; HI, Hydrogen Index; PI, Production Index; CPI, Carbon Preference Index; OEP, odd-even preference; and PR/PH, Pristane/Phytane Ratio.

O.G.S. OIL SHALE EVALUATION: HYTORT ANALYSES

SAMPLE	%TOC	YP	L/TONNE OIL	GAL/TON OIL	DEPTH RANGE (m)
CH2-1	6.9 7.1 7.0 6.8	2.0	66.7 16.0		67.79-68.79
CH2-2	6.4 6.7 6.6 6.6	1.6	65.5 15.7		67.79-68.79
CH2-3	2.6 2.6 2.5 2.6	0.7	27.1 6.5		67.79-68.79

CH2-1 to CH2-3 - Clarksburg OGS-83-4. (Lithological log unpublished - M.D. Johnson, pers. comm.)
Data from Barker (1985).

ELEMENTAL ANALYSIS

BOREHOLE	SAMPLE DEPTH (m)	% C	% H	% N	% O	% ASH
SIS 1	42.52-42.62	49.78	4.17	1.59	—	—
SIS 3	31.85-31.85	54.37	4.98	1.67	—	39.16
SIS 6	44.20-44.20	66.60	6.46	1.92	6.52	37.23
CLGD 1	52.56-52.66	69.16	7.04	2.19	—	—
"	52.66-52.83	67.56	6.76	2.09	—	—
"	52.83-52.93	65.18	6.74	1.98	—	—
"	52.93-53.03	66.87	6.65	2.06	—	—
"	53.03-53.19	66.61	6.76	2.07	—	—
CLGD 1C	52.66-53.03	66.37	6.67	2.02	—	—
CLGD 4B	46.75-46.85	68.37	7.00	2.00	—	—
"	47.35-47.45	68.35	6.91	1.99	8.46	27.57
"	47.45-47.55	66.88	6.94	1.98	—	—
"	47.75-47.92	66.87	6.62	2.01	—	—
"	48.07-48.17	66.91	6.64	2.00	—	—
"	48.17-48.27	68.78	6.84	2.15	—	—
"	48.27-48.37	68.60	6.91	2.10	—	—
"	47.25-47.25	66.87	6.97	2.01	—	—
"	48.07-48.37	67.53	6.77	2.07	—	—
CLGD 16	69.29-69.39	69.48	7.04	2.10	—	—
"	69.39-69.49	67.53	6.86	2.09	—	27.49
"	69.49-69.59	66.55	6.86	2.08	—	—

Data from Barker (1985).

AVERAGED ISPG ROCK-EVAL DATA

AREA	HOLE SAMPLED	NO. OF SAMPLES	TOC AVER. %	Tmax AVER.	HI AVERAGE	PI AVERAGE	YIELD *
Collingwood	2	14	5.20	436	563	0.06	6.41
Manitoulin Is.	3	15	6.53	439	470	0.06	5.04
Whitby	1	7	4.96	444	195	0.23	2.51
Ottawa	1	12		2.56	466	26	0.57

0.57 * Yield = $\frac{\text{Yield}}{\text{C Ratio}}$
Av. kg/t/%TOC

Data from Macauley and Snowden (1984)

ANALYSES FROM A COLLINGWOOD SAMPLE-BITUMEN PYROLYSATE

Parameter

Replicates	CPI	OEP	PR/PH	PR/C ₁₇	PH/C ₁₈
1	1.06	1.03	1.44	1.36	0.991
2	0.882	0.847	1.48	1.30	0.811
3	0.954	0.943	1.27	1.08	0.900
4	0.868	0.864	0.831	0.978	0.935
Mean	0.941	0.906	1.26	1.18	0.912
Standard Deviation (S)	0.088	0.101	0.297	0.180	0.075
S as % of Mean	9.35%	11.0%	23.6%	15.3%	8.22%

Data from Johnson et al. (1989).

CONVERSION FACTORS FOR MEASUREMENTS IN ONTARIO GEOLOGICAL SURVEY PUBLICATIONS

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	Multiplied by	Gives	Imperial Unit	Multiplied by	Gives
LENGTH					
1 mm	0.039 37	inches	1 inch	25.4	mm
1 cm	0.393 70	inches	1 inch	2.54	cm
1 m	3.280 84	feet	1 foot	0.304 8	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	1.609 344	km
AREA					
1 cm ²	0.155 0	square inches	1 square inch	6.451 6	cm ²
1 m ²	10.763 9	square feet	1 square foot	0.092 903 04	m ²
1 km ²	0.386 10	square miles	1 square mile	2.589 988	km ²
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm ³	0.061 02	cubic inches	1 cubic inch	16.387 064	cm ³
1 m ³	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m ³
1 m ³	1.308 0	cubic yards	1 cubic yard	0.764 555	m ³
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	4.546 090	L
MASS					
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	31.103 476 8	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	0.453 592 37	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	907.184 74	kg
1 t	1.102 311	tons (short)	1 ton (short)	0.907 184 74	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	1016.046 908 8	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	1.016 046 908 8	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.



ELEVATIONS IN FEET

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ELEVATIONS IN FEET

(Joins Manitoulin - Owen Sound 41 S.E.)

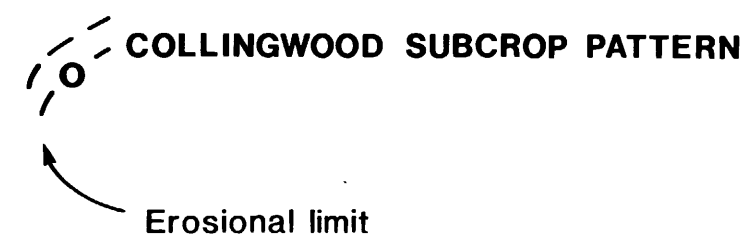
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ELEVATIONS IN FEET
CHAPLEAU - SUDBURY
N.T.S. No. 41 N.E.
Base Map, 5th Edition 1978

LEGEND

- OGS CORED HOLES** ● 158.45 Top Collingwood (metres)
10.55 Thickness Collingwood (metres)
- OIL AND GAS BOREHOLE (CORED)** ● C-6 Well ID
91.89 Top Collingwood (metres)
10.45 Thickness Collingwood (metres)
- OIL AND GAS BOREHOLE CUTTINGS** ○ WC-8 Well ID
28.35 Top Collingwood (metres)
7.62 Thickness Collingwood (metres)
- NC-9 Well ID
121.92 Top of Lindsay Fm. (m; Collingwood absent)



Map 1A:
DATA AND SUBCROP MAP COLLINGWOOD MEMBER, LINDSAY FM.
(NORTHWEST SHEET)

MANITOULIN - OWEN SOUND
ELEVATIONS IN FEET

CANADA
DEPARTMENT OF
ENERGY, MINES AND RESOURCES
SURVEYS AND MAPPING BRANCH
(Join Chapleau-Sudbury 41 N.E.)

ELEVATIONS IN FEET

Transverse Mercator Projection

ELEVATIONS IN FEET

HYPSONETRIC TINTS
HYPSONETRIC TINTS
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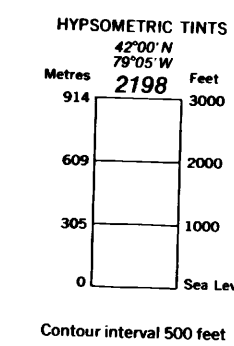
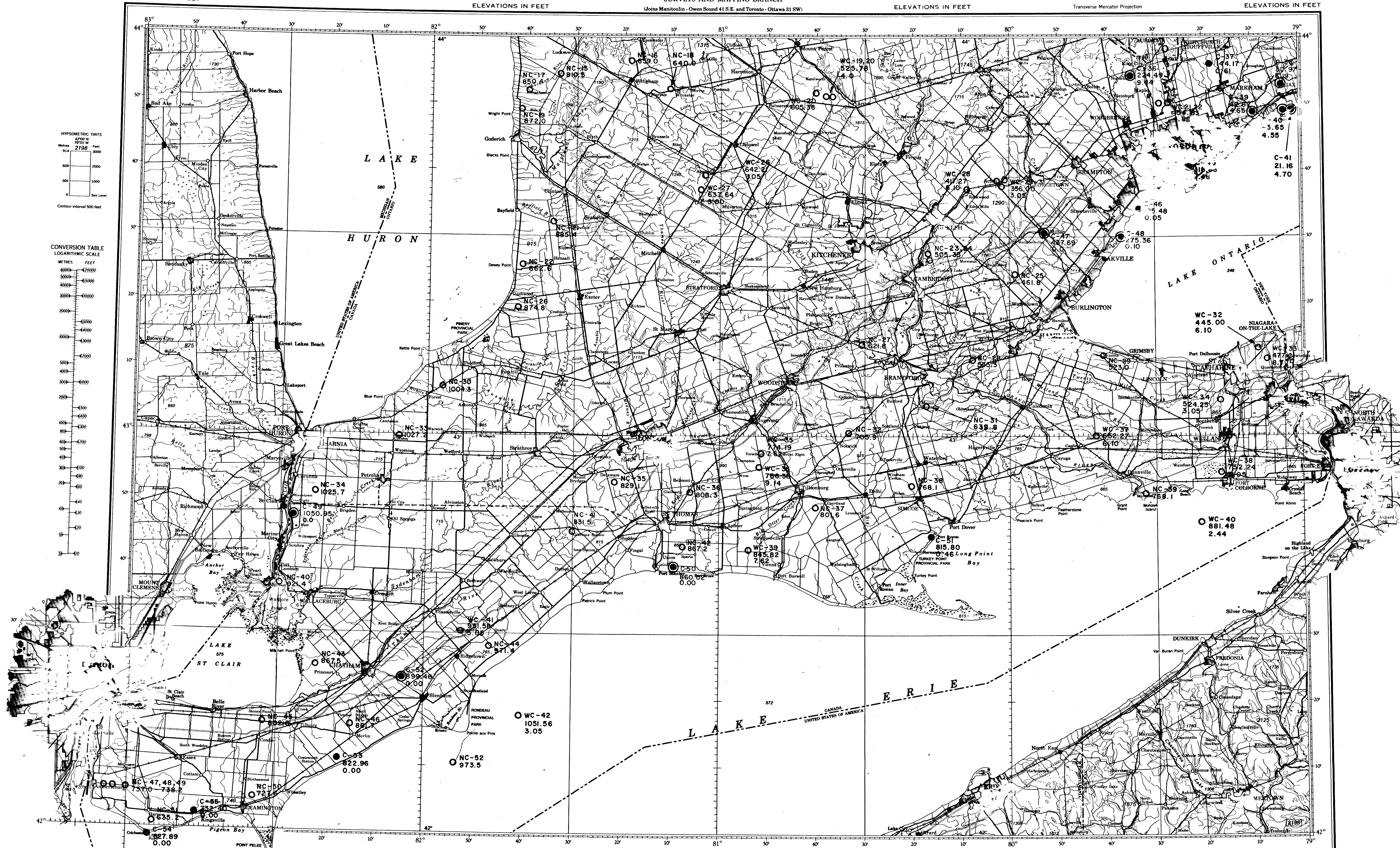
WINDSOR - TORONTO
ELEVATIONS IN FEET

CANADA
DEPARTMENT OF
ENERGY, MINES AND RESOURCES
SURVEYS AND MAPPING BRANCH
(Joining Manitoulin - Owen Sound 41 S.E. and Toronto - Ottawa 31 S.W.)

ELEVATIONS IN FEET

Transverse Mercator Projection

ELEVATIONS IN FEET



CONVERSION TABLE
LOGARITHMIC SCALE

FEET	METRES
1000	305
2000	610
3000	914
4000	1219
5000	1524
6000	1829
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8000	2438
9000	2743
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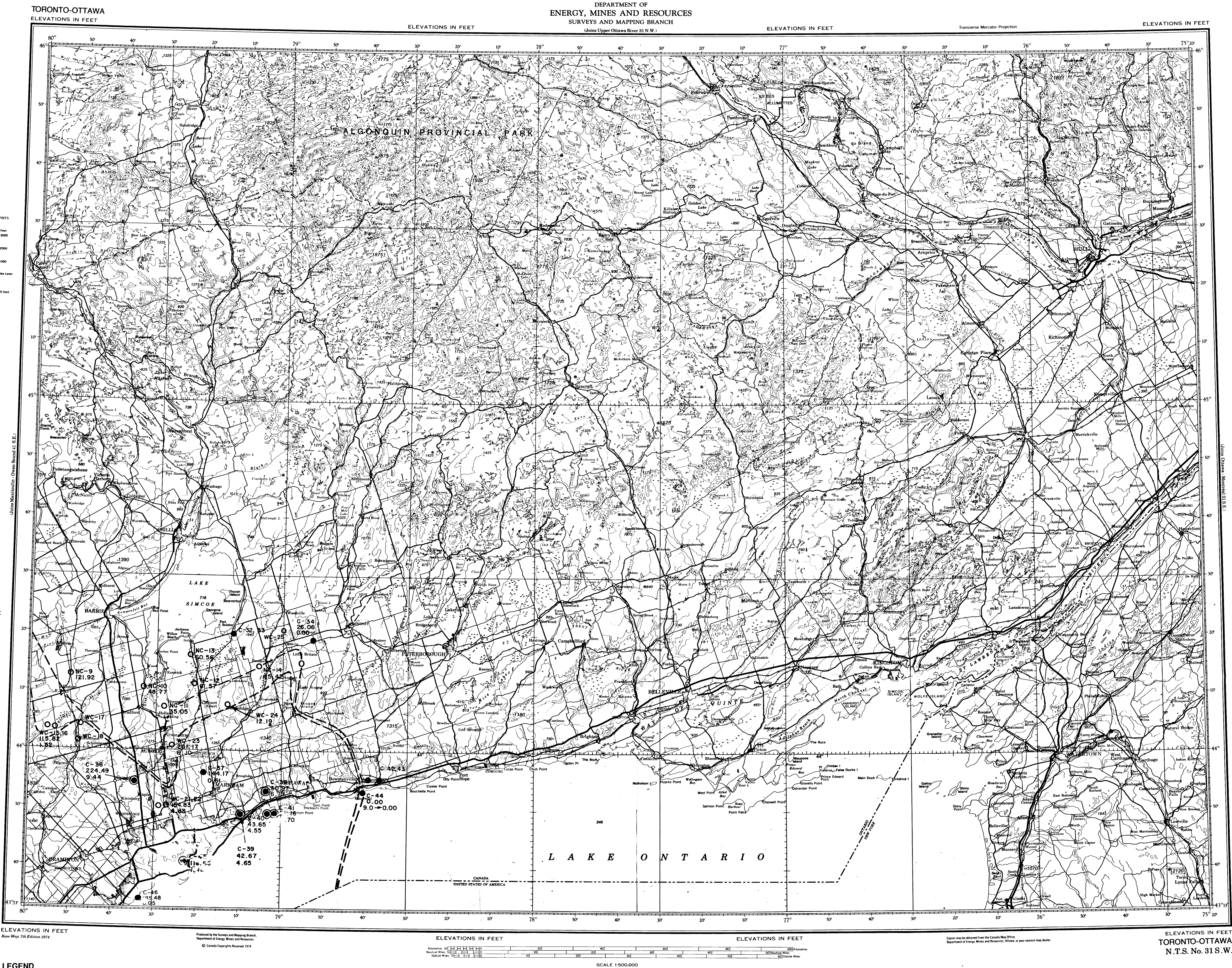
LEGEND

- OGS CORED HOLES ● C-7 Well ID
158.45 Top Collingwood (metres)
10.55 Thickness Collingwood (metres)
- OIL AND GAS BOREHOLE (CORED) ● C-6 Well ID
91.89 Top Collingwood (metres)
10.45 Thickness Collingwood (metres)
- OIL AND GAS BOREHOLE CUTTINGS ○ WC-8 Well ID
28.35 Top Collingwood (metres)
7.62 Thickness Collingwood (metres)
- NC-9 Well ID
121.92 Top of Lindsay Fm. (m; Collingwood absent)

COLLINGWOOD SUBCROP PATTERN
Erosional limit

Map 1C:
DATA AND SUBCROP MAP COLLINGWOOD MEMBER, LINDSAY FM.
(SOUTHWEST SHEET)

ELEVATIONS IN FEET
WINDSOR - TORONTO
Parts of N.T.S. Nos. 40 N.E. and 30 N.W.



CANADA
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ENERGY, MINES AND RESOURCES
SURVEYS AND MAPPING BRANCH
(Joins Hearst-Cochrane 42 S.E.)

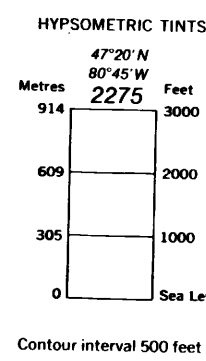
CHAPLEAU - SUDBURY
ELEVATIONS IN FEET

ELEVATIONS IN FEET

ELEVATIONS IN FEET

Transverse Mercator Projection

ELEVATIONS IN FEET



Joins Michipicoten - Sault Ste. Marie 41 N.W.

Joins Upper Ottawa River 31 N.W.

ELEVATIONS IN FEET

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ELEVATIONS IN FEET

(Joins Manitoulin - Owen Sound 41 S.E.)

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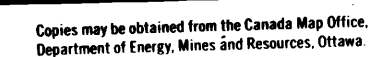
ELEVATIONS IN FEET
CHAPLEAU - SUDBURY
N.T.S. No. 41 N.E.
Base Map, 6th Edition 1978

LEGEND

- OGS CORED HOLES
- OIL + GAS CORED HOLES
- OIL + GAS HOLES (Cuttings only)
- ISOPACH THICKNESS
COLLINGWOOD MEMBER (metres)

Map 2A:

ISOPACH MAP COLLINGWOOD MEMBER, LINDSAY FM.
(NORTHWEST SHEET)



Map 2B:

- ◎ OGS CORED HOLES
- OIL + GAS CORED HOLES
- OIL + GAS HOLES (Cuttings only)

ISOPACH THICKNESS
COLLINGWOOD MEMBER (metres)

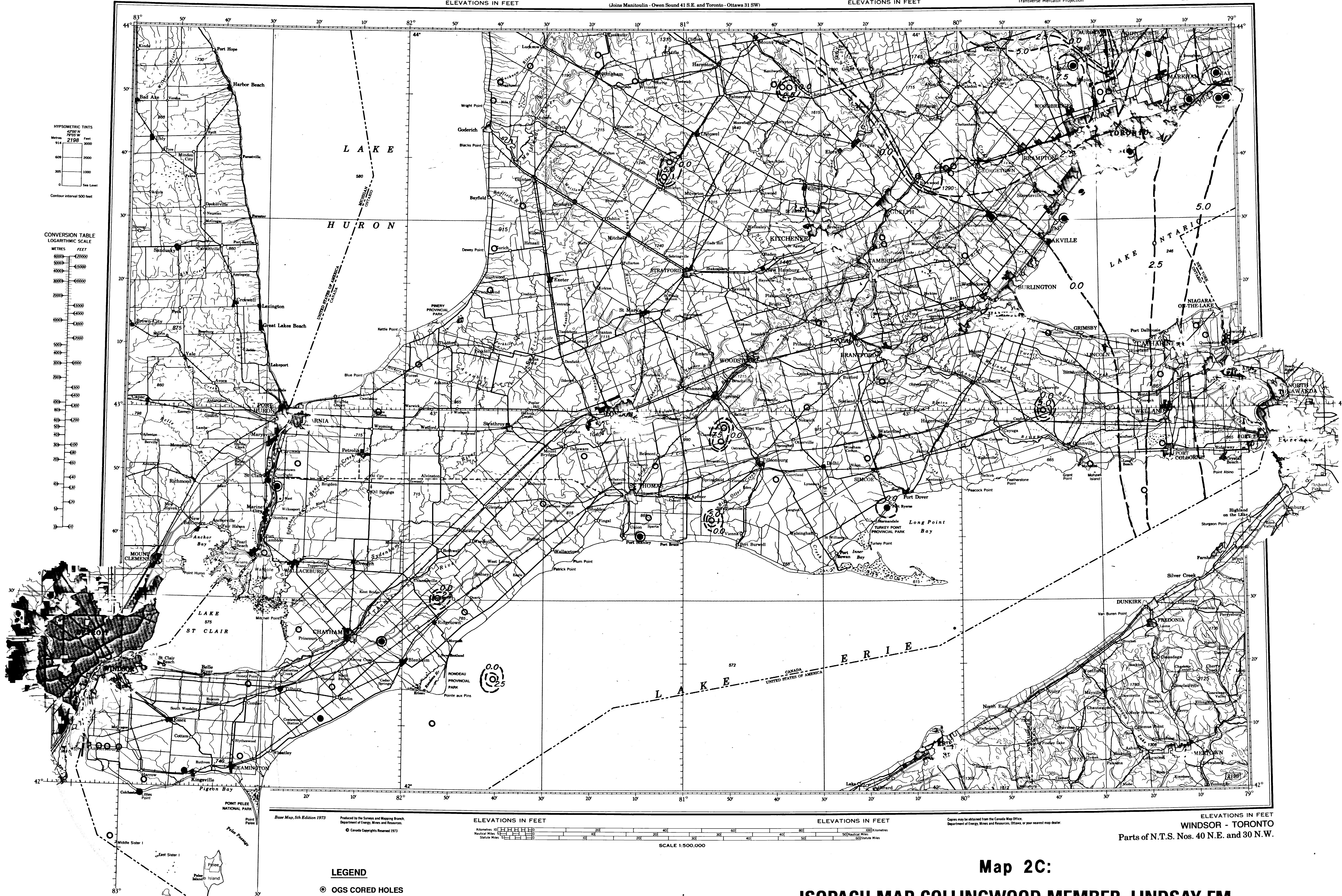
WINDSOR - TORONTO
ELEVATIONS IN FEET

CANADA
DEPARTMENT OF
ENERGY, MINES AND RESOURCES
SURVEYS AND MAPPING BRANCH
(Joins Manitoulin - Owen Sound 41 S.E. and Toronto - Ottawa 31 S.W.)

ELEVATIONS IN FEET

Transverse Mercator Projection

ELEVATIONS IN FEET



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ELEVATIONS IN FEET

Kilometres 0 10 20 30 40 50 60 70 80 90 100
Statute Miles 0 10 20 30 40 50 60 70 80 90 100

SCALE 1:500,000

ELEVATIONS IN FEET

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ELEVATIONS IN FEET

WINDSOR - TORONTO
Parts of N.T.S. Nos. 40 N.E. and 30 N.W.

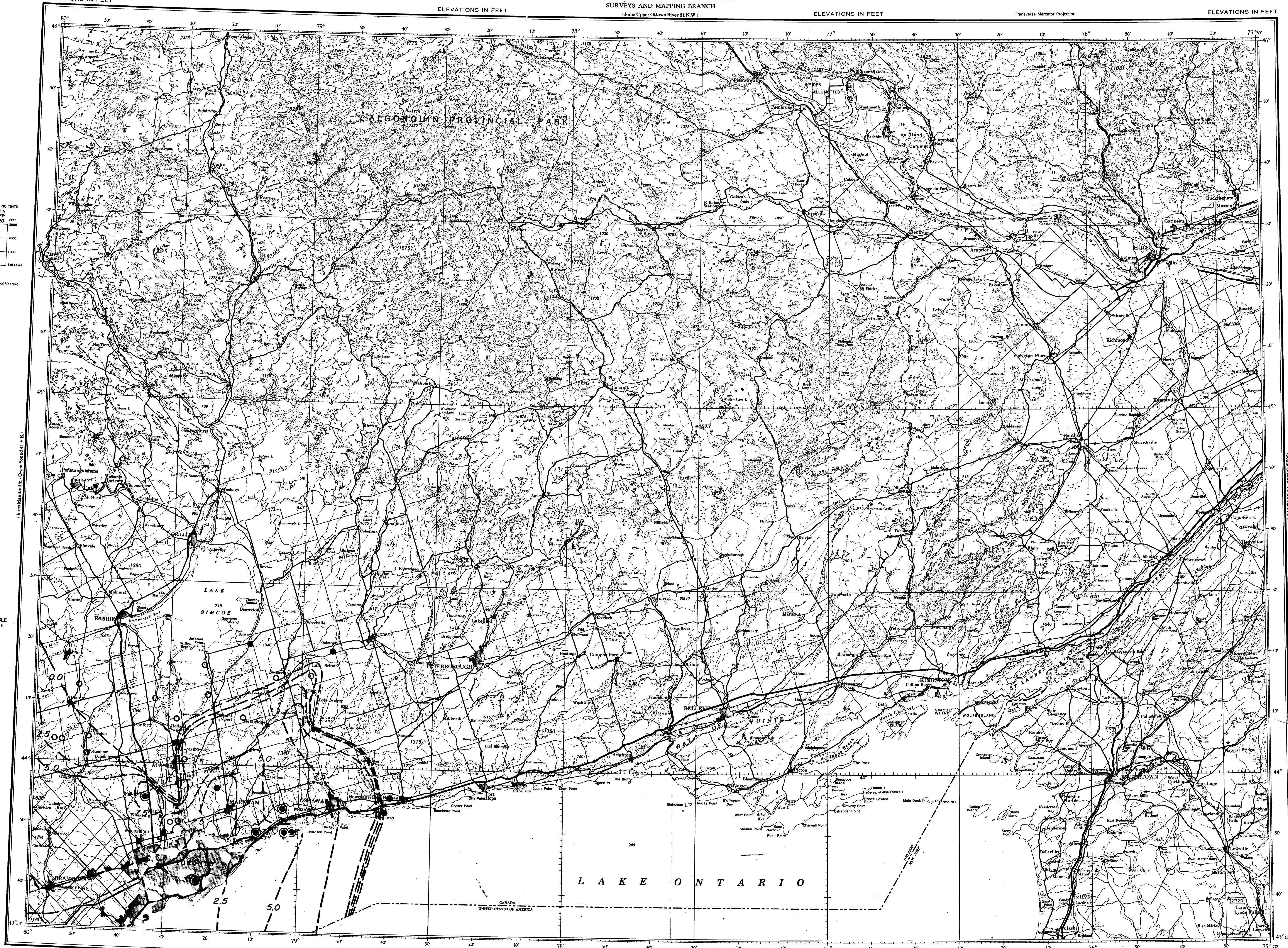
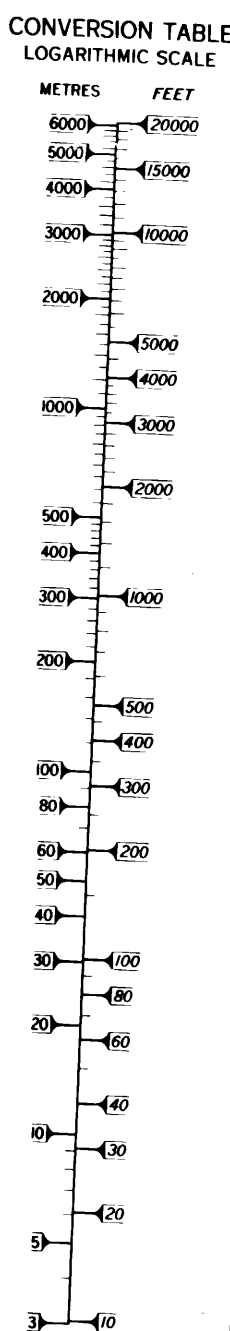
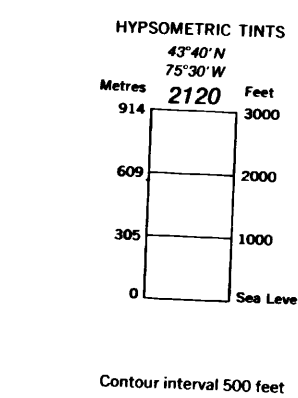
TORONTO-OTTAWA
ELEVATIONS IN FEET

CANADA
DEPARTMENT OF
ENERGY, MINES AND RESOURCES
SURVEYS AND MAPPING BRANCH
(Join Upper Ottawa River 31 N.W.1.)

ELEVATIONS IN FEET

Transverse Mercator Projection

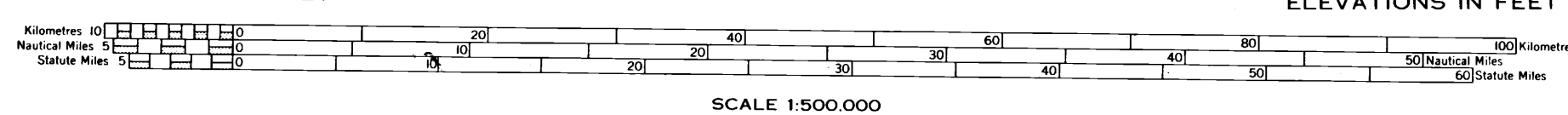
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ELEVATIONS IN FEET
TORONTO-OTTAWA
N.T.S. No. 31 S.W.

LEGEND

- OGS CORED HOLES
- OIL + GAS CORED HOLES
- OIL + GAS HOLES (Cuttings only)
- ISOPACH THICKNESS
COLLINGWOOD MEMBER (metres)

Map 2D:

ISOPACH MAP COLLINGWOOD MEMBER, LINDSAY FM.
(SOUTHEAST SHEET)

