“COLLINGWOOD” STRATA IN SOUTH-CENTRAL ONTARIO – A PETROPHYSICAL CHEMOSTRATIGRAPHIC APPROACH TO COMPARISON AND CORRELATION USING GEOPHYSICAL BOREHOLE LOGS.

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science

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ABSTRACT

A petrophysical chemostratigraphic comparison and correlation of “Collingwood” strata across central Ontario was conducted using geophysical borehole log data and core produced by the Ontario Oil Shale Assessment Project (OSAP). Outcrop sections were also measured, sampled and described. The resultant geophysical correlation was compared to sections in the Michigan Peninsula. Microfacies analyses and a biostratigraphic review were also conducted. The dark organic rich rocks collectively referred to as the “Collingwood Member, Lindsay Formation”, in Ontario were deposited during the progressive drowning of a mid to late Ordovician carbonate ramp. Due to variability in ramp palaeotopography, condensation intensity (sedimentation stress) varied across the region during drowning. This variability resulted in regional differences in Collingwood section thickness and facies. Less condensed carbonate rich “Collingwood” sections are associated with palaeotopographic highs such as the Algonquin Arch in Ontario and grade upwards and outwards (off-arch) from predominantly deep-shelf carbonates (microfacies type SMF 9, FZ 2 – open sea shelf – deep undatherm below wave base) to more condensed deeper water shale rich strata (microfacies type SMF 3, FZ1- basin fondotherm below oxygen level) – that contain abundant graptolites and *Triarthrus* trilobites.
ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Between 1980 and 1983 the economic potential of Ontario's "oil shales" was investigated by the Ontario Geological Survey. The study was known as the “Ontario Oil Shale Assessment Project” OSAP (See Johnson et al., 1983, 1985). In South-central Ontario the Collingwood Member of the Lindsay Formation, at that time the Craigleith Member of Liberty's (1969) Whitby Formation were among some of the “oil shales” assessed (see Collingwood distribution map Figure 1 and historic stratigraphic nomenclature Figure 2). Because these strata were known from only a scant few geographically isolated outcrops (Figure 3), none of which exposed complete sections, OSAP’s borehole program promised to provide much needed stratigraphic data (Russell and Telford, 1983).

Since the publication of OSAP data by Johnson et al., (1983-1985), biostratigraphic, petrographic, petrochemical, and stratigraphic analyses (including a stratigraphic revision) have been conducted and published by various authors (See Russell and Telford (1983); Churcher et al. (1986); Churcher et al. (1991); Hiatt (1985); Hiatt and Nordeng (1985); Wilson and Sengupta (1985); Snowdon (1984); Macauley et al. (1990); Johnson et al. (1991); Lehman et al. (1995). Yet despite the new OSAP data, analyses, and stratigraphic revision, our understanding of these organic-rich strata does not appear to have advanced significantly, as the wide range in post-OSAP palaeoenvironmental interpretations bear witness. These include normal marine shallow-shelf, deep-shelf, stratified marine, stranded basin and restricted lagoon interpretations.

The areal distribution of Collingwood strata was estimated by Churcher et al. (1991) (Figure 1). Pleistocene glacial scouring removed the Collingwood Mbr. north and east of St. Joseph's Island, Manitoulin Island, Craigleith, and Bowmanville, exposing older parts of the carbonate shelf and Precambrian Shield (Churcher et al., 1991). Collingwood Mbr. strata were reported to thin basinward toward the Michigan and Appalachian basins (Churcher et al., 1991; Johnson et al., 1983; Hiatt, 1985; Hiatt and Nordeng, 1985). According to Russell and Telford (1983) total organic carbon content (TOC) also decreases basinward. A thin phosphatic bed was reported to replace Collingwood Mbr. strata basinward (Michigan Basin) of its pinchout (Churcher et al., 1991). According to Churcher et al. (1991), Collingwood strata have been identified as outliers in only a few holes in Southwestern Ontario (see Figure 4).
The lithologic content of the Collingwood Mbr. and its stratigraphic boundary contacts were defined in the stratigraphic revision proposed by Russell and Telford, (1983). Russell and Telford (1983) based their stratigraphic revision and conception of the “Collingwood Mbr.” on (a) mappable geophysical borehole log signatures and (b) similarities in correlative lithologies across the region. However, preliminary investigation of these strata and geophysical borehole logs indicated to the author regional differences in facies, section thickness, and contact boundary conditions that suggest the lithostratigraphic formation model adopted by Russell and Telford (1983) is problematic.

Regional differences in facies, section thickness, and contact boundary conditions would explain much of the variability not only in environmental interpretations but also in pre-OSAP geologic reports on lithologic content and boundary contacts. “With great understatement” was the comment Russell and Telford (1983) used to acknowledge Winder’s (1961) declaration that geologic reports showed inconsistencies.

Geophysical borehole log profiles (gamma and resistivity) of Collingwood Mbr. strata have been described as “characteristic” in the Michigan Peninsula by Hiatt and Nordeng (1985); Wilson and Sengupta (1985), and in Ontario by Russell and Telford (1983); Churcher et al., (1991). The purpose of this study was to determine if a petrophysical chemostratigraphic approach (using geophysical borehole logs) to compare and correlated Collingwood strata in South-central Ontario would provide a better understanding of these strata. In addition to the petrophysical chemostratigraphic comparison and correlation a microfacies analysis and review of the biostratigraphic data was also conducted. The petrophysical chemostratigraphic comparison and correlation of Collingwood strata in central Ontario was also compared to reportedly correlative strata in the Michigan Peninsula.
2.0 **STRATIGRAPHIC REVIEW**

A comprehensive review of pre-1983 stratigraphic nomenclature and age attribution for strata equivalent to the Collingwood was conducted by Liberty (1955; 1969). Another researcher, Winder (1961), produced a lexicon of Palaeozoic names in Southwestern Ontario, in which the various stratigraphic nomenclature uses were discussed. Figure 2 summarizes and compares the historic and current stratigraphic nomenclature use in South-central Ontario. In addition Figure 2 presents the current stratigraphic nomenclature for Southwestern Ontario and Eastern Ontario.

In 1983, Russell and Telford used OSAP data to propose a stratigraphic reassignment of Liberty’s (1969) Craigleith Mbr. of the Whitby Fm. (see Figure 2). The Craigleith Mbr. was re-named the Collingwood Mbr. and re-assigned to the Lindsay Fm. The name “Collingwood” (first used by P.E. Raymond in 1912) has historically been in use variably as an age and/or lithologic assignment. Historic descriptions of lithologic content and contact definitions will in part be discussed in later sections of this study.

At present Collingwood strata are interpreted to be early Upper Ordovician in age (biostratigraphic age: Maysvillian). In South-central Ontario Collingwood strata are included as the upper most strata of the combined Simcoe and Basal Groups (equivalent to the Trenton-Black River Group of Southwestern Ontario and the Michigan Peninsula). In Ontario the upper Collingwood contact boundary represents the upper boundary of Depositional Sequence 2. According to Johnston et al. (1991), Depositional Sequence 2 is comprised of primarily craton derived clastic rocks succeeded by shallow water carbonates and is roughly equivalent to the Sauk-Tippecanoe sequence of Sloss (1963, 1988)(Johnston et al., 1991) Figure 2. Note however, that this “sequence boundary” was largely based on the break between predominately carbonate vs. clastic deposition and does not represent an erosional unconformity in the sense of Mitchum et al. (1977) (Melchin et al., 1994).

Collingwood strata are reported to be equivalent to the Boas River Fm. (Hudson Bay and Moose River basins) and the Eastview Mbr. of the Lindsay Fm. (Eastern Ontario) (see Johnston et al. (1991). However, it was beyond the scope of this study to review those strata. The Boas River Fm. and the Eastview Mbr. (Lindsay Fm) are separated from Collingwood strata in South-central Ontario by large distances over which equivalent strata have been removed during
Pleistocene glaciation. Therefore, a petrophysical chemostratigraphic comparison of these strata would require much speculation. To date the relatedness of these strata is based on similar lithologic and biostratigraphic data.
3.0 **GEOLOGICAL SETTING**

During the Middle Ordovician, closure of the Iapetus Ocean resulted in a series of collision events at the eastern margin of Laurentia (North America). The subduction of Iapetus crust and collision with an island arc (Rowley and Kidd, 1981; Cisne et al., 1982; Hay and Cisne, 1988) and or microcontinent/s (Delano et al., 1990) produced the Taconic orogen. Lithospheric downwarping associated with cratonward loading of thrust blocks (taconic allochthon) produced a peripheral foreland basin (the Western Taconic Foreland) (Rowley and Kidd, 1981; Quinlin and Beaumont, 1984; Lash 1988; Bradley and Kidd, 1991). The eastern portion of a shallow marine carbonate platform now drowned and faulted formed the floor of the basin. Movement along high-angled faults with strike parallel to the basin axis (north-northeast-south-southwest) produced grabens and half grabens on the deeper eastern portion of the basin (Cisne et al., 1982; Bradley and Kidd, 1991). Siliciclastic deposition in the basin migrated with time to the northwest encroaching on the Trenton carbonate platform/ramp (Rowley and Kidd, 1981; Bradley and Kusky, 1986; Lehman et al., 1995). The upper Collingwood Mbr. boundary (base of Blue Mountain Fm.) is thought to represent the first arrival in Ontario of the migrating siliciclastics (see Johnson et al., 1991).

Today the Michigan and Appalachian basins separated by the Central and Western St. Lawrence platforms dominate the subsurface (see Figure 5). The Algonquin Arch runs centrally through the Western St. Lawrence platform producing the only significant topographic relief on the platform. Similarly the Frontenac Arch (Johnson et al., 1991) interrupts the Western and Central St. Lawrence platforms. The Laurentian Arch continues northeastward from the Algonquin Arch.

At the northernmost outcrop (Manitoulin Island), Figure 3, a localized Precambrian metaquartzite mound is unconformably overlain by Lower Mbr. and Collingwood Mbr. strata (Johnson and Jia-yu, 1989) (Goldman and Bergstrom, 1997). The development of a short-lived metaquartzite boulder beach in that area is interpreted to indicate a rapid transgression across the Precambrian metaquartzite mound (Johnson and Jia-yu, 1989. The Collingwood Mbr. has not been recognized south of Lake Ontario (Lehman et al., 1995).
4.0 LOCALTIES AND DATA COLLECTION

Collingwood Mbr. strata, as defined by Russell and Telford (1983), outcrop in 3 laterally isolated areas in South-central Ontario (Fig. 3). At each of the three outcrop localities the lower boundary can reportedly be observed. The upper boundary has not been recognized in outcrop. Therefore, to examine the Collingwood Mbr. and both boundaries at any given geographic point requires subsurface data (geophysical borehole-logs and/or core). In this study, 3 outcrop and 15 borehole localities (represented by geophysical borehole logs - 7 with core) were examined. Outcrop and OSAP borehole locations are shown in Figure 6.

5.0 REGIONAL SUBSURFACE STRATIGRAPHY

A stratigraphic cross section through the preserved palaeozoic units in South-central Ontario is presented in Figure 7. The cross section runs from northwest to southeast along the Niagara escarpment and shows the generalized progression of lithologic units upwards from the Precambrian discontinuity. The units have been grouped into Johnston et al.’s (1991) depositional sequences 1 through 6 (see discussion of depositional sequences in section 3). The cross section was based on the subsurface correlation work conducted by Armstrong and Carter (2006) and generalized lithologic descriptions of formation units in Johnston et al. (1991). Table 1 (after Johnston et al., 1991) below, compares the relevant six depositional sequences to the North American Sequences of Sloss (1963, 1988) (Johnston et al., 1991) and provides the epoch, period and generalized depositional mode.
Table 1

Period, Epoch and Sequence Comparison

<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Depositional Sequence</th>
<th>North American Sequence</th>
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<tbody>
<tr>
<td>Silurian</td>
<td>Late</td>
<td>Upper</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>6 - carbonate and evaporitic deposits. Some orogen derived clastic sediments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Upper</td>
<td>Tippecanoe</td>
</tr>
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<td></td>
<td></td>
<td>5 - extensive carbonate deposition with some shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>Upper</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 - orogen derived fluvial to shallow marine clastics and marine carbonates</td>
<td></td>
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<tr>
<td></td>
<td>Lower</td>
<td>Lower</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td>3 - orogen derived clastic rocks</td>
<td></td>
</tr>
<tr>
<td>Ordovician</td>
<td>Late</td>
<td>Upper</td>
<td>Sauk</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 - initial craton derived clastics then dominated by shallow marine carbonates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Upper</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 - predominantly craton derived clastic sediments</td>
<td></td>
</tr>
</tbody>
</table>

After Johnston et. al. (1991)
6.0 MICROFACIES ANALYSIS

The Collingwood Mbr. was reported by Russell and Telford, (1983) to consist of interbeded limestone and marlstone. The mineral content was reported to be calcite (up to or greater than 50%), quartz (35%), clays (15% illite and iron chlorite), pyrite, phosphate, and locally dolomite (Russell and Telford, 1983; Snowdon, 1984; Macauley et al., 1991; Churcher et al., 1991). Although the lithology and mineralogy of the Collingwood Mbr. has been investigated and generalized little has been discussed with respect to stratigraphic and lateral variation of these components. Therefore samples from core and outcrops were collected from the nodular limestone of the Lower Mbr., marlstones and carbonate interbeds of the Collingwood Mbr., and shales of the Blue Mountain Fm. A thin phosphatic bed observed at the upper Collingwood Mbr. boundary, Clarksburg locality, was also sampled.

Thin sections made from core and outcrop samples collected from the nodular limestones of the Lower Lindsay Mbr., marlstones and carbonates of the Collingwood Mbr., and shales of the Blue Mountain Fm. were prepared and examined under reflected and transmitted plain and cross-polarized light using a petrographic microscope. The sections were described by comparison to the carbonate microfacies of Wilson (1975) and Flugel (1982). A representative image for each microfacies type appears beside the description. In addition acid resistant microfossils and minerals were obtained through acid digestion of carbonate samples (2 kg each) collected from outcrop localities. The microfossils were used as palaeoenvironmental indicators (note: microfossils collected during this study have been lost).

6.1 Lower Mbr. (Lindsay Fm.) Nodular Limestones. SMF 9, Facies Zone 2

Samples of nodules represent highly bioturbated argillaceous, organic biomicrite/wakestones with burrows. The sample shown here was imaged under transmitted light.

Circular cross-sections of burrows indicate early burial lithification with compression of burrow cross-sections increasing (up to 100%) toward the darker envelopes surrounding the nodules. The micritic fabric may be described as microsparite. Pockets of sparry calcite...
replacement are common in areas of coarser bioclastic concentration (see Appendix A, Plate 1, slides 3 & 4).

Sparry dolomite replaces much of the calcite at the Manitoulin Island localities (see Appendix A, Plate 1, slides 1&2). At the Manitoulin Island outcrop locality, the upper contact is marked by a brecciated quartzite and fining upward (subangular to rounded) Quartzite cobbles, pebbles, sand and silt. The quartzite clasts appeared in association with a local Precambrian metaquartzite outlier. Sparse disseminated quartz silt was observed at other localities. At the Manitoulin Island outcrop locality the Lower Mbr. did not exhibit the nodular bedding. Lack of nodular bedding at this locality may be due to deposition within a zone of higher energy associated with the "short-lived boulder beach" interpretation of Johnson and Jia Yu, (1989). The lack of nodular bedding at the Manitoulin Island locality negated the use of Russell and Telford’s (1983) described criteria for locating the upper boundary (i.e. – last nodular interbed).

In general these Lower Member samples were comparable with microfacies SMF 9 of Wilson (1975), in Flugel (1982). While type SMF 9 is associated with either Facies Zone 7 (FZ 7 - Shelf Lagoons with open circulation) or Facies Zone 2 (FZ 2 - Open sea shelf - Deep undatherm below wave base) Flugel (1982), the nodular bedding and marl associations indicate they belong to the later Facies Zone (FZ 2).

Recurrent textural inversion from 1 to 8cm thick grainstone interbeds (Facies SMF 10 of Wilson (1975); Facies Zone 2 of Flugel (1978), is a common feature of these facies and continues to be a feature in the Collingwood beds described below. These grainstone units were noted by Tufnell (1986) and Moffat et al. (1998). Tufnell (1986) described these units as laterally extensive graded storm beds and noted that within drab carbonate facies these units were often obliterated due to bioturbation. Moffat and Brett (1998) interpreted these units as autochthonous condensed sections formed during short-term fluctuations in relative sea-level. Handford and Louks (1993) state that down-dip transport of carbonate turbidites can be initiated by storms or changes in relative sea-level. According to the carbonate platform facies models of Read (1985, 1995); Handford and Louks (1993) and Loucks and Sarg (1993), argillaceous nodular limestone facies represent deep-shelf facies common to drowning carbonate platforms.

Residues produced by acid digestion of outcrop samples contained hexactinellid sponge spicules, phosphate nodules and conodonts. Preliminary analysis of conodont elements indicated that Amorphognathus superbis(?) was representative of these facies. At locality 2, abundant
large rounded conodont fragments suggested energy sorting and support the higher energy zone interpretation of Johnston and Jia Yu, (1989) for that locality.

A deep, phosphate rich, cool-water environment is indicated by the presence of Amorphognathus (Sweet, 1988). However, Sweet (1988) argued that upwelling of cool phosphate-rich waters may have brought Amorphognathus into shallower water.

6.2 Collingwood Mbr. (Lindsay Fm.)
Marlstone SMF 3, Facies Zone 1

Samples represent fine grained (often fossiliferous) dark organic-rich mudstones, ranging from calcareous shale to argillaceous micrite. The sample shown here was imaged under transmitted light.

Alternating dark and light grey laminations are common. Bioturbation is rare to absent with marked reduction in macrofauna diversity noted. Fine disseminated pyrite with pyrite replacement of fossils common. Dolomite replaces most of the Calcite at the Manitoulin Island localities (Appendix A, Plate 1, slide 1&5). At the Manitoulin Island localities a quartz- sand and silt component, associated with a local Precambrian metaquartzite outlier is restricted to the base of this unit and rapidly fines upward (Appendix A, Plates 1, slides 1&5). Sparse disseminated quartz silt was occasionally observed elsewhere – often as a component of grainstone interbeds. Thin to fine carbonate grainstone units (SMF 10) (textural inversion) fine upward and are absent in the upper-most Collingwood Mbr. They also appear to be much reduced in number, thickness, and grain size at localities southeast and northwest of the Algonquin Arch region.

These samples are comparable with SMF 3 of Wilson (1975) and are associated with Facies Zone 1 of Flugel (1982) (Basin fondotherm below oxygenation level). Within the Facies Zone scale of Flugel (1982), (FZ 1) represents an incremental increase in palaeodepth relative to FZ 2.

Residues produced by acid digestion of outcrop samples (2kg) produced some conodonts including Amorphognathus superbus? but not hexactinellid spicules or phosphatic pellets. It is
unknown whether or not this was due to environmental exclusion or a shift in preservation potential.

In the Clarksburg locality core (Clarksburg site is located within the Collingwood cluster, Figure 6) a phosphatic bed presumably the “phosphatic” bed described by Churcher et al. (1991) as erosional remnants of the Collingwood strata was observed. The sample shown here was imaged under retransmitted light.

The sample represents an intrasparite/ironstone (Appendix A, Plate 1, slide 1 through 6) that contains lithoclasts, worn bioclasts, peloids, ooids(?), and clasts of phosphatic micrite. The carbonate matrix appeared to be dolomitic. Geopetal filling of shell fragments can be observed.

This unit was comparable to SMF 14 of Wilson (1975)(slow accumulation of coarse material in a zone of winnowing) and is associated with Facies Zone 6 (FZ 6 - Winnowed platform edge sands) Flugel (1982). Although autochthonous components are typical of SMF 14 (Wilson, 1975), in this case the dramatic environmental and textural inversion from the deep-water laminated marlstone facies, SMF 3, (below), indicates a down-dip transport of this material (allochthonous carbonate turbidite).

According to Churcher et al. (1991), this phosphatic unit was reported to be found where Rouge River Mbr. and Collingwood Mbr. strata were absent and was interpreted to represent erosional remnants of these members. However, a review of the geophysical log for the Clarksburg locality indicated that the locality contains one of the thicker Collingwood sections. The Clarksburg log will be presented and discussed further in later sections of this report.
6.3 Collingwood Mbr. (Lindsay Fm.) Pale Grey and Buff -coloured Carbonate interbeds SMF 9, Facies Zone 2

Samples represent biomicrite/wackestones. The sample shown here was imaged under transmitted light.

Pockets of sparry calcite replacement are common in areas of coarser bioclastic concentration. Sparse disseminated quartz silt. Fine pyrite crystals occasionally cluster around fossils. Grainstone interbeds (1 to 8cm packstone/coquina interbeds), representing SMF 10 of Wilson (1975), Facies Zone 2 of Flugel (1982), occur, as textural inversion.

The absence of well developed and or total lack of nodular bedding distinguishes these facies from the Nodular Limestone of the Lower Mbr. of the Lindsay Fm. These carbonate interbeds were not observed in core from localities north and south of the Algonquin Arch region.

Residues produced by acid digestion of outcrop samples (2kg) contained hexactinellid sponge spicules, phosphate nodules and conodonts. Preliminary analysis of conodont elements indicates that Amorphognathus superbus(?) is representative of these facies.

6.4 Blue Mountain Fm. Shale/calcareous shale

Samples are best described as calcareous claystones (often dolomitic) with sparse to rare disseminated pyrite, bioclasts and silt. The sample shown here was imaged under reflected light.

The dolomitic component of the shales make Russell and Telford’s (1983) criteria for locating the upper Collingwood boundary (i.e. the “last calcareous shales” problematic.

6.5 Microfacies Analysis Results

The observed progression of carbonate microfacies types from SMF 9, FZ 2 (Lower Mbr.) to SMF 3, FZ 1(Collingwood Mbr.) indicated deepening upward conditions. At some localities upward deepening appeared to be intermittently interrupted as evidenced by brief
periods of re-established carbonate deposition (SMF 9, FZ 2). In South-central Ontario these localities were invariably associated with the centroid (represented by the Collingwood cluster and Corbetton locality) of the study area from the Lower Mbr. through the Collingwood Mbr. There was a distinct upward reduction in carbonate content, though dynamic, accompanied by an increase in clay until the carbonate dominated system was ultimately replaced by a clastic clay dominated system (Blue Mountain Fm.).

7.0 BIOSTRATIGRAHY AND PALAEOBIOLOGY

The data for the biostratigraphic component of this study consists of published ranges for trilobites, graptolites, conodonts, and chitinazoa (Figure 8). Data obtained from OSAP core and outcrop localities, published by others, was restored to stratigraphic position and will be presented and discussed in a latter section of this report. The use of current nomenclature for generic and specific names was adopted here but reference is made to synonymous names appearing in the original literature.

7.1 Trilobites

The high abundance of Triarthrus trilobite remains in the shaley interval equivalent to the Collingwood Mbr through Blue Mountain Fm. inspired Parks (1928) to construct a biostratigraphic scheme based on the trilobite genus Triarthrus. Utilizing data collected by Tuffnell (1986) from OSAP core - restored in Figure 1A - Tuffnell (1986); Tuffnell and Ludvigsen (1984); Ludvigsen and Tuffnell (1984), re-evaluated Park's (1928) trilobite biostratigraphy. These authors concluded that ranges of Triarthrus species overlapped and cautioned against the use of Triarthrus as a conventional biostratigraphic tool. However, because certain species appeared more representative of specific lithostratigraphic intervals, Tuffnell and Ludvigsen (1984); Ludvigsen and Tuffnell (1984), proposed a battleship type Triarthrus biostratigraphy (Figure 8). According to Tuffnell and Ludvigsen (1984); Ludvigsen and Tuffnell (1984), a higher abundance of Triarthrus etoni was associated with Collingwood Mbr. strata while higher abundances of T. canadensis, T. rougensis and T. spinosus were associated with Blue Mountain strata (Figure 8).

7.2 Graptolites

According to Riva (1974), strata equivalent to the Collingwood Mbr. were assigned to the Climicograptus pygmaeus syn. Geniculograptus pygmaeus zone while strata equivalent to the
Blue Mountain Fm. were assigned to the Amplexograptus manitoulinensis zone (Riva, 1974). The Upper Geniculograptus pygmaeus zone was later designated as lower Maysvillian in age while the A. manitoulinensis zone was designated as upper Maysvillian in age (Bergstrom and Mitchell, 1986) (Goldman and Bergstrom, 1997) (Figure 8).

7.3 Conodonts

Conodont zonation is reported to be coarse during Maysvillian times and is represented by a single conodont zone (Amorphagnathus superbus zone) (Goldman and Bergstrom, 1997) (Figure 8). Conodont specimens recovered during this study appeared consistent with the Amorphognathus superbus conodont zone.

7.4 Chitinozoa

Chitinozoan data (Figure 8) support a lower Maysvillian age for Collingwood Mbr. strata but do not offer further time-stratigraphic resolution (Melchin et al., 1994).

The lower sub-unit of the Lower Mbr. (Lindsay Fm.) contains chitinozoan assemblage ChA-6 dominated by species of Herchochitina with species of Angochitina and Belochitina also representative (Melchin et al., 1994). The upper Lower Mbr. (Lindsay Fm.) contains chitinozoan assemblage ChA-8 marked by high species diversity with no individual species dominant (Melchin et al., 1994). Chitinozoan assemblage ChA-8 is also representative of the Collingwood Mbr. (Lindsay Fm.). Upward-increasing chitinozoan diversity (from ChA-6 to ChA-8) (Figure 8) in the Lindsay Fm. is interpreted to indicate deepening-upward conditions (Melchin et al., 1994). Based on the persistence of high planktic chitinozoan diversity across the lower Collingwood Mbr. Boundary, environmental change, indicated by marked reduction in (a) bioturbation, (b) infaunal and benthic macrofaunas and (c) increased organic preservation relative to the Lower Mbr., is interpreted to be restricted to bottom waters (Russell and Telford, 1983; Melchin et al., 1994).

7.5 Biostratigraphy and Palaeobiology Results

The biostratigraphic and palaeobiology data appear to support three conclusions:

- Upward deepening conditions from the Lower Mbr. through the Collingwood Mbr.
- Gradational change from the Lower Mbr. through to the Blue Mountain Fm.
The Lower Mbr. and Collingwood Mbr. strata appear to be Lower Maysvillian in age with the Blue Mountain Fm. strata assigned as upper Maysvillian in age.
8.0 GEOPHYSICAL BOREHOLE LOG CORRELATION

8.1 Method

Churcher et al. (1991) produced a “schematic” gamma log signature depicting the Collingwood as a linear transition from argillaceous limestone (Lower Member of the Lindsay Formation) to shale (Blue Mountain Fm.) (Figure 9). According to Churcher et al. (1991), if the transition zone was absent then the Collingwood was absent. For comparison, Churcher et al. (1991) presented two examples of each type of “actual” gamma-logs (figure 10). The sample localities illustrated were from Southwestern Ontario where Collingwood strata, according to Churcher et al. (1991), exist in a few areas as outliers – presumably the Collingwood was eroded away from the rest of Southwestern Ontario (see location of outliers in Figure 4). In the Collingwood distribution/isopach maps presented in Churcher et al. (1991), localities with Collingwood strata present were identified with the pre-fix WC (“With Collingwood”) while holes without Collingwood were denoted with the pre-fix NC (“No Collingwood”). A significant technical problem with their comparison reproduced in figure 10 is that the gamma log scale (API units) for the NC holes should read 0 to 200 API and not 0 to 100 API. In addition transposition of signals higher than 100 API units in the WC logs was not conducted for the comparison. When scaled for comparison the geophysical log signatures for the WC holes no longer appeared significantly different from the NC hole logs (Figure 11).

WC-36 (with Collingwood) was compared to NC-36 (no Collingwood) (Figure 12). The two holes are approximately 25 kilometres apart. Re-scaled and normalized NC-36 showed a very similar “transition zone” and the Collingwood unit (gamma log/petrophysical chemostratigraphic unit) appeared to be equally present in NC-36 -then why do we not recognize Collingwood strata in NC-36? – or in general Collingwood strata in Southwestern Ontario?

8.2 Geophysical Borehole Log Identified Unit (Petrophysical Chemostratigraphic approach)

The gamma log line is used to review down-hole changes in stratal clay content. Natural gamma radiation detected by the tool emanates from radioisotopes of potassium, thorium, and uranium associated with clay (shale) and organic deposits. The more clay and/or organic enriched the strata are the higher the gamma log signals are until levels reach the theoretical “shale line” - indicating shale strata. The resistivity log line is a measure of electrical resistance to current flow. Accumulation of organic material (hydrocarbons) results in high electrical
resistance and thus is an important tool for hydrocarbon exploration. The neutron log line is produced by irradiating the strata and measuring induced radioactivity. The amount of induced radiation is proportional to the density of the strata. Therefore the neutron log line is used to examine differences in stratal density.

Geophysical borehole logs (gamma, neutron, and resistivity) from OSAP holes were traced, scanned and scaled/normalized for comparison. The upper Trenton boundary (upper Collingwood Mbr. boundary) was used as the datum. For initial review purposes the Collingwood boundaries/contacts identified in the OSAP logs by Johnston et al. (1983-1985) were used. During review of the geophysical and written logs it was noticed that discrepancies in logged depth existed for many of the Collingwood cluster holes. In those cases where discrepancies existed between written and geophysical logs the upper and lower Collingwood boundaries were estimated based on the authors interpretation of the geophysical logs (core was not available to qualify the estimates).

In South-central Ontario, OSAP data was obtained from three geographically isolated regions. Within each region a cluster of shallow boreholes exists. These clusters were located in Toronto, Collingwood, and on Manitoulin Island (Figure 13). There were three deep OSAP boreholes advanced to tie-in the three clusters (Figure 14). Two of the deep boreholes were located between the Toronto and Collingwood clusters (the Corbetton and Nobelton holes) and the other hole was located between the Collingwood and Manitoulin Island clusters (the Wiarton hole).

Figure 15 shows the Collingwood as it appears in the geophysical record from the three OSAP clusters in South-central Ontario. A review of Collingwood petrophysical chemostratigraphy in the Collingwood cluster, Figure 15, revealed that the strata were consistent and mappable over the entire Collingwood region. Note that Collingwood strata were not fully penetrated at CLGD4b, CLGD6a, and CLGD7a. The same cannot be said for the Toronto and Manitoulin Island clusters in Figure 15, where signatures showed differences between localities within each cluster and between clusters. In the Toronto cluster, Collingwood signatures indicated that strata thin from left to right (from northeast to southwest). In the Manitoulin Island cluster the two signatures were similar but did not share the “carbon copy” appearance that the Collingwood cluster signatures exhibited. Overall the signatures were different between clusters and the transition interval (Collingwood) showed significant variation in length.
Collingwood section thickness ranged from approximately 11.5 to 1.5 metres. The signatures presented in Figure 15 also revealed that the transition from carbonate dominated to shale dominated deposition was dynamic.

In order to better evaluate the relatedness of these clusters, geophysical borehole log signatures for OSAP “tie-in” localities were examined and compared to the cluster signatures. First, tie-in locality logs were compared to the Collingwood cluster signatures (Figure 16). Comparison of the Collingwood cluster with the Corbetton Tie-in log (approximately 40 kilometres away) showed little change in stratal composition and revealed that Collingwood strata were readily mappable between these localities. Collingwood section thickness changed from approximately 9.58 to 11.5 metres. Comparison between the Collingwood cluster and the Wiarton Tie-in locality (approximately 30 kilometers away) showed that signatures/strata, though mappable, were more condensed (reduced in thickness) from Collingwood (9.58 metres) to Wiarton (6.2 metres). Note the contacts were transposed from the positions indicated in the Johnston et al. (1983-85) log for Wiarton. The transposition is indicated in Figure 16.

A comparison between the three clusters and tie-in localities is presented in Figure 17. While Figure 17 provides the reader with a good comparison of overall Collingwood strata characteristics from north to south in central Ontario, the OSAP tie-in localities are not sufficient to map changes north and south of the tie-in localities to the Manitoulin Island and Toronto cluster localities.

The tie-in localities provided the data necessary to map with confidence Collingwood strata over an approximately 100km distance within the centroid of the study area. However, an environmental gradient exited somewhere between the Tie-in localities and the Toronto and Manitoulin Island clusters. An investigation was conducted to determine if logs from sources other than the OSAP, existed to serve as additional tie-in localities. The unpublished OSAP log for the Nobelton hole was obtained from the Ministry of Northern Development and Mines. Other localities that could be used as Tie-in logs were not found. Review of the Nobleton log indicated that Johnston et al. (1983-1985) placed the lower contact boundary at a stratigraphically lower position in this well. The boundary was moved to a position that was more consistent with other localities. This decision will be supported further in latter sections of this report. The OSAP Nobelton hole was located between the Corbetton hole and the Toronto cluster (see Figures 14 and 18). Examination of Collingwood strata in the Nobelton log showed
that condensation of strata there was comparable in degree to the Toronto cluster and that the
signature did not appear to be serviceable as a tie-in log. In order to proceed with the study a
different approach was needed.

Because the carbonate microfacies and palaeobiology indicated that the nodular
limestone facies of the Lower Mbr. were, like Collingwood strata, consistent with a drowning
carbonate ramp scenario the author decided to determine if these strata too were mappable in the
subsurface and whether or not they could be used to better understand the stratigraphic
relationship between the clusters. However, only three OSAP logs (represented by the tie-in
localities) fully penetrated the Lower Mbr. Therefore, borehole logs from other sources were
obtained and examined.

Comparison of Lower Mbr. strata in the centroid of the study area showed that mappable
geophysical units could be constructed (Figure 19). Comparison of these geophysical borehole
log units to the Toronto and Manitoulin Island clusters (Figure 20) showed that like Collingwood
strata Lower Mbr. strata too exhibited regional differences in relative stratal condensation.
Moreover, like Collingwood strata Lower Mbr. strata become more condensed (thin) north and
south of the Collingwood cluster. The use of geophysical units below the Collingwood provided
stratigraphic control from which to review, in context, regional changes in Collingwood strata in
South-central Ontario. While the correlation of strata from the tie-ins to the Manitoulin Island
and Toronto clusters is here presented as tentative it is clear that Collingwood and Lower Mbr.
strata are more condensed north and south of the centroid (Wiarton, Collingwood cluster, and
Corbetton) of the study area. In some cases the added control required that the lower
Collingwood boundary be moved. The resultant differences are indicated in Figure 20. The
implication of these boundary changes will be discussed in subsequent sections. The next
section is dedicated to an explanation and discussion on condensation and a comparison between
the geophysical signatures and correlative facies observed in core.

8.3 Condensation

The statement that strata are “condensed” implies deposition occurred during a period of
diminished sedimentation rates. Potential causes of diminished sedimentation rates might
include sediment starvation during relative sea-level rise, depth related carbonate stress,
sediment bypass (hard grounds or omission surfaces). While there are many references to
“condensed sections” in the literature including descriptions of how to recognize them and
comments about their utility in stratigraphic correlation it is not often stated that condensation is a relative term. The term is relative because a sediment interval at any given locality may be more or less condensed compared to the same time correlative interval at other localities within the region. For example, during drowning of a carbonate dominated system, the effects of depth related carbonate stress would occur later in shallower areas and earlier in deeper areas. While both areas will eventually be stressed the shallower area will be less condensed overall. The converse is true in a clastic dominated deposition system.

In clastic dominated systems chemical/biochemical deposition and preservation are not important factors therefore, when sediment supply to the basin is interrupted, for example during sea level rise, a single (hypo) deposition mode (slow rate of sediment supply and accumulation) produces a thin “starved” sediment deposit across the basin. Sediment by-pass of topographic highs may intensify starvation. Therefore in regions of variable palaeotopographic relief we should expect to observe a range of condensation intensity with gradations in between expressed in the facies and ultimately time correlative section thickness. In carbonate dominated systems strata will be thickest over topographic highs and thin toward topographic lows such as basins. In clastic dominated systems strata may be thickest in topographic lows and thin toward topographic highs (see schematic drawing in Figure 21). Recognition of these two different condensation responses to relative sea level rise is important and will be revisited.

Note in Figure 22a, that the “transition intervals” (Collingwood strata) observed in the gamma logs for the Corbetton and Toronto cluster locality SIS3 are quite different. In the Corbetton gamma log the transition does not start from the base of the Collingwood like it does in the SIS 3 log. The less condensed Corbetton section which contains recurrent interbeded carbonates does not transition until carbonate sedimentation all but ceases in the uppermost portion of the section. This is in contrast to the Toronto cluster locality SIS 3. In the SIS 3 gamma log the transition begins at the base of the Collingwood and continues upward throughout the Collingwood. If Collingwood section thickness at SIS 3 were reduced in thickness compared to the Corbetton section due to post depositional erosion as proposed by others then the SIS 3 log would appear more carbonate rich and lack a “transition” (Figure 22b).

To demonstrate how regional differences in stratal condensation indicated in the geophysical record are exhibited in the lithofacies a comparison of OSAP core with corresponding gamma logs was conducted. Some of the core recovered during the OSAP project
was available for study through the Ontario Ministry of Northern Development and Mines (MNDM). The core was re-measured, sampled, and described. A comparison of the available core sections with their corresponding gamma log signatures is presented in Figure 23.

One significant observation to be made in Figure 23 is that the thickest Collingwood strata which are located in the centroid of the study area (represented by the Collingwood cluster and Corbetton hole) contained interbeded light coloured carbonates while Collingwood strata in the Toronto and Manitoulin Island clusters did not. Much of the core in the Manitoulin Island locality was missing, however, in the Toronto localities Collingwood strata were very dark, graptolitic, and finely laminated throughout indicating they are more condensed compared to the Collingwood cluster and Corbetton localities. In addition the grainstone interbeds observed in the Collingwood cluster and Corbetton cores were in the Toronto cluster localities significantly reduced in thickness and grain size indicating their position as more distal to the source compared to the centroid of the study region. Clearly the Collingwood sections in Toronto could not have been reduced to their observed thickness simply by having eroded the tops of thicker Collingwood cluster like sections – a conclusion already supported by the chemostratigraphic petrophysical signatures presented in Figures 22a and 22b. This study proposes that variability in Collingwood section thickness observed in this study resulted from variability in stratal condensation.

In South-central Ontario the Algonquin Arch (a palaeotopographic high) underlies the centroid of the study area (refer back to see Figure 5). The presence of less condensed strata overlying a palaeotopographic high (a topographic high known to pre-date deposition of Collingwood strata) is consistent with the drowning carbonate ramp scenario supported by the microfacies and palaeobiology and will be discussed further in later sections.

During review of Collingwood strata in OSAP core it was often difficult to distinguish grossly between dark coloured carbonates and “marlstones”. This fact resulted in the appearance (see Figure 23) of carbonate interbeds appearing to dissolve into marlstone from north to south in the Collingwood cluster through to the Corbetton core. Note however, in the same figure that in corresponding gamma logs the carbonate rich intervals are indicated to be consistent and mappable. A look at the outcrop section in the Collingwood area shows that due to weathering it was more readily subdivided making it appear different from the Collingwood cluster core. Clearly the gamma log line provides a more accurate measure of lithic changes compared to
gross examination. That said gross examination of the strata and comparison with the gamma logs revealed that Collingwood strata exhibit significant regional differences in light vs. dark colouring (the reader is notified that the fill pattern used in Figure 23 does not show the reader the range in dark colouring – from dark grey to black and even brown-black).

The Clarksburg core, which shared the same “carbon copy” gamma log signature with the other Collingwood cluster sites, was the lightest in colour overall and appeared to contain the fewest number of “marlstone” interbeds (Figure 23). This was noteworthy because the light coloured appearance of these strata made them look less Collingwood-like. Furthermore, at the top of this Collingwood section was a “thin phosphatic bed” like that reported by others to replace the Collingwood at localities where it was interpreted to be removed due to erosion.

Another OSAP hole (CLGD No. 17, geophysical log unpublished and unavailable) located just west of the Clarksburg hole was described by Johnston et al. (1983), to contain only 2 metres of Collingwood strata. This seems anomalous since the same authors reported approximately 10 metres of Collingwood strata throughout the rest of the Collingwood cluster. CLDG No. 17, like the Clarksburg hole may have contained light coloured facies much of which were not recognized as “Collingwood”. The association of lighter coloured lithology and the phosphatic bed (interpreted here as a down dip transport deposit from shallower water) in the Clarksburg hole suggests that shallower water with relatively higher oxygen content must have existed locally.

In Figure 20, compared to Collingwood cluster holes, the Collingwood base appears to be placed (by OSAP workers) in a stratigraphically older position in the Nobleton hole. Evidently increased condensation experienced in the Nobleton area resulted in formation of Collingwood-like strata at an earlier period in time (also refer to Figure 23). Similarly gross examination of the lighter coloured lithologies in the Clarksburg and CLGD No. 17 localities might result in a decision to place the Collingwood base at a stratigraphically younger position. In summary, regional differences in stratal condensation have led to miss-identification of the lower Collingwood boundary. That said the lighter coloured facies variant though related to condensation was not necessarily accompanied by differences in Collingwood section thickness (see Figure 23). Differences in light vs. dark colouring observed in the carbonate interbeds are interpreted to be due to variation in organic preservation potential. It would appear that organic preservation potential like condensation increased off-Arch.
The characteristic and mappable petrophysical chemostratigraphic signatures presented in this study are interpreted by the author to be formed in the following manner. Concomitant with carbonate sedimentation on the ramp is entrainment of trace amounts of terrigenous clay minerals from suspension. While carbonate sedimentation rates fluctuate over time and across the region the clay content at any given time in suspension would remain somewhat uniform regionally. Thus due to dynamic fluctuations in sedimentation through time the entrained clay minerals at a given point in time produce a signal that is regionally encoded. Together these clay mineral encoded points in time begin to stack and produce unique mappable signatures across the region.

8.4 “Collingwood” Strata in Central Ontario and the Michigan Basin

In order to better understand the relatedness between Collingwood strata in Ontario and the Michigan Peninsula their respective stratigraphic positions in the geophysical record were reviewed in context to the entire carbonate ramp sequence from the “Collingwood” down to the Shadow Lake Fm. In South-central Ontario these combined strata are referred to as the Simcoe Group while in Southwestern Ontario and in the Michigan Peninsula they are referred to as the Trenton and Black River Group. A comparison between representative Trenton and Black River Group sections in the Michigan Peninsula with the Corbetton hole in South-central Ontario is presented in Figure 24a & b.

The Michigan Peninsula correlation was conducted by others using the “TG-1 and TG-2 doublets” (highly mappable bentonites) used by subsurface workers to locate boundaries in the subsurface (Wilson and Sengupta, 1985; Wilson et al., 2001). Figure 24a & 4b illustrate 3 important facts:

1) there is significant regional variation in combined section thickness. (Note: this comparison does not present the full range of regional differences in section thickness. Sections in the southern portion of the basin in Ontario and the US are much thicker still).

2) while overall Trenton -Black River Group sections in the Michigan Peninsula correlation thin northward in a shallowing direction – Collingwood strata become significantly thicker in that direction.

3) Collingwood strata are mappable into the Michigan Peninsula but the base of the Collingwood in the Michigan Peninsula correlation appeared to be placed
stratigraphically lower/older than in Ontario (again like the Nobelton hole in Ontario, the increased degree of condensation exhibited in these Michigan Peninsula localities compared to the Corbetton locality appeared to result in earlier deposition of Collingwood-like strata there).

In the Michigan Peninsula correlation and in the South-central Ontario study area Collingwood strata appear to become less condensed in a shallowing direction, north toward the basin rim in the Michigan Basin and over the Algonquin Arch in South-central Ontario.

8.5 Datum, Stratal Condensation and Boundary Contacts

The “Upper Collingwood boundary” is reportedly equivalent to Johnson et al.’s (1991), “upper boundary for depositional sequence 2”, and was used as the datum in this study. According to Johnson et al. (1991), the datum is supposed to represent the boundary between two modes of deposition (from carbonate dominated to clastic dominated) (see Johnson et al. (1991). However, due to regional differences in stratal condensation and palaeotopography the datum, like the lower Collingwood boundary, may not represent a strict time-stratigraphic feature – a result that should be expected. To explain this fully we need to return to the discussion on differences in carbonate vs. clastic deposition response to sea level rise. During initial deposition of “Collingwood” strata under upward deepening conditions, rate of carbonate deposition was the limiting factor in Collingwood section condensation. However, during clastic dominated deposition the limiting factor in section condensation would be sediment supply (proximity of the locality to the prograding clastic wedge and potential by-pass of topographic highs.

In South-central Ontario the datum was placed at the upper Collingwood Mbr. boundary identified in the OSAP geophysical logs. Placement of the datum in the centroid of the study and to a lesser degree in the Toronto cluster appeared intuitive; however, placement of the datum in the Manitoulin Island cluster appeared to be more arbitrary. In the Manitoulin Island sections, upper Collingwood like conditions appeared to re-establish above the datum. The reader can observe this by reviewing the Upper Collingwood boundary in Figure 17. To understand better these uppermost Collingwood strata more extensive borehole coverage linking tie-in localities with the Toronto and Manitoulin Island clusters would be necessary.

The conventional explanation for the more concentrated upper Collingwood boundary in the Collingwood area is that the bituminous Rouge River Mbr. shales of the Blue Mountain Fm.
identified in the Toronto area were subsequently eroded from the Collingwood area sites (see Churcher et al., 1991). An alternative explanation but similar in result would be that sediment by-pass of the Arch may have produced a much condensed interval/surface there while accumulation of organic clays was experienced in deeper localities (less condensed) north and south of the Algonquin Arch. In either event the biostratigraphic zonation boundaries and palaeobiology data presented in Figures 8 and 25 do not offer evidence for a natural boundary (upper Collingwood boundary). The upper “Collingwood” boundary appeared to be transitional with no significant loss of time indicated.

The phosphatic unit observed at the upper Collingwood boundary in the Clarksburg locality and apparently found at other localities in Southwestern Ontario and the Michigan Basin, suggests that shallower water conditions existed in proximity to those localities. In the Michigan Basin, Wilson and Sengupta (1985), report that sections consistently reflect facies that grade from crinoidal shoal facies in the south along the north flank of the Findley Arch (southwestward extension of the Algonquin Arch) to deeper water dark organic wakestone facies in the north. With the Taconic foreland basin to the south of the shoal shelf-like environment along the Findley Arch these authors concluded that a restricted lagoon environment existed north of the Findley Arch and that Collingwood strata were deposited in the lagoon during a period of maximum restriction (during sea level drop) – a similar conclusion was drawn in Ontario by Churcher et al. (1991). However, in Central Ontario maximum observed Collingwood unit thickness occurs in the region over the Algonquin Arch and since it is well established that the Algonquin Arch pre-dates the Collingwood, a “restricted lagoonal environment” was unlikely. Moreover, as previously discussed above, microfacies analyses of the “nodular limestones” and “marlstones” over the Algonquin Arch region in South-central Ontario indicated a deep open shelf and deeper environments rather than a lagoonal one. That said the observation of less condensed Collingwood strata in the Algonquin Arch region in Central Ontario was consistent with the findings of Wilson and Sengupta (1985) and Hiatt and Nordeng (1985), that the Findley Arch (southwestward extension of the Algonquin Arch) was the site of shallower higher energy water relative to regions north and south of the arch.
9.0 DISCUSSION AND CONCLUSIONS

CONCLUSIONS

The OSAP drilling program/sampling strategy, designed primarily to assess the economic potential of Ontario’s oil shales, resulted in some regions being under-represented (where Collingwood strata were located deep within the subsurface) while other regions (where Collingwood strata were located at or near surface) were well represented by clusters of shallow boreholes. Presumably with “economic potential” being the main consideration, Collingwood strata located deep within the subsurface would not be readily exploitable and thus not as important to the OSAP mandate. Only 3 deep boreholes exist from which to tie-in and investigate Collingwood strata between outcrop localities – some tens of kilometers apart. While this sampling strategy was considered adequate for the gross lithostratigraphic survey conducted by Johnson et al. (1983-1985), and Russell and Telford (1983), the sampling bias presents a challenge to those who wish to study in more detail development of strata across the region. To this limitation was added the fact that where Collingwood strata were well represented by drill holes the drill holes did not penetrate much if at all beyond the Collingwood.

These limitations were in part overcome by the use of data from strata located below the Collingwood and by incorporating geophysical data from sources other than the OSAP. To qualify further the conclusions made using the geophysical correlation of Collingwood strata a microfacies analysis was conducted using core and outcrop samples. In addition a palaeobiologic and a palaeostratigraphic review were also conducted. The Lower Mbr. strata of the Lindsay Fm. like Collingwood strata appeared to be deposited during upward drowning of the ramp. Both “Collingwood” and “Lower Mbr.” strata appeared to be highly correlatable across the region in South-central Ontario.

The gross lithostratigraphic correlation and lithostratigraphic formation re-assignment advanced by Russell and Telford (1983) did not appear to resolve questions regarding palaeoenvironmental context and timing. The failure to recognize in the “Collingwood” both regional and temporal changes in facies as related to changes in environment has led to historic confusion about Collingwood boundaries and composition and frustrated attempts to reconstruct palaeoenvironmental conditions. Historically, palaeoenvironmental interpretations tended to be isostatic environmental settings such as “normal shallow marine shelf”, “deepest shelf”, stranded
basin” or “lagoonal” and neither of these static environments would explain the wide variety of facies collectively referred to in South-central Ontario as the “Collingwood”.

A study of the geophysical borehole log records, core, palaeobiologic and biostratigraphic data were used to examine Collingwood strata in South-central Ontario. The following is a brief summary of results:

- **Carbonate Microfacies types**: in Ontario, carbonate microfacies types grade upwards and off arch from SMF 9 (FZ2) to SMF 3 (FZ1). This facies progression represents a shift from open sea shelf –deep undatherm below wave base to basin fondotherm below oxygenation level – consistent with deepening upward conditions.

- **Palaeobiologic and Biostratigraphic data**: a shift from Chitinozoan assemblage ChA-6 to ChA-8 in the upper Lower Member, Lindsay Formation and extension into the Collingwood Mbr. indicated upward deepening conditions. The dominance of the *Triarthrus* trilobites (a slope biofacies) and deep cool water conodonts *Amorphognathus* are consistent with a deeper water interpretation.

- **Geophysical**: An upward and off-arch increase in strata condensation was observed in the petrophysical chemostratigraphic data. The data was consistent with the carbonate microfacies observed in core and outcrop samples. Comparison of a South-central Ontario section with a Collingwood correlation in the Michigan Basin showed that upward deepening conditions caused a significant regional shift in overall stratal geometry from basinward thickening carbonate sequences to strata that thicken in a shallowing direction – toward the Algonquin arch and the Michigan basin rim. Together the data presented in this study support an upward drowning ramp scenario.

**DISCUSSION**

- Without a stratigraphic reference point from which to compare Collingwood strata to extrabasinal formations such as the Boas River Fm. it is not possible to determine whether or not they represented part of an extensive time correlative event or if they represent separate events staggered in time. Even comparison of
Collingwood strata in South-central Ontario with localities in Ottawa, Ontario, would be problematic. Not only are these Ottawa sections isolated by hundreds of kilometers from sections to the west but thermal maturation experienced in the Ottawa region had significantly altered the electrical resistance of the unit and therefore the “Characteristic” resistivity borehole log profile. That being said Ottawa localities exhibited both bio- and litho-facies development most comparable to Collingwood cluster localities suggesting they shared a similar palaeoenvironmental history. Raymond (1912) first coined the “Collingwood Formation” based on similarities between these two localities.

➢ In Ontario, the Collingwood has been reported to share the same geochemical characteristics as reservoir hydrocarbons in Southwestern Ontario Snowdon, (1984); Obermaeyer et al. (1999). However no satisfactory explanation existed to account for the migration of hydrocarbons from South-central Ontario to Southwestern Ontario. Currently Trenton strata in Southwestern Ontario (where Collingwood strata were reported absent) are now thought to be self- sourcing (see Obermaeyer et al. 1999). Based on the conclusion here that the Collingwood was deposited under a widespread drowning ramp scenario combined with a preliminary look at the petrophysical chemostratigraphic data in a few localities located in Southwestern Ontario it is likely that the “self sourcing strata” are time correlative with the Collingwood. In part the time correlative facies in Southwestern Ontario may be a lighter coloured facies variant. According to the drowning carbonate ramp model hydrocarbon accumulation is expected to occur in palaeotopographic highs which are often dolomitic much like the reservoirs in Southwestern Ontario.

➢ Beyond the academic interest in Collingwood strata there may be an economic reason to advance further the work initiated by this study. A recent study by Carter et al. (2005) states that since 1984, 39 new Trenton-Blackriver oil and gas pools have been discovered with oil production up from 60,000 barrels/year to over 1,000,000 barrels/year. Carter et al. (2005) estimated that 83% of the natural gas and 40% of the oil resources are still undiscovered. A detailed borehole-log and facies study of Southwestern Ontario should prove invaluable both from the standpoint of hydrocarbon exploration and to further our recognition of the extent
and scope of facies produced during this drowning event. Because this region of the basin contains hydrocarbons many boreholes were advanced from which data is available for future investigation.

Since initiation of this study two significant geophysical subsurface studies have been conducted (one in the Michigan Basin by Wilson et al. (2001), and one in central and Southwestern Ontario by Armstrong and Carter (2006)). It appears in both cases that the researchers constructed the correlations using a lithostratigraphic approach for control rather than using the petrophysical chemostratigraphic data and core to examine facies progressions. For example, if the Collingwood was not recognized in the core then regardless of the petrophysical chemostratigraphic data/signature the Collingwood would be dismissed from the correlation at that point.
10.0 REFERENCES


Inferred Isopach map of Collingwood according to Churcher et.al. (1991)

Canadian Shield (Precambrian)

Figure 1
Collingwood distribution and Isopach Map, Collingwood Member, Lindsay Formation
## Lithostratigraphy

### Ordovician
- **Precambrian**
- **Silurian**
  - Upper
  - Time

#### Gonioceras anceps
- Rafinesquina deltoidea
- ‘Calcarenite’ pre simplex
- Climacogratus typicalis
- Ogygites canadensis beds
- Onchometoptus
- Damanella
- Columnaria
- Beatricea
- Crinoid beds (Liberty)

#### Lower Pamelia
- Collingwood
- Rockland
- Lowville
- Trenton
- Leray
- Utica

#### Upper
- Time

### Historic (South-Central Ontario)

#### Lithostratigraphy

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### Current (South-Central Ontario)

#### Lithostratigraphy

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#### Interpretation

- Figure 2: Historic and Current Collingwood Nomenclature for Central Ontario

- **After Johnston et al. (1961)**
Figure 3
Location of Collingwood outcrops in South-central Ontario
Figure 4

Inferred Isopac map of Collingwood according to Churcher et al. (1991)

Canadian Shield (Precambrian)

Isopac Map showing outliers, Collingwood Member, Lindsay Formation
Figure 5
Structural setting
Figure 6
OSAP Borehole and outcrop location map.
Figure 7
Cross section through palaeoic units (southcentral Ontario) with depositional sequences indicated by (S#). Based on subsurface correlation work conducted by Armstrong and Carter (2006) and generalized lithologic descriptions of formations in Johnston et al. (1991).
### Ranges of Graptolite Species

- **CINCINNATIAN**
  - Amplexograptus manitoulinensis
  - Geniculograptus pygmaeus
  - *C.* (D.) Spiniferus

- **MAYSIVILLIAN**
  - Dicellograptus complanatus

- **RICHMONDIAN**
  - Rectograptus amplexicaulis
  - Orthograptus quadrimucronatus
  - Orthograptus spingerus
  - Geniculograptus typicalis typicalis
  - Geniculograptus pygmaeus
  - Climicograptus tubuliferous
  - 'Glyptograptus' lorrainensis
  - Othograptus eucharis
  - Geniculograptus typicalis magnificus
  - Amplexograptus manitoulinensis

- **EDENIAN**
  - Climicograptus putilis
  - Arnheimograptus anacanthus
  - Rectograptus peosta
  - Climicograptus nevadensis
  - Dicellograptus gravis
  - Dicellograptus complanatus
  - Dicellograptus ornatus
  - Climicograptus hastatus
  - Aphelognathus politus
  - Amorphognathus superbus
  - Icriodella superba
  - Rhodesognathus elagans
  - Periodon grandis
  - Rhipidognathus symmetricus
  - Columbodina occidentalis
  - Columbodina penna
  - Protopanderodus insculptus
  - Pseudobelodina inclinata
  - Plectodina florida

- **MAYSVILLIAN**
  - Amorphognathus ordovivicus

- **RICHMONDIAN**
  - Protopanderodus insculptus

- **CINCINNATIAN**
  - Protopanderodus insculptus
  - Pseudobelodina vulgaris vulgaris

### Ranges of Conodont Species

- **SEQUENCE 3**
  - Amorphognathus suberbus
  - From Goldman and Bergstrom (1997)

- **SEQUENCE 2**
  - From Ludvigsen and Tuttle (1984)
  - From Melchin et al. (1994)

### Trilobite Biostrat

- **SEQUENCE 3**
  - Johnson et al. (1991)
  - Triarthrus beckii
  - Triarthrus eatoni
  - Triarthrus canadensis
  - Triarthrus rougensis
  - Triarthrus spinosus

- **SEQUENCE 2**
  - Triarthrus beckii
  - Triarthrus eatoni
  - Triarthrus canadensis
  - Triarthrus rougensis
  - Triarthrus spinosus

### Chitinozoan Diversity

- **SEQUENCE 3**
  - 20
  - 30
  - 40

**Figure 8**

Comparison of biostratigraphic ranges.
Figure 9

Schematic illustration showing how to determine if Collingwood strata are present in the subsurface (Figure 9 from Churcher et al. (1991)).
Actual gamma log examples comparing two holes where collingwood are indicated (WC-35 and WC-36) and two holes where Collingwood strata are not indicated (NC-42 and NC-44) (from Curcher et al. (1991), Figures 10 and 11). Note that the API scales are not comparable. WC-35 and WC-36 log responses above 100 API have not been transposed.
WC-35 and WC-36 from Figure 9 have been re-scaled (approximate) to provide a more meaningful comparison with NC-44 and NC-42. Note that in WC-35 and WC-36, when scaled, the transition from carbonate to shale no longer appears distinctively gradual as was proposed by the authors.
Figure 12

Note that the petrophysical chemostratigraphic units are very similar yet Collingwood strata were not identified in NC-36. Both NC-36 and WC-36 localities are located in Southwestern Ontario approximately 25km apart.
Figure 13
Location map for borehole cluster and outcrop localities
Figure 14
Location Map for tie-in boreholes, borehole clusters and outcrops
Comparison of Collingwood strata represented in OSAP geophysical logs from the 3 clusters (Manitoulin Island, Collingwood, and Toronto) in Central Ontario. The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) "Collingwood" boundaries were used as tie-in lines. Each locality is numbered for reference to Locality Map Figure 6.

Manitoulin Island Cluster

Collingwood Cluster

Toronto Cluster
Comparison between representative Collingwood cluster signatures and signatures from OSAP tie-in localities (Wiarton and Corbetton). The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) "Collingwood" boundaries were used as tie-in lines. The two grey lines on the Wiarton log show the position of the contacts in the Johnston et al. (1983-1985) log.
Comparison between OSAP tie-in localities and the Manitoulin Island, Collingwood, and Toronto clusters. The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) "Collingwood" boundaries were used as tie-in lines.
Comparison between OSAP tie-in localities (including the Nobleton locality) and the Manitoulin Island, Collingwood and Toronto clusters. The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) "Collingwood" boundaries were used as tie-in lines. In the Nobleton log the two gray lines mark the position of the Collingwood boundary contacts indicated in the Johnston et al. (1983-1985) log.
Comparison between deep OSAP borehole Tie-in localities and signatures from two localities outside of the known Collingwood range. The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) “Collingwood” boundaries were used as tie-in lines.
Comparison between signatures of representative Collingwood, Toronto, and Manitoulin Island clusters, OSAP tie-in localities, and two additional borehole logs (Elma and Maryborough). The Elma and Maryborough localities are located outside of the recognized range of Collingwood strata. The log lines are gamma (G), resistivity (R) and Neutron (N). The upper (U) and lower (L) "Collingwood" boundaries were used as tie-in lines.
Comparison of condensation response between (A) carbonate vs (B) clastic dominated systems over a topographic high.
Figure 22a

Variability in Collingwood strata thickness and apparent rate in transition from carbonate to shale chemistry observed in two south-central Ontario borehole logs.

Figure 22b

Variability in Collingwood strata thickness if caused by post depositional erosion (the upper portion of the Corbetton section was removed to create the hypothetical Toronto Cluster locality). Note that the transition would be lost and the gamma log indicates that the Collingwood is much more carbonate like which is in contrast to the shale/clay rich composition indicated in the actual Toronto Cluster logs such as SIS3 in Figure 21a above.
Figure 23
Comparison between geophysical data and facies. The lower contacts indicated in the Johnston et al. (1983-1985) logs are shown as light grey lines.
LOGS FROM MICHIGAN PENINSULA REGION

Figure 24a

Figure 24b

NOTE: Published pics (base of formations) for well logs included for comparison as follows:

Bl = Bluemountain Fm.
S = Sherman Falls Fm.
L = Lindsay Fm.
C = Coboconk Fm.
Bo = Bobcageon Fm.
Gu = Gull River Fm.
S = Shadow Lake Fm.
Appendix A, Plate 1

(1) Gradational contact between Lower Mbr. and Collingwood Mbr. showing angular quartz clasts in organic rich dolomite matrix. Transmitted light (Manitoulin Island Outcrop).

(2) Sparry dolostone, Lower Mbr.. Transmitted light (Manitoulin Island, SIS 5).

(3) Secondary sparry calcite infilling of brachiopod. Note pressure solution features in calcite on right hand side of slide. Transmitted light (Ottawa Outcrop).


(5) Collingwood Mbr. Transmitted light (Manitoulin Island outcrop). Note dolomite rombs. Quartz is now rare to absent.

(6) Dolomitic Bluemountain Fm.. Transmitted light (Manitoulin Island, SIS 5).
Appendix A, Plate 2

(1) Phosphatic intrasparite/ironstone. Upper Collingwood Mbr. contact. Transmitted light (Clarksburg) Note lithoclast. Also see details A,B,C.

(2) Upper Collingwood contact detail showing soft sediment inversion – not erosional. Transmitted light (Clarksburg).

(3) Detail showing iron sulfide replacement of bioclasts. Reflected light (Clarksburg).

(4) Detail showing iron sulfide replacement of bioclasts. Transmitted light (Clarksburg).

(5) Detail of cluster (pelloids?) Note concentric rings in central body. Transmitted light (Clarksburg).

(6) Detail of cluster (pelloids?). Reflected light (Clarksburg).