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Paleoenvironmental Reconstruction of an Upper Ordovician Rocky Shoreline: The Lindsay Formation of Heywood and Partridge Islands, Ontario

Hiba-tul Naseer Maheen
The University of Western Ontario

Supervisor
Dr. Patricia Corcoran
The University of Western Ontario Joint Supervisor
Dr. Cameron Tsujita
The University of Western Ontario

Graduate Program in Geology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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PALEOENVIRONMENTAL RECONSTRUCTION OF AN UPPER ORDOVICIAN ROCKY SHORELINE: THE LINDSAY FORMATION OF HEYWOOD AND PARTRIDGE ISLANDS, ONTARIO

(Thesis format: Monograph)

by

Hiba-tul Naseer Maheen

Graduate Program in Earth Sciences

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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Abstract

The islands of Heywood and Partridge, located northeast of Manitoulin Island in Georgian Bay, Ontario, preserve a major unconformity between the Paleoproterozoic Bar River and Lorrain Formation quartz arenite and Upper Ordovician Lindsay Formation carbonate and mudrock. The Lindsay Formation strata record two transgressive pulses of an epeiric sea that flooded the North American continent during the Late Ordovician. During this time, mountain building processes associated with the Taconic Orogeny were taking place to the present east, and the tectonic effects of this orogeny resulted in subsidence of the Michigan Basin. The Lindsay Formation of the Trenton Group was deposited in this basin during a prolonged period of low siliciclastic input. Based on outcrop investigations, the Lindsay Formation in the Manitoulin Island area is divided into six distinct facies: (1) quartz clast dolostone, (2) lower crinoidal dolostone, (3) brachiopod dolostone, (4) stromatoporoid dolostone, (5) upper crinoidal dolostone, and (6) shale-mudstone. These facies differ from those identified in cores extracted from Manitoulin Island and the Bruce Peninsula in that they have been dolomitized and they contain less of a mud component. This difference is attributed to the development of a carbonate ramp dipping to the present south, which would have allowed for greater accumulation of muds in slightly deeper water. Major and trace element geochemistry of the Lindsay Formation mudrocks suggests that the detritus was derived from a mixed mafic-felsic source. The felsic component was eroded from quartz-rich Paleoproterozoic basement, whereas the mafic material may have been eroded from a distal Taconic arc or more proximal volcanic rocks of the Canadian Shield. The paleodepositional model for the Lindsay Formation on the islands of Heywood and Partridge involves a tropical homoclinal ramp passing seaward from a rocky shoreline to an outer ramp setting. The presence of hummocky cross-stratification, tempestites, large-scale wave ripples, and fragmented and disarticulated fossils, combined with the abundance of quartz clasts in the carbonate and mudstone units indicates frequent influence of storm activity during deposition.

Keywords: Trenton Group; Lindsay Formation; Heywood Island; Partridge Island; Tropical; Late Ordovician; rocky shorelines; carbonates; ramps; facies; stratigraphy; sedimentology; geochemistry of shale; provenance; depositional model.

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Table of Contents

List of Tables

List of Figures

Chapter 1 - Introduction

1 General Introduction

The paleoenvironmental conditions and depositional dynamics of ancient rocky shorelines are relatively poorly known. This is largely due to their general rarity in the geologic record that, in turn, is a natural consequence of having required exceptional circumstances for their preservation. There were only 35 well-documented studies of ancient rocky shorelines by the time the review paper appeared by Johnson (1988). Almost 20 years later, 230 references to rocky shore deposits were provided in Johnson (2006). These examples include a diversity of ancient rocky shoreline deposits in many parts of the world representing nearly all periods in the geological time scale. However, by 2006, only 14 Ordovician rocky shoreline deposits had been studied (see Table 1 for examples), thus indicating the importance of the present investigation for improving the understanding of these deposits during the Ordovician period.

Approximately 33% of the world's modern coastlines are represented by rocky shorelines (Figure 1.1). The greatest concentration of modern rocky shorelines is associated with tectonically active regions, including island arcs, hot spots, and continental arcs (Johnson, 2006). Given the abundance of tectonic settings in which rocky shorelines can potentially develop, the question remains: why are descriptions of ancient rocky shorelines so scarce in the geological and paleontological literature? A rise in relative sea level induced either eustatically and/or tectonically, can reduce the overall extent of rocky shoreline development and preservation due to the erosional effects of wave, tide and current activity. Where preserved, unconformities located between carbonate strata and underlying basement rocks are the most useful sources of information concerning rocky shoreline deposits (e.g. Surlyk & Christensen, 1974; Johnson, 1988; Johnson & Rong, 1989; Johnson, 2006). The islands of Heywood and Partridge are two localities at which the development of such an unconformity is well preserved. Here, quartz arenites (basement rocks) of the Paleoproterozoic Bar River and Lorrain formations are abruptly overlain by an onlapping succession of Upper Ordovician to Lower Silurian carbonates and shales that record the transgression of an epeiric sea during that interval of time. The irregularity of the Precambrian terrain was such that the study area would have appeared as a rocky archipelago during at least the initial phase of this major transgressive episode (Harland & Pickerill, 1984; Brookfield & Brett, 1988).

During the last two decades, most sedimentological studies associated with ancient rocky shoreline environments have concerned attributes of: 1) fossil assemblages (e.g. Surlyk & Christensen, 1974; Libbey & Johnson, 1997; Desrochers, 2006), 2) mineralogy of clast and grain components found in the basal beds of overlying successions (e.g. Harland and Pickerill, 1984; Corcoran, 2008), and 3) size distribution of large clasts in the basal beds as indicators of erosional and depositional conditions (e.g. Dott, 1974; Ledesma-Vazquez et al., 2006). Some authors have attempted to formulate depositional models to account for various characteristics of rocky shoreline successions (e.g. Jutras et al., 2006; Corcoran, 2008). However, there remain relatively few paleo-reconstructions of such environments in the geological literature.

AGE	REGION	NATURE OF SUBSTRATE	SPECIALIZED BIOTA	REFERENCES
Late Ordovician	Manitoba, Canada	Precambrian quartzite	Cephalopods	Skinner & Johnson (1987)
	Manitoba, Canada	Precambrian quartzite	Trilobites	Rudkin et al. (2003)
	Manitoulin Island, Canada	Precambrian quartzite	Trilobites, brachiopods, cephalopods, graptolites	Johnson & Rong (1989)
	Manitoba, Canada	Precambrian quartzite	Tabulate corals, worm borings	Johnson & Baarli (1987)
	Manitoba, Canada	Precambrian quartzite	Corals, brachiopods, trilobites, burrows	Johnson et al. (1988)
Middle Ordovician	Quebec, Canada	Precambrian gneiss	None reported	Harland & Pickerill (1984)
	Ontario, Canada	Precambrian quartzite	None reported	Sanford (1978)
	Virginia, USA	Ordovician limestone	Calcareous algae	Read & Grover (1977)

Table 1: Examples of Ordovician rocky shorelines.

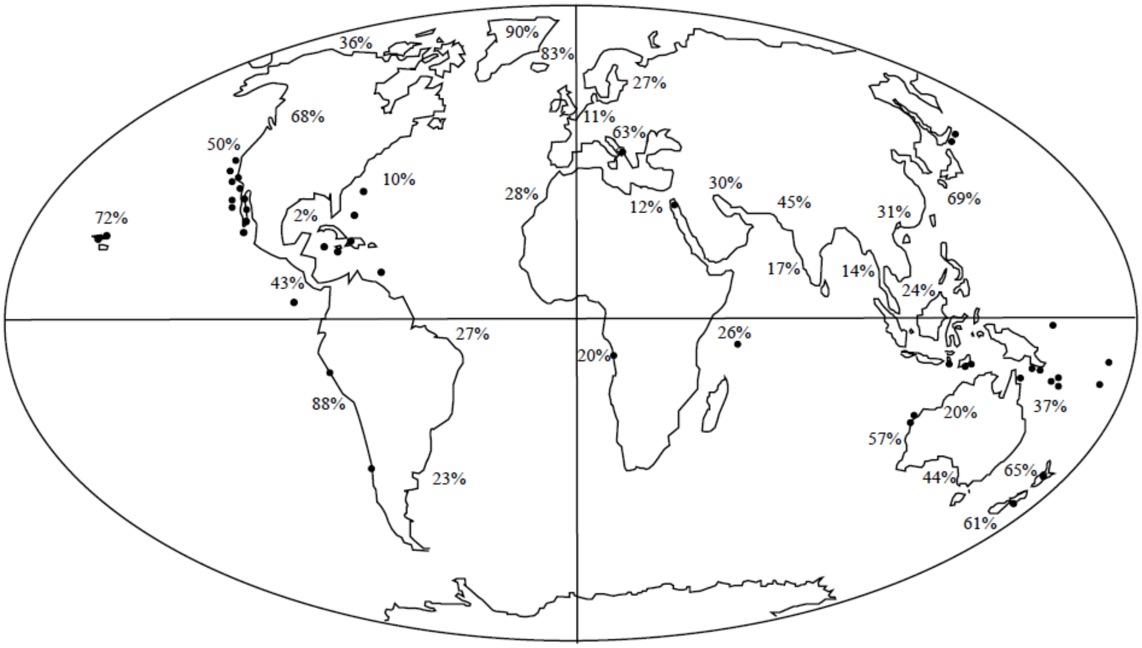

Figure 1.1: Concentration of rocky shorelines as a percentage of all shores in the modern world (modified from Johnson, 2006).

1.1 Purpose and Rationale of Study

In an effort to address the need for additional detailed studies on Ordovician rocky shoreline deposits, the present investigation focuses on Ordovician strata exposed on the islands of Heywood and Partridge in the Manitoulin area of Ontario. There are four main objectives of this project:

1) To study the stratigraphy of the Lindsay Formation on the islands of Heywood and Partridge, and in core from Manitoulin Island and the Bruce Peninsula,

2) To identify and describe the faunal characteristics of the Lindsay Formation in the study areas,

3) To characterize the major and trace element geochemistry of the Lindsay Formation shale from three different localities,

4) To interpret the paleoenvironmental conditions that existed during deposition.

The results of this study are significant because they contribute to the understanding of Ordovician rocky shoreline dynamics.

1.2 General Geological Setting

The Precambrian basement rocks exposed in northern Georgian Bay are part of the Southern Province, which bounds the Superior Province to the north (Figure 1.2). More specifically, rocks of the Southern Province belong to a succession of metasedimentary strata known as the 2.45-2.2 Ga Huronian Supergroup (Krogh et al., 1984; Corfu and Andrews, 1986).

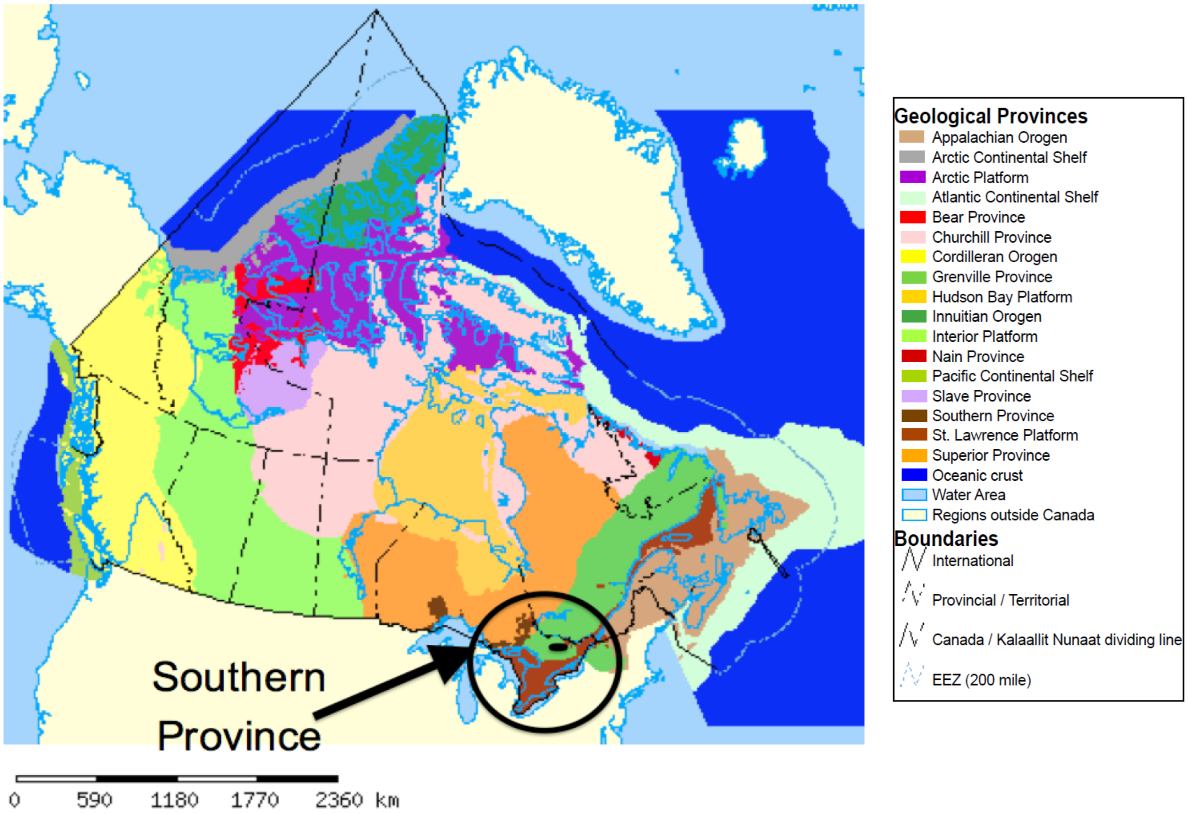

Figure 1.2: Map representing the seventeen geological provinces of Canada, with the Southern Province highlighted (modified after Natural Resources Canada, 2004).

Unconformably overlying the Huronian rocks on the islands of Manitoulin, Heywood and Partridge are Paleozoic strata that range from Late Ordovician to Lower Silurian in age (Coniglio et al., 2006). The unconformity, which represents a depositional hiatus of approximately 1.7 billion years (Corcoran, 2008), is well exposed at several sites on eastern Manitoulin Island, Heywood Island and Partridge Island. Previous studies have established that the basement rocks underlying the unconformity in the Manitoulin area belong to the Lorrain and Bar River formations of the Cobalt Group (Huronian Supergroup), whereas the overlying Paleozoic dolostone and shale succession belong to the Late Ordovician Trenton Group (Liberty, 1969; Johnson & Rong, 1989; Corcoran, 2008).

According to Johnson & Rong (1989), Lorrain and Bar River quartz arenite exposures were at least 125 m higher than their present day elevation and were exposed as an archipelago of small, rocky islands during the Late Ordovician when the Canadian Shield was extensively inundated by shallow epeiric seas. This flooding event, which is recorded throughout Southern Ontario by extensive limestones and dolostones of the Trenton Group, is one of the greatest eustatic sea level rises recorded in the geological record (Brookfield & Brett, 1988).

Due to significant surface relief of exposed Precambrian quartz arenites prior to Trenton Group deposition, evidence of this transgression (most notably, the onlap of Trenton strata on the basement rocks) is especially dramatic in the Manitoulin area, as observed on both the islands of Heywood and Partridge. Evidence that the islands were skirted by rocky shoreline is provided by quartz arenite inliers and quartz clasts in the basal beds throughout the study area (Johnson and Rong, 1989). Quartz clasts range widely in size, from silt-sized grains to boulders of quartz arenite as large as 4.5 m in diameter (Corcoran, 2008).

The depositional dynamics recorded in Paleozoic rocks throughout most of the interior of North America appears to reflect fluctuations in relative sea level, resulting from both eustatic and tectonic controls. In eastern North America the latter included lithospheric flexure that accompanied the Taconic Orogeny (and development of the Appalachian Foreland Basin) and subsidence of the Michigan Intracratonic Basin. At times of more rapid erosion and uplift of the Taconic Highlands, pulses of alluvial sediments (i.e. from streams) would have extended into the sea to the north-east into the Ontario-Michigan area (Coniglio et al., 2006). Marine carbonates were deposited on the islands of Manitoulin, Heywood and Partridge during the Late Ordovician (Blackriverian - Edenian) time (Brunton et al., 2009).

Outcrops on these islands show evidence of erosion attributed to regression (Sproule, 1936), followed by the deposition of carbonates and siliciclastic muds of the Lindsay Formation that lasted throughout much of the later part of the Late Ordovician (Maysvillian- Richmondian) (Johnson & Rong, 1989). Apart from local enhancement of dip angle, which is attributed to compaction against the irregular relief of the underlying quartzite inliers, the Paleozoic dolostone and shale on Manitoulin, Heywood and Partridge islands is predominantly flat-lying, undeformed, and unmetamorphosed. The Paleozoic strata were once continuous for thousands of square kilometres and covered all of the islands in the present study, but erosion has reduced their areal extent considerably (Coniglio et al., 2006).

Heywood and Partridge islands are located off the northeastern tip of Manitoulin Island in Lake Huron, Ontario, Canada (Figure 1.3). Heywood Island is currently located at longitude 45°55’45.76” N and latitude 81°45’43.53” W, and Partridge Island is located at longitude 45°55’42.40” N and latitude 81°41’15.21” W. The Manitoulin area is situated on the northeast margin of the Michigan Basin and during the Ordovician was probably situated south of the paleoequator (Coniglio et al., 2006). Although the exact latitude is still under debate, paleogeographic reconstructions by Torsvik et al. (2012) have placed southern Ontario in a tropical setting, approximately 15° south of the paleoequator, during the Late Ordovician (Figure 1.4). However, Brookfield (1998) suggested that the Black River and Trenton groups were located in a temperate carbonate shelf setting, implying a latitude further (south) from the equator. Nevertheless, it appears that at its maximum height, a warm (tropical) shallow sea covered most of North America, with favorable living conditions for relatively diverse marine communities dominated by corals, bryozoans, brachiopods, and crinoids (Coniglio et al., 2006).

1.3 Materials and Methods

In August of 2009, Patricia Corcoran, Cameron Tsujita and Meriem Grifi conducted field work on Heywood Island, focusing on the stratigraphy of Ordovician strata and relationships of these strata to the underlying Precambrian quartzites, ultimately allowing for the drafting of preliminary stratigraphic logs. Grifi wrote a B.Sc. Honours thesis concerning the stratigraphic relationships between units on Heywood Island, but a thorough petrographic study was lacking, and the strata were not related to those of neighbouring Partridge Island. Fieldwork was conducted on Partridge Island by the author and Patricia Corcoran during the summer of 2010 during the month of August. A successful attempt was made to scout the entire island to study Ordovician carbonates and their relationship with the underlying Precambrian quartzites.

Laboratory work, focusing on detailed descriptions of both macroscopic (hand sample-based) and microscopic (petrography-based) characteristics of the rocks was conducted at Western University. Sixty-three thin sections were examined, of which twenty thin sections were utilized for manual point counts of sedimentary components using a petrographic microscope with 1mm spacing. Three hundred points per thin section were counted in order to ascertain the percentage of quartz, dolomite, calcite, and fossil components in each sample.

Two cores were examined at the Oil, Gas and Salt Resources Library in London, Ontario and detailed stratigraphic sections were constructed accordingly. One core was drilled from the Township Albemarle in Bruce County (OGS 82-4) and the second core log was derived from the Township Bidwell in Manitoulin County (Imperial # 644) (Figure 1.3).

The field work conducted on Heywood and Partridge islands included: 1) strike and dip measurements of dolostone beds, 2) construction of stratigraphic sections at scales of 1:10, 3) sampling of dolostone, shale, and quartz arenite, and 4) clast counting using a 1x1 m, 100 point grid. In addition, body- and trace-fossils in the succession were identified and recorded, their dimensions measured where applicable (e.g. for large coral colonies), and were photographed and incorporated into the preliminary logs.

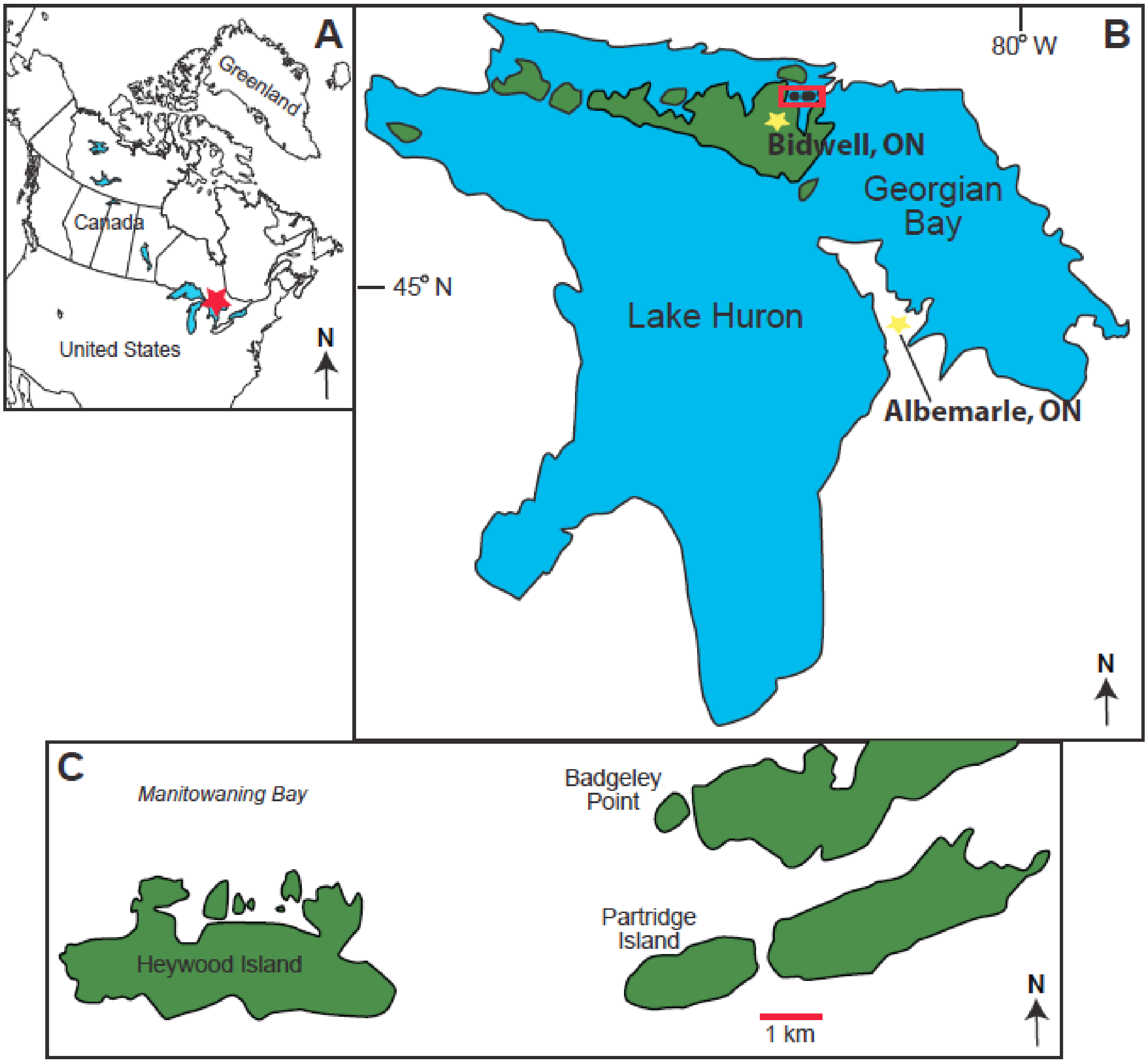

Figure 1.3: Regional locations of study areas. A) Lake Huron (red star) in Canada. Locations of the two OGSR cores that were logged (yellow stars). B) Location of study areas off northeastern tip of Manitoulin Island (rectangle). C) Map of Heywood and Partridge Islands in Manitowaning Bay.

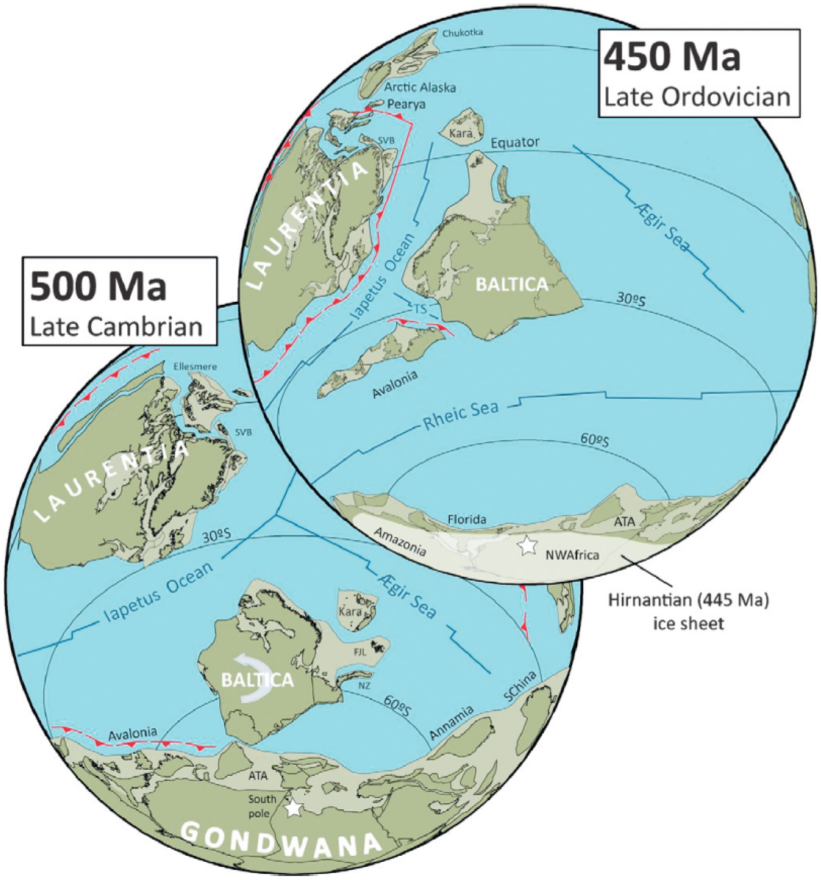

Figure 1.4: Paleogeographic reconstruction of Laurentia during Late Cambrian and Late Ordovician times (from Torsvik et al., 2012).

Major and trace element geochemistry of shales from eastern Manitoulin Island, and the islands of Heywood and Partridge was conducted by X-ray fluorescence (XRF) at the Geoscience Laboratories, Ontario Geological Survey (see Chapter 4).

A general literature review was conducted on the lithology and fossil content of Ordovician units recognized on Manitoulin Island and the southern (mainland) Georgian Bay area, for the purpose of identifying equivalent units in the study area for comparison of lithological and faunal characteristics. A general review was also conducted on ancient rocky shorelines and modern rocky shorelines both in the local area and in other areas of the world to gain insight into the factors influencing the development and preservation of rocky shorelines as well as their influence on the deposition of carbonate sedimentary units.

Chapter 2 – Stratigraphy and Lithology of Units

2 Previous Work Concerning the Study Region

This thesis builds upon previous investigations of the Ordovician stratigraphy of the Georgian Bay region by providing information concerning the lithology and stratigraphy of carbonate and shale units specifically on Heywood and Partridge islands, in the Manitoulin area. This chapter discusses multiple revisions of the stratigraphic nomenclature of the Trenton and Black River Groups that were deposited during the Late Ordovician in Southern Ontario.

The Paleozoic strata of Manitoulin Island, its surrounding islands and the Bruce Peninsula are predominantly composed of carbonates and mudrocks that unconformably overlie quartz arenite basement rocks. Early studies specifically pertaining to the Paleozoic stratigraphy of Manitoulin Island include the pioneering work of Foerste (1912) who described the stratigraphic framework of the Ordovician succession on eastern Manitoulin Island, and that of Williams (1913a, 1913b, 1919) who described the Silurian succession there and in the surrounding region. Somewhat later came stratigraphic studies that were more expanded in a real scale and set Manitoulin Island stratigraphy in a regional context. Among the best known of these are studies by Bolton (1953, 1954, 1957, 1966), Bolton & Liberty (1955), Liberty (1966, 1968), Liberty & Bolton (1971), Copper (1978), Copper et al. (1995), Armstrong and Goodman (1990), and Armstrong et al. (2002).

The Ordovician sedimentary succession of southern Ontario has been divided into lithostratigraphic units by various authors who have applied different names to these units according to different criteria (e.g. fossil content vs. lithology). As such, the nomenclature of Ordovician stratigraphic units in Ontario has changed repeatedly over several decades of study. In general, the Ordovician succession in Ontario has traditionally been subdivided into Lower, Middle and Upper series (Barnes et al., 1981; Johnson et al., 1992; Sanford, 1993). The carbonate-dominated strata exposed in eastern Ontario are considered Lower Ordovician deposits, whereas those of south-central Ontario are Middle Ordovician. Calcareous and terrigenous sediments exposed from Georgian Bay to Toronto and west to the Niagara Escarpment have been assigned to the

Upper Ordovician (Armstrong and Carter, 2006; Armstrong and Dodge, 2007). Recent changes made to the Ordovician time scale (Webby et al., 2004; Gradstein et al., 2004; Bergström et al., 2006) and inconsistent nomenclature of the stratigraphic units between workers has resulted in reconstruction of the Middle – Upper Ordovician boundary and renaming/grouping of stratigraphic units in Ontario.

2.1 General Description of the Ordovician Units

Most of the Upper Ordovician carbonates in southern Ontario belong to the Black River and Trenton Groups (Figure 2.1). Paleogeographic reconstruction indicates that these rocks were deposited during a regional marine transgression and represent an overall deepening-upward succession, from basal siliciclastics to supratidal and tidal flat carbonates to lagoonal/shoal mudstones and shales, and finally to deep shelf carbonates (Kobluk and Brookfield, 1982). This succession was deposited on a ramp northwest of the Taconic foreland basin and unconformably overlies Upper Cambrian siliciclastics and carbonates or lies directly on Precambrian basement rocks of the Canadian Shield depending on erosion of basal beds (Brunton et al., 2009). The Black River Group is composed of the Shadow Lake, Gull River and Coboconk formations, in ascending order. Near its erosional edge in eastern Ontario, the Black River Group measures only 10 m thick, however it can range up to 150 m thick, as seen near the Detroit River (Bailey Geological Services Ltd. and Cochrane, 1983; Trevail et al., 2004). The Trenton Group comprises, in ascending order, the Kirkfield, Sherman Falls and Cobourg formations, and attains a thickness of more than 170 m in southern Ontario (Brunton et al., 2009). The Blue Mountain, Georgian Bay and Queenston formations were deposited during late Ordovician time. These units are largely siliciclastic, in contrast to units of the Trenton and Black River groups, which are carbonate-dominated.

2.1.1 Shadow Lake Formation (Black River Group)

The Shadow Lake Formation is approximately 3-15 m thick, represents the basal unit of the Black River Group, and is the oldest Ordovician unit in central and southwestern

Ontario (Sanford, 1969; Johnson et al., 1992). Red and green shales, argillaceous and arkosic sandstones, minor sandy argillaceous dolostones and rare basal arkosic conglomerates compose the Shadow Lake Formation (Brunton et al., 2009).

2.1.2 Gull River Formation (Black River Group)

The Gull River Formation gradationally overlies the Shadow Lake Formation, and is up to 25 m thick in the Lake Simcoe area (Liberty, 1969), 135 m thick in the subsurface of southwestern Ontario (Johnson et al., 1992) and <40 m thick on Manitoulin Island (Armstrong and Carter, 2006; Amstrong and Dodge, 2007). The Gull River Formation has a variable contact (thickness) character with the overlying Coboconk Formation (= lower Bobcaygeon Formation) (Armstrong and Carter, 2006; Armstrong and Dodge, 2007). Its contact with the underlying Shadow Lake Formation is difficult to determine because of its variable character across southern Ontario and Manitoulin Island (Armstrong and Carter, 2006; Armstrong and Dodge, 2007). The formation was subdivided informally into three members by Liberty (1969): lower, middle and upper. Very finely crystalline, light-grey to dark brown limestone, with lesser amounts of dolostone, shale and argillaceous sandstone compose these deposits (Brunton et al., 2009). The rocks are locally fossiliferous, and contain tetradiid corals, tabulate corals (e.g. *Foerstephyllum*), small calcified sponges of *Stromatocerium* and *Lophiostroma*, ostracodes, and rare small strophomenid brachiopods (Brunton et al., 2009).

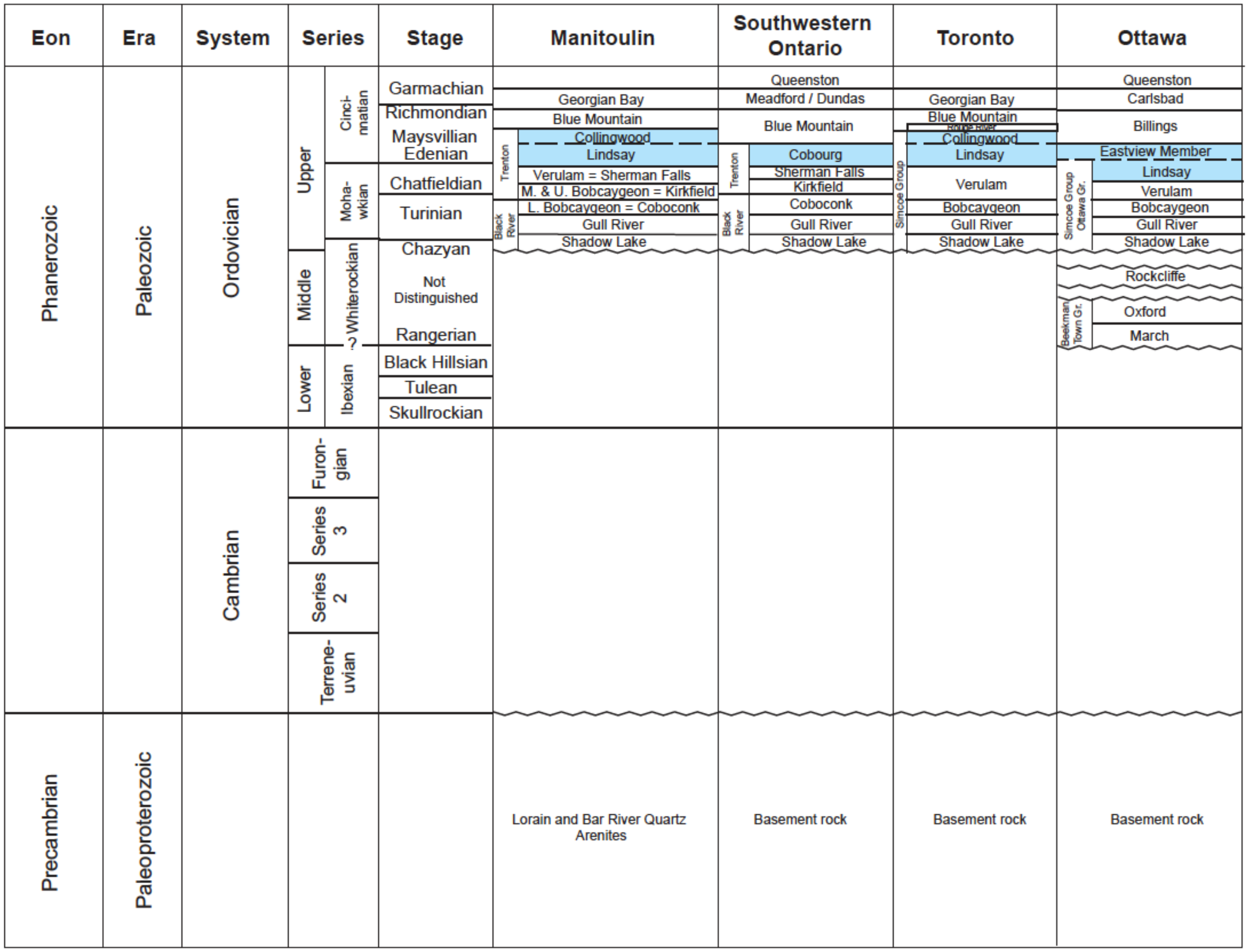

Figure 2.1: Ordovician stratigraphy of Ontario. Stratigraphic nomenclature in text follows the scheme of south central Ontario and the Niagara Escarpment (Modified from Armstrong and Dodge, 2007).

2.1.3 Coboconk Formation (Black River Group)

The Coboconk Formation is equivalent to the Lower Bobcaygeon Formation and Cloche Island beds in the Lake Simcoe area. The Coboconk Formation overlies the Gull River Formation and varies from <5 m thick in the vicinity of Manitoulin Island to approximately 28 m thick elsewhere (Copper et al., 1995; Armstrong and Carter, 2006). In stratigraphic nomenclature, the deposits are also considered the Lower Bobcaygeon Formation or the Cloche Island Beds (Figure 2.1; Brunton et al., 2009). The formation is composed of light grey-tan to brown-grey, medium-to very thick-bedded, fine- to medium crystalline, horizontally bioturbated to current-laminated, skeletal and intraclastic limestones (Brunton et al., 2009). The fossils mainly consist of echinoderm debris, large tabulate corals and stromatoporoids, rugose corals, brachiopods, bryozoans, gastropods, bivalves, nautiloids and trilobites (Copper, 1978; Melchin et al., 1994; Copper et al., 1995).

2.1.4 Kirkfield Formation (Trenton Group)

The approximately 15-55 m thick Kirkfield Formation is equivalent to the upper and middle Bobcaygeon Formation. It is the lowermost unit of the Trenton Group (Figure 2.1; Armstrong and Carter, 2006), and unconformably overlies the Coboconk Formation. Thin- to thick-bedded, fossiliferous limestones with shaley partings and locally significant shale beds compose the Kirkfield Formation. East of Lake Simcoe, the deposits are subdivided into two informal units: lower and upper, which correspond to the Middle and Upper members of the Bobcaygeon Formation, respectively (Liberty, 1969; Melchin et al., 1994). The contact between the lower Kirkfield Formation (= middle Bobcaygeon) and the upper Kirkfield Formation (= upper Bobcaygeon) is gradational (Brunton et al., 2009). Fossils in the Kirkfield Formation include echinoderms (e.g. crinoids), trilobites, bryozoans and brachiopods (Brunton et al., 2009).

2.1.5 Sherman Falls Formation (Trenton Group)

The Sherman Falls Formation is equivalent to the Verulam Formation. It ranges from approximately 60-66 m thick in south-central Ontario (Melchin et al., 2004), and unconformably overlies the Kirkfield Formation. The Sherman Falls Formation was introduced by Kay (1929) as the stratigraphic equivalent of the type section in Trenton Falls, New York (Winder, 1961). Liberty (1955) proposed the name Verulam Formation for these deposits, and this term remains in current usage (Figure 2.1; Liberty, 1969; Johnson et al., 1992). The formation consists of two subunits, a lower shaley or argillaceous unit and an upper, thinner, coarsely crystalline or skeletal fragmental unit (Beards, 1967). In the Manitoulin area, the Sherman Falls Formation is highly fossiliferous and preserves abundant encrinite storm beds with giant ripple marks. Common fossils include the brachiopod *Rafinesquina*, branching bryozoans, rhodolites of *Solenopora* and *Paratetradium* colonies, solitary rugosans, and clusters of the calcified stromatoporoid *Stromatocerium*. Remains of the trilobite *Isotelus* occur in some micritic beds (Brunton et al., 2009).

2.1.6 Cobourg Formation (Trenton Group)

The approximately 17-60 m thick Cobourg Formation, also known as the lower member of the Lindsay Formation, represents the uppermost unit of the carbonate-dominated Trenton Group (Sanford, 1961; Beards, 1967; Liberty, 1969). It is comprised of very fine- to crystalline fossiliferous, bluish-grey to grey-brown limestones and argillaceous limestones with shaley partings, and thin shale interbeds are common (Brunton et al., 2009). Common fossils in the Cobourg Formation include crinoids and crinoidal fragments, gastropods, brachiopods, bryozoans and trilobites. Bioturbation is particularly evident in the nodular beds, and some grainstone beds show grading, cross-lamination and locally contain intraclasts (Melchin et al., 1994). In the subsurface of Kent, Essex and part of Lambton counties, the uppermost few metres of the Cobourg Formation is dolomitized (Sanford, 1961). On Heywood and Partridge islands the Lindsay carbonates are equivalent to the Cobourg Formation and have been completely dolomitized. The original limestone has been replaced by either pervasive matrix-replacement dolomite, which mimics the fabric of the original limestone, or by coarse-grained, white, void-filling saddle dolomite (Brunton et al., 2009).

2.1.7 Lindsay Formation (Trenton Group)

The uppermost member of the Lindsay Formation (the outcrop belt equivalent of the Cobourg Formation) that was formally defined as the Collingwood Member has been redefined several times and has had a long and complicated history of nomenclature, as noticed in reviews by Russell and Telford (1983) and Hamblin (1999). Often referred to as the Collingwood shale or Craigleith Member of the Whitby Formation (Liberty, 1969), it is comprised of dark grey to black, organic-rich, calcareous shales containing very thin, fossiliferous bioclastic interbeds mainly composed of trilobites or brachiopods (Rudkin et al., 1998). Bivalves, conulariids, and orthoconic nautiloids are locally present in the formation (Rudkin et al., 1998). The Collingwood Member gradationally overlies the Cobourg Formation. Its upper contact with the Blue Mountain Formation is reported to vary from sharp to gradational (Russell and Telford, 1983). In some places where the Collingwood Member (Lindsay Formation) is absent, a phosphatic lag exists at the contact between the Blue Mountain and Cobourg (or lower member of the Lindsay Formation) formations (Churcher et al., 1991).

2.1.8 Georgian Bay and Blue Mountain Formations

The Blue Mountain Formation was previously assigned to middle and upper members of the Whitby Formation, informally known as Thornbury and Rouge River members of Liberty (1969) and Russell and Telford (1983). The Blue Mountain Formation is characterized by blue-grey to grey-brown shales that contain thin, minor interbeds of limestone and siltstone (Brunton et al., 2009). The conformably overlying Georgian Bay Formation is 125-200 m thick, and is equivalent to the Dundas and Meaford formations (Figure 2.1; Liberty and Bolton, 1971). The Georgian Bay Formation is composed of greenish- to bluish-grey shale that is interbedded with limestone, siltstone and sandstone (Byerley and Coniglio, 1989; Kerr and Eyles, 1991; Johnson et al., 1992). Due to the gradational nature of the contact between the Georgian Bay and Blue Mountain formations, these two are commonly combined in subsurface mapping (Brunton et al., 2009). Trace fossils (bryozoans, crinoids, pelecypods and brachiopods), gutter casts, ripple marks and graded beds are common in the Georgian Bay Formation (Johnson et al., 1992). The Georgian Bay Formation is conformably overlain by the Queenston Formation (Brunton et al., 2009) (Figure 2.1).

2.1.9 Queenston Formation

The uppermost Ordovician unit in Ontario is the Queenston Formation. The Queenston Formation in Ontario ranges from over 275 m thick beneath Lake Erie to less than 50 m thick at the north end of the Bruce Peninsula (Sanford, 1961). Lithologically, it is characterized by brick red to maroon, noncalcareous to calcareous shale, with minor amounts of green shale, siltstone, limestone and dolostone (Donaldson, 1989b; Johnson et al., 1992, Brogly et al., 1998). The Queenston Formation is unconformably overlain by Silurian strata (Brunton et al., 2009) (Figure 2.1).

Chapter 3 – Sedimentology of the Lindsay Formation

3 Introduction

Sedimentological studies concerning ancient rocky shoreline environments provide information on: 1) fossil assemblages (e.g. Surlyk and Christensen, 1974; Libbey and Johnson, 1997; Desrochers, 2006), 2) clast and grain components within basal beds overlying the unconformities (e.g. Harland & Pickerill, 1984), 3) possible wave heights responsible for the erosion and transportation of boulders (e.g. Dott, 1974; Ledesma-Vazquez et al., 2006) and 4) depositional models (e.g. Jutras et al., 2006; Corcoran, 2008). The carbonate sedimentology of Heywood and Partridge Islands is a representation of the paleoenvironmental conditions that were operating along a rocky shoreline in central North America during the Ordovician period. The carbonate succession overlies the Paleoproterozoic Bar River and Lorrain Formation quartz arenites (basement rocks) and is part of an Ordovician rocky archipelago.

Grifi (2009) reported on the carbonate stratigraphy of Heywood Island, and her results are summarized in this chapter. In addition to the work of Grifi (2009), this chapter contains petrographic descriptions of each carbonate unit, stratigraphy of Partridge Island, as well as descriptions of two cores sampled from the Bruce Peninsula and Manitoulin Island. The lithological and faunal characteristics of the studied units serve as a basis for the paleoenvironmental reconstruction provided in Chapter 5.

3.1 Sedimentology of Cobourg/Lindsay Formation

The Ordovician sedimentary succession exposed on Heywood Island can be subdivided into six units on the basis of stratigraphic position and sedimentary characteristics (sedimentary structures, grain size, and fossil content) (Figure 3.1). Outcrops on Partridge Island offer a more limited stratigraphic coverage, exposing only two of the six units recognized on Heywood Island (Figure 3.2).

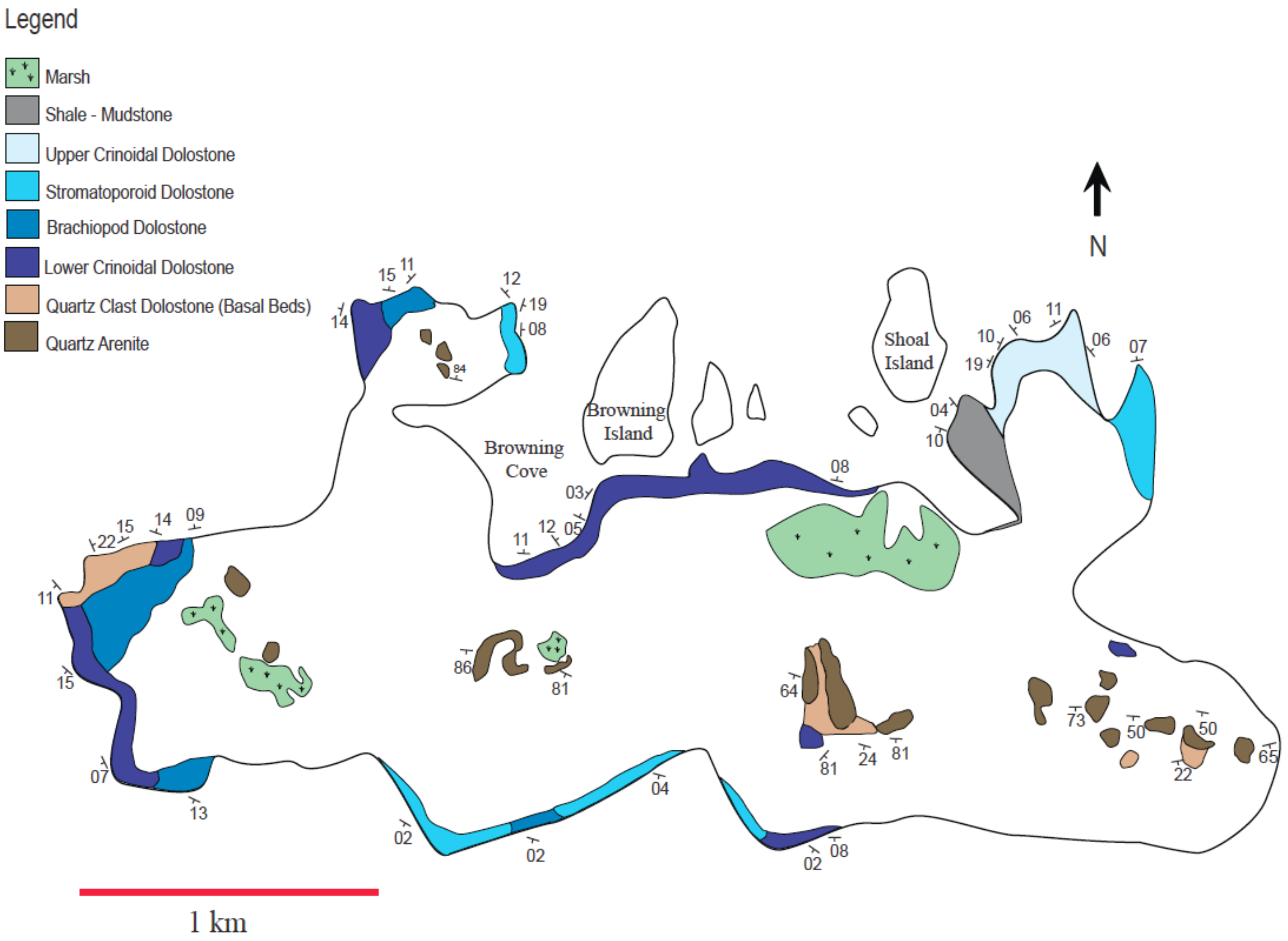

Figure 3.1: Map of Heywood Island illustrating the Lindsay Formation units with strike and dip measurements (From Grifi, 2009).

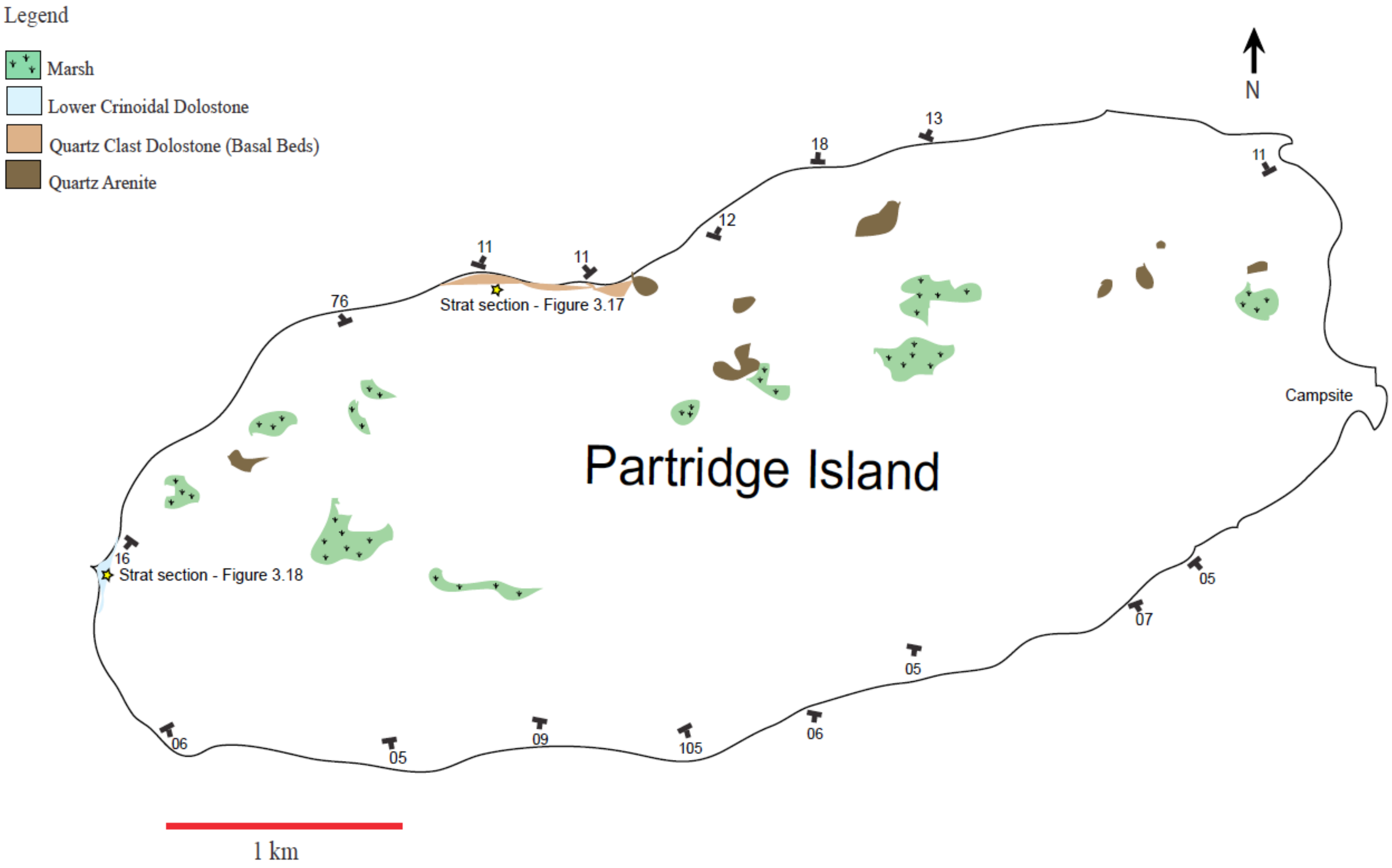

Figure 3.2: Map of Partridge Island illustrating the Lindsay Formation units with strike and dip measurements and locations of stratigraphic sections (yellow stars).

3.2 Overview of Heywood and Partridge Islands

Heywood Island is located 12 km southeast of Little Current, Manitoulin Island, and forms part of a 35 km long group of islands stretching from Sheguaindah to Killarney in Georgian Bay. Ridges of Bar River Formation quartz arenite form the centre of the island, whereas Ordovician rocks of the Lindsay Formation are located along the island periphery. Grifi (2009) divided the Lindsay Formation on Heywood Island into six units: 1) quartz clast dolostone, 2) lower crinoidal dolostone, 3) brachiopod dolostone, 4) stromatoporoid dolostone, 5) upper crinoidal dolostone, and 6) shale (Figure 3.1). The shale unit is considered the shale-mudstone unit in the present thesis, as much of the mudrock does not show fissility.

Partridge Island is located approximately 4 km east of Heywood Island in Georgian Bay (Figure 1.3c). Carbonate outcrops on Partridge Island are uncommon, and where exposed, are weathered and partly covered in vegetation. Two stratigraphic sections were recorded and contain the quartz clast dolostone and lower crinoidal dolostone units.

3.2.1 Quartz Clast Dolostone Unit

The quartz clast dolostone unit is exposed along the northwestern and western shore of Heywood Island, and along the northwestern shore of Partridge Island. On Heywood Island, beds of the quartz clast dolostone dip 11° - 22° away from the unconformity with quartz arenite of the Paleoproterozoic Bar River Formation (Figures 3.1, 3.3) (Grifi, 2009). The 0.5-3.0 m thick quartz clast dolostone unit, which is equivalent to the "basal beds" of Sanford (1978) and Liberty (1978), is massive to planar bedded, and is characterized by rounded to angular boulders up to 3.2 m in diameter (Figures 3.3, 3.4a, b) (Grifi, 2009). The proportion of quartz relative to dolostone is high, and quartz clast size decreases up section (Figures 3.3, 3.5) (Grifi, 2009). Fossil shells of orthoconic cephalopods characterize this unit, including both whole and fragmented specimens that range from 3 to 7 cm in length (Figure 3.4c, 3.6a). Minor disarticulated crinoids, brachiopods, bryozoans, and rugose coral fragments were also identified. Local colonies of tabulate corals up to 1 m in diameter were also found (Figure 3.6b).

Figure 3.7 illustrates the sample locations on Heywood Island. Samples MG-08-11 and MG-08-12 collected from the northwest part of the island show similar compositional attributes as observed in thin sections. Dolomite crystals account for >96.5% of the grains, whereas quartz grains and fossil fragments compose the remaining 1.5% and 2% of the samples, respectively. The dolomite is fine to medium grained with euhedral, subhedral and anhedral crystal forms. The quartz grains in these two samples are mainly monocrystalline, subangular, and measure 0.25-0.5 mm (Figure 3.8a). Also observed in the two thin sections are two larger, rounded quartz arenite rock fragments. Patches of iron oxide such as hematite and magnetite coat some of the dolomite grains. Shelly remains constituting the fossil debris include bryozoans, crinoids, brachiopods, and coral fragments. Samples MG-08-04 and MG-09-48 collected from the southeast and southern part of the island (Figure 3.7) are also predominantly composed of dolomite crystals (>96.5%) with fewer monocrystalline quartz grains (<3.5%). The dolomite crystals are mainly subhedral to anhedral, with minor euhedral crystals. The dolostone locally contains 0.5-7.0 mm size quartz arenite rock fragments composed of polycrystalline, moderately sorted, subrounded to subangular quartz grains (Figure 3.8b).

3.2.2 Interpretation

Quartz arenite clasts as large as 3.2 m suggest high energy transport (Dott, 1974; Corcoran, 2008) and their subangularity indicates proximity to the source area. The decrease in clast size up-section suggests changes in basement relief (topographic highs and topographic lows) and/or fluctuating wave energy (Corcoran, 2008). The quartz arenite boulders could represent detached blocks that were weathered along joints in the source rock, fallen blocks from a rocky cliff that were too heavy to be rolled by waves, or blocks that represent planar expressions of small sea stacks that are attached to the main basement at depth (Corcoran, 2008). Comparable textures of quartz fragments and unconformably underlying quartz arenite indicate mechanical erosion of the highly resistant basement, which is consistent with a rocky shore environment where high-energy processes occur (Corcoran, 2008). The low abundance of articulated fossils in this unit could also reflect the high energy of the rocky shoreline, which may have prohibited undisturbed growth of organisms. The presence of disarticulated crinoids, brachiopods, bryozoans, cephalopods and corals supports high energy conditions in which shells were fragmented by wave reworking. Cephalopod shells between quartz arenite boulders may indicate that they were transported to the shoreline post-mortem (Reyment, 2008).

Bedding surfaces of the quartz clast dolostone unit were carefully examined and there were no traces of boring or encrusting organisms. This suggests that the high level of wave energy prevented colonization by rocky-shore organisms and that most of them were deposited post-mortem (Johnson & Rong, 1989). This unit was deposited in a very shallow, near-shore environment (Figure 3.9).

A rocky shoreline setting is commensurate with previous interpretations by Johnson & Rong (1989) and Corcoran (2008) for similar deposits on Manitoulin Island. Several geological and geomorphological characteristics of the Ordovician deposits are diagnostic of a rocky-shore setting. These characteristics include: 1) limitation of clast lithology to the immediate parent source, 2) mixtures of shelly fragments, quartz granules and dolostone in basement cracks, joints and crevices, 3) lenticular conglomerate beds of subrounded pebbles indicating a high degree of reworking, 4) presence of subangular boulders formed by mechanical erosion, or may represent small quartz arenite stacks connected to the main basement at depth, 5) an irregular nonconformity between the quartz arenite and carbonate-matrix or shale-matrix conglomerate, and 6) boulders in basal conglomerate as large as 3 m, indicating erosion of high relief basement by strong wave, current, and/or storm activity (Johnson, 1988; Corcoran, 2008).

Two distinctive sea-level events are recorded in the Upper Ordovician succession exposed on Heywood Island. The initial transgression is marked by the quartz clast dolostone unit and the second transgressive pulse is clearly marked by the appearance of shale (see section 3.2.11) (Johnson & Rong, 1989). The conformable succession of strata between these two units represents a long phase of shallow carbonate deposition (Copper, 1978).

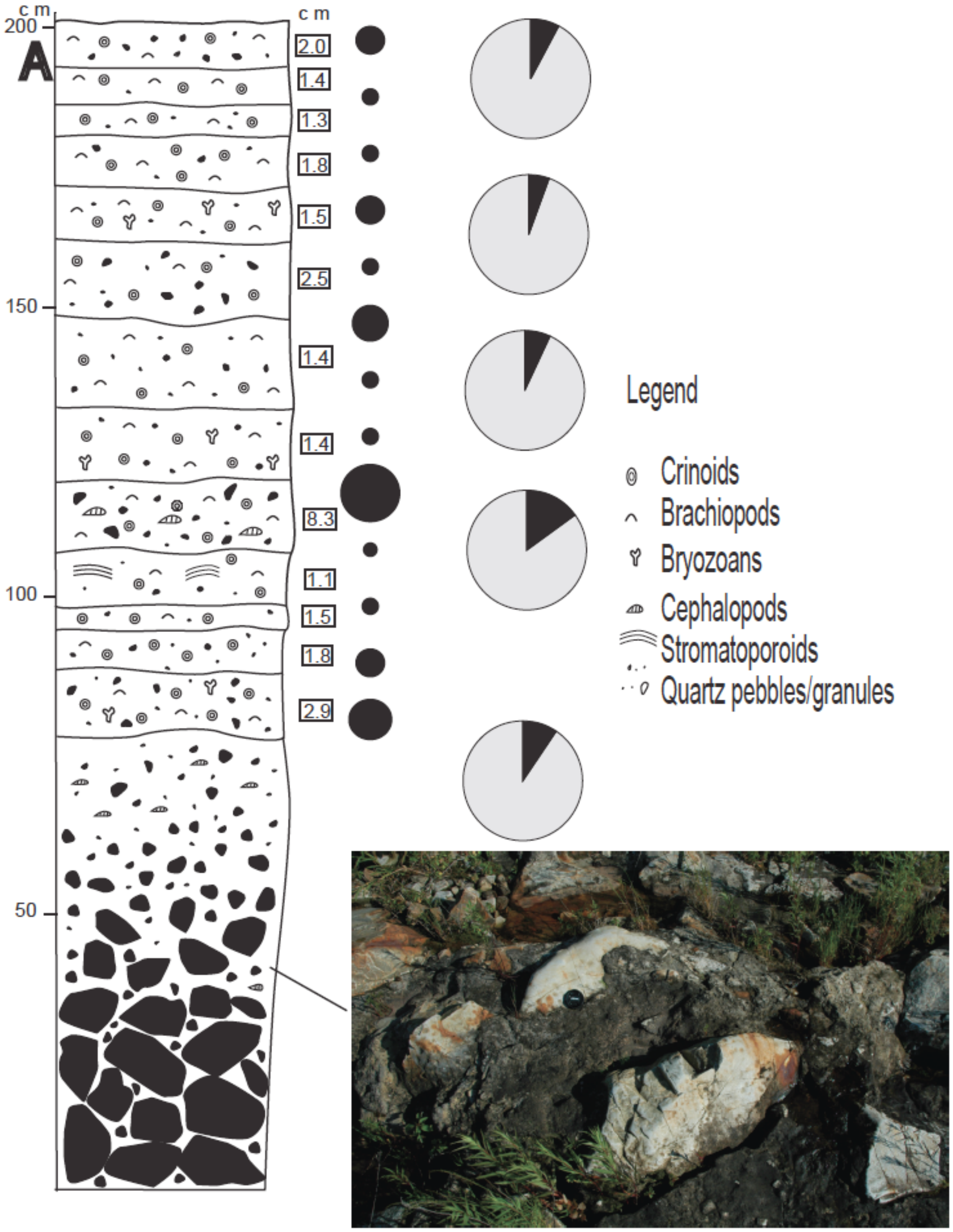

Figure 3.3: Lower section of the stratigraphy on Heywood Island showing the quartz clast dolostone and lower crinoidal dolostone units. The pie diagrams indicate the percentage of quartz clasts, whereas the solid circles represent the relative average sizes of quartz clasts in the dolostone. Note lens cap in photo for scale (5 cm). Photo courtesy of P.L. Corcoran. Diagram from Grifi (2009).

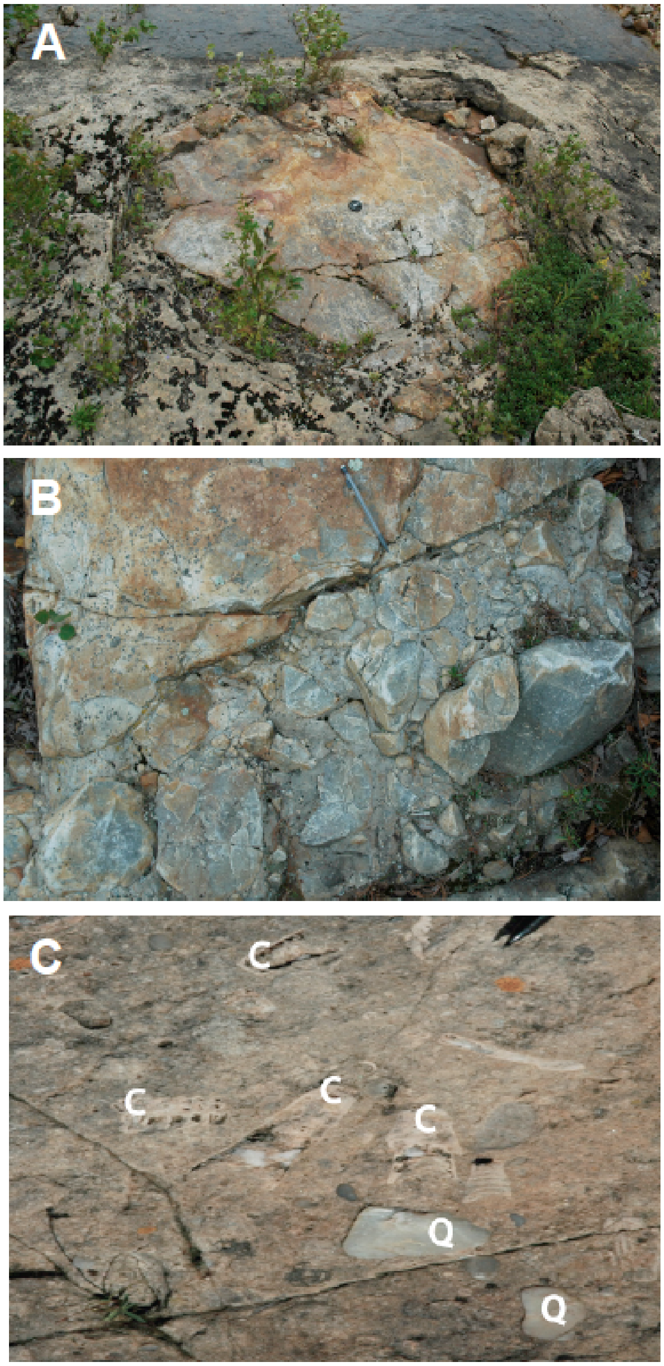

Figure 3.4: Field photos from Heywood and Partridge islands illustrating the quartz clast dolostone unit. A) A rounded quartz arenite boulder (5 cm diameter lens cap for scale). B) Angular and rounded cobbles adjacent to quartz arenite basement (14 cm pencil for scale near top-centre of photograph). C) Orthoconic cephalopod shells (C) and quartz arenite (Q) clasts (4 cm pencil for scale near top-left of photograph). Photo courtesy of P.L. Corcoran.

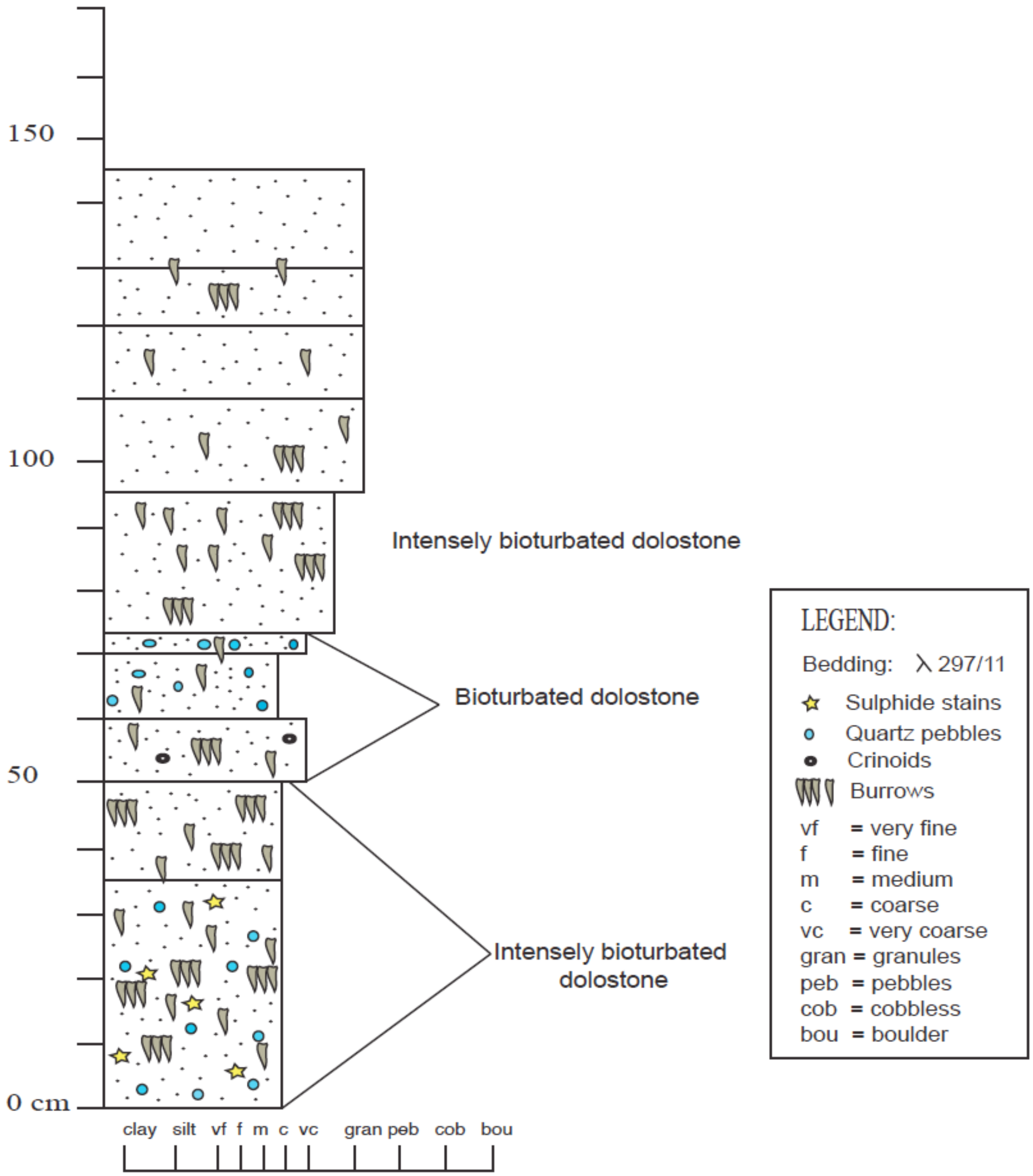

Figure 3.5: Stratigraphic section showing the quartz clast dolostone unit on Partridge Island. Note the disappearance of quartz clasts up-section.

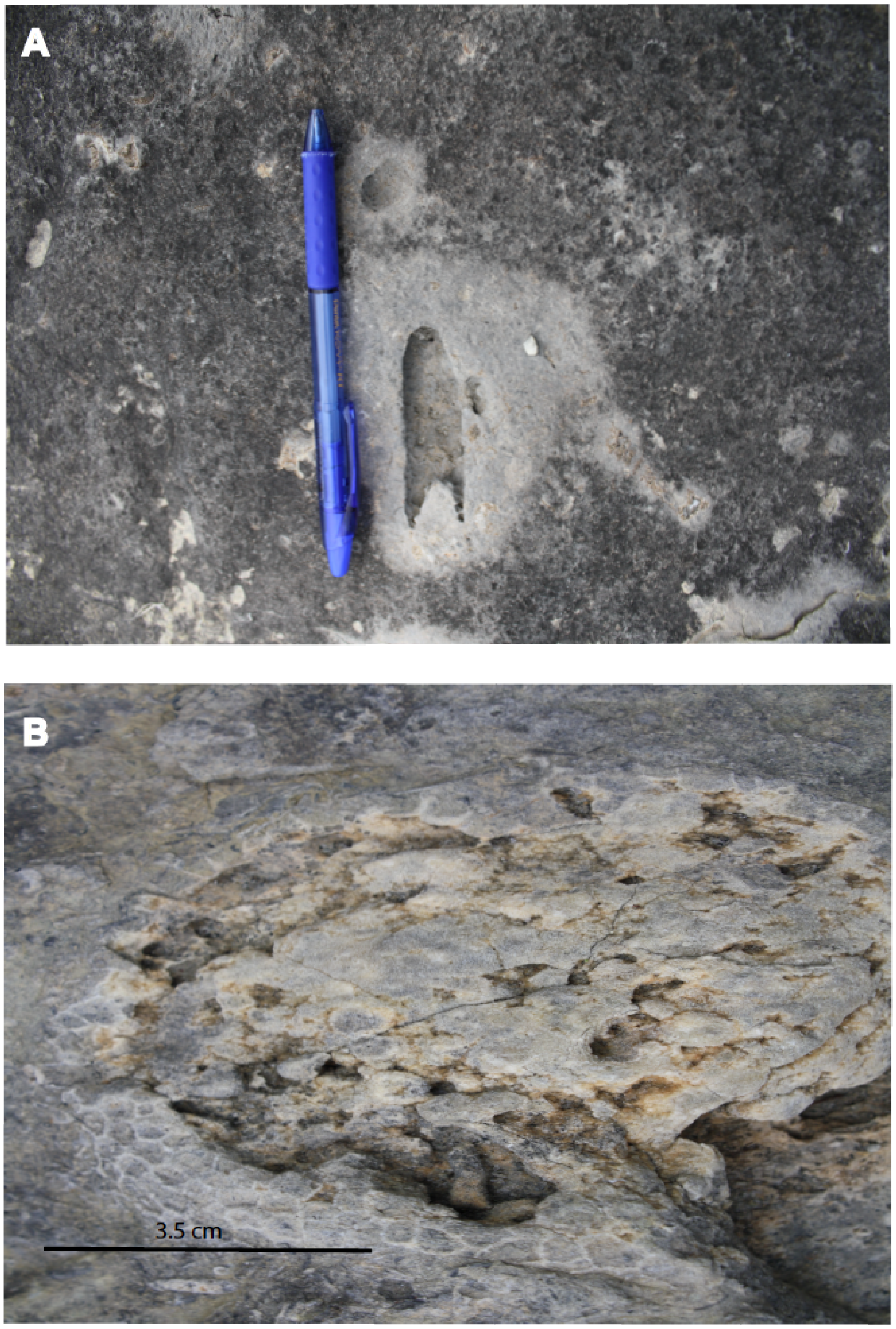

Figure 3.6: (A) Mold of an orthoconic cephalopod in the quartz clast dolostone unit on Partridge Island. Note: Pen used for scale (21 cm). (B) Tabulate coral exposed in the quartz clast dolostone unit on Partridge Island.

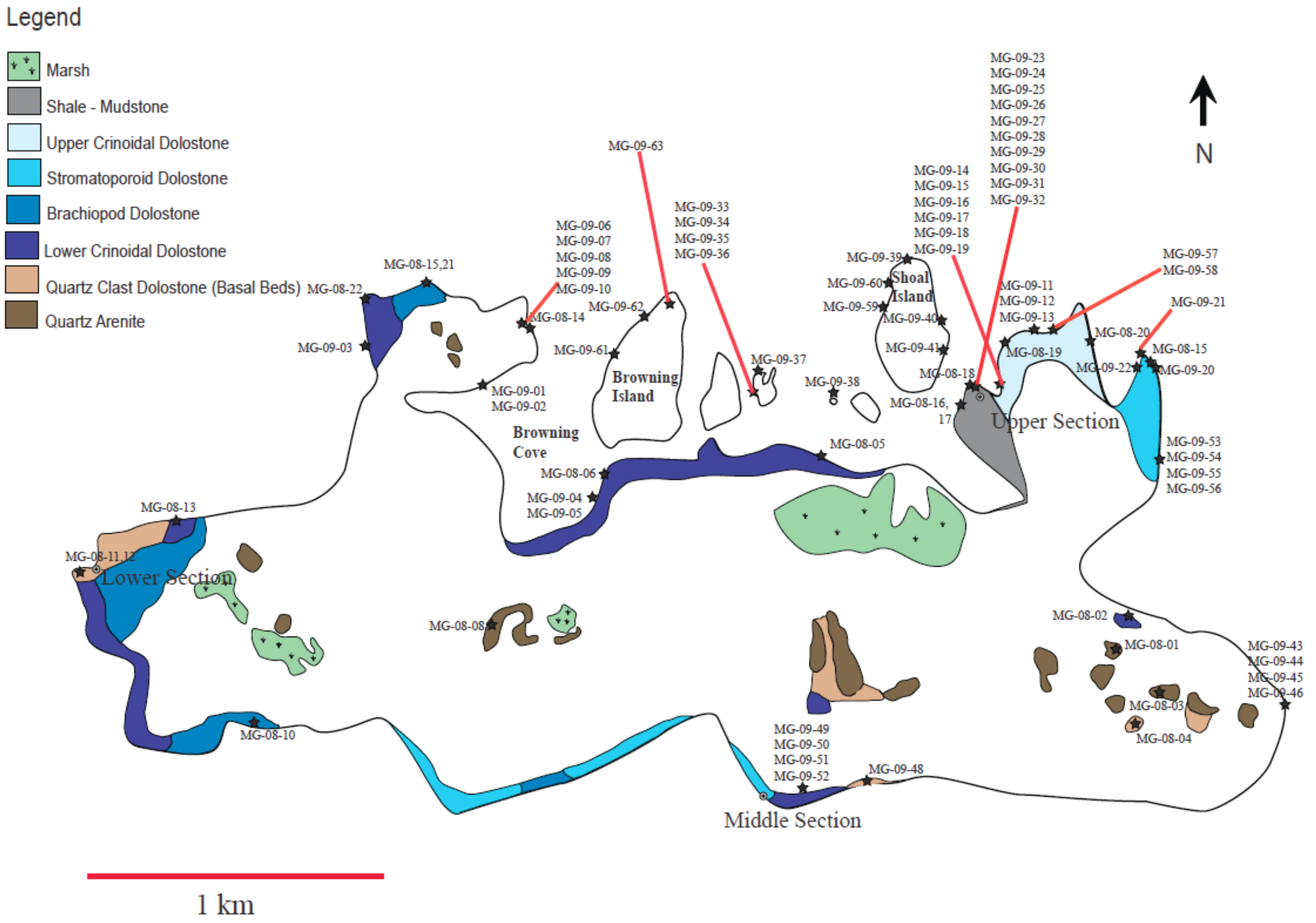

Figure 3.7: Map of Heywood Island exhibiting the sample locations and locations of stratigraphic sections. Modified from Grifi (2009).

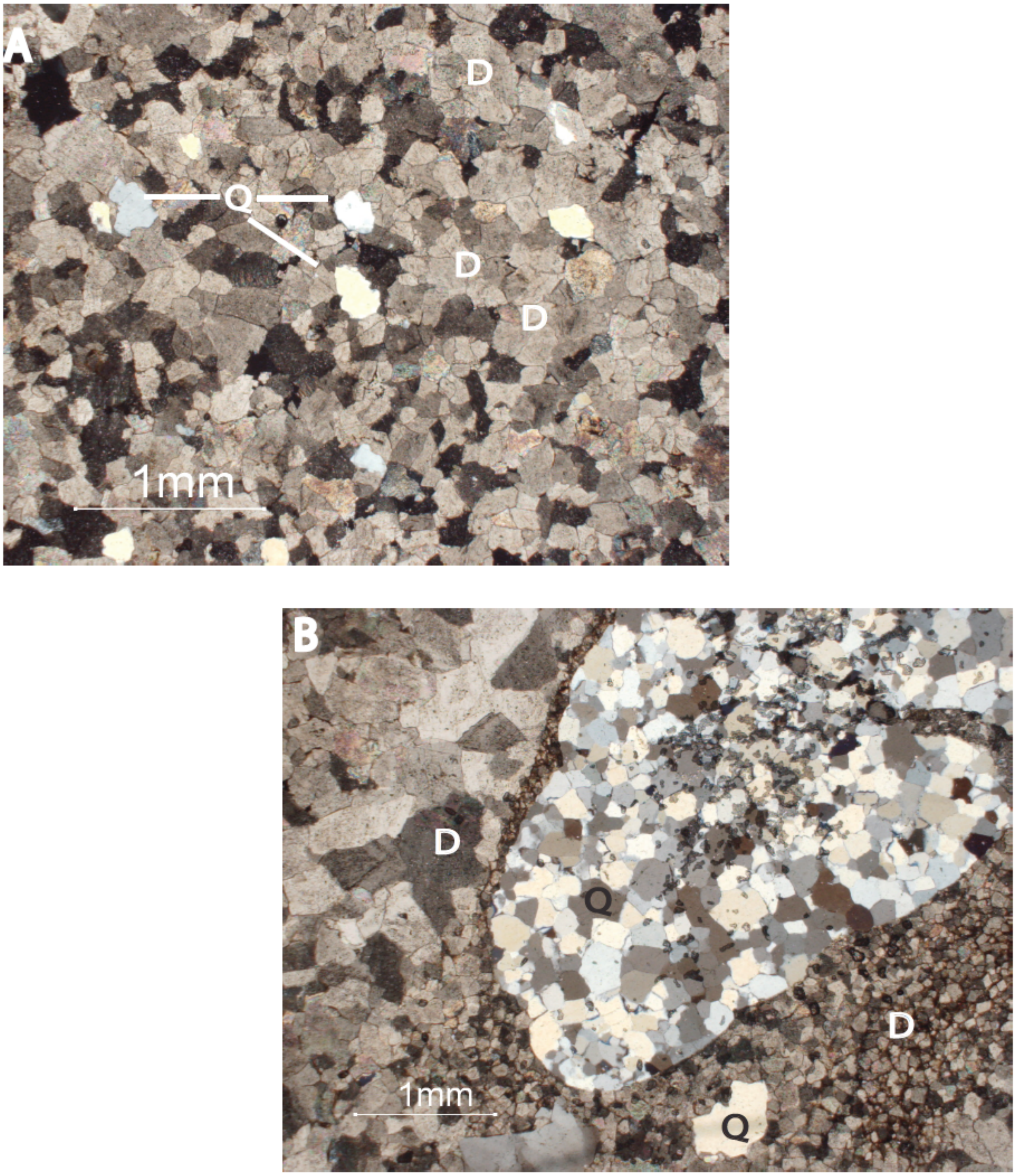

Figure 3.8: Thin section photos of the quartz clast dolostone unit. A) Dolomite crystals (D) are euhedral to anhedral. The quartz grains (Q) are monocrystalline and subangular. B) A quartz arenite (Q) rock fragment surrounded by fine to medium grained dolostone (D).

3.2.3 Lower Crinoidal Dolostone Unit

Immediately overlying the basal beds (quartz clast dolostone unit) of the Lindsay Formation is the lower crinoidal dolostone unit (Grifi, 2009). This unit is largely composed of grainstone and ranges from 1.0-1.5 m thick on Heywood Island and 1.45-3.5 m thick on Partridge Island (Figures 3.3, 3.10). The beds are mainly planar to low-angle and are 10-20 cm thick (Grifi, 2009). Local desiccation cracks and abundant *Thallasinoides* burrows were also identified in this unit. The fossil assemblage is mainly composed of 2-7 cm long broken crinoid stems and 0.25-1 cm crinoid ossicles (Figures 3.11a, b, 3.12a). However, a small number of bryozoans ranging in size from 2-5 cm, orthoconic cephalopods 2.5-7 cm long, 2-4 cm size brachiopods, and stromatoporoids up to 30 cm in diameter were also identified in this unit. In outcrop, quartz arenite clasts are subangular to subrounded, and 0.5-16 cm in size. The number and sizes of clasts decrease up-section, but in alternating beds (Figure 3.3) (Grifi, 2009).

Petrographic analyses revealed that the majority of the lower crinoidal dolostone unit is composed of dolomite crystals (>98%) with minor quartz grains (<1.5%) and fossil fragments (<0.5%). However, one sample contained 90.5% dolomite and 9.5% quartz (Table 2). The rock is very fine to coarse grained, containing dolomite crystals that are mainly subhedral. The primary grainstone texture has been overprinted/mashed by the effects of dolomitization. The quartz grains are predominantly monocrystalline, and are subangular to subrounded (Figure 3.12b). One sample contained a rock fragment composed of monocrystalline quartz in a dolomite matrix. Hematite is locally present between dolomite crystals, and other iron oxides such as magnetite were also identified. Rare fossil fragments were observed in thin section as ghost brachiopod remains and crinoid fragments.

3.2.4 Interpretation

Beds of crinoid-rich dolostone containing quartz clasts alternating between granule- to pebble-sized quartz represent changing flow energy during deposition. The mainly subangular quartz clasts indicate proximity to the source area. The presence of disarticulated and fragmented versus disarticulated and whole fossils may also indicate changing flow energy conditions during deposition of this unit. The disarticulated/ fragmented state of the shelly fossil remains also indicates that the fossil rich component of this unit was allochthonous (Johnson & Rong, 1989). That the lower crinoidal dolostone unit contains beds of grainstone suggests deposition as sheet-like grainstone units typical of shoal deposits on a shallow inner ramp setting (Burchette & Wright, 1992). The presence of minor dessication cracks supports this interpretation as this suggests episodic subaerial exposure.

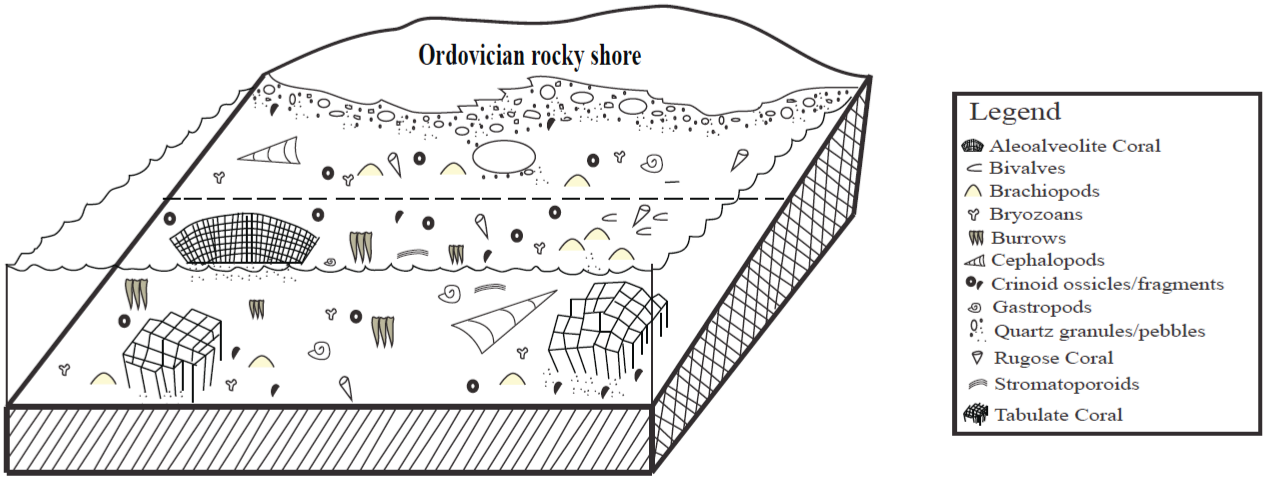

Figure 3.9: Organisms related to water depth along an Ordovician rocky shoreline, as represented on Heywood and Partridge Islands. Modified from Johnson & Rong (1989).

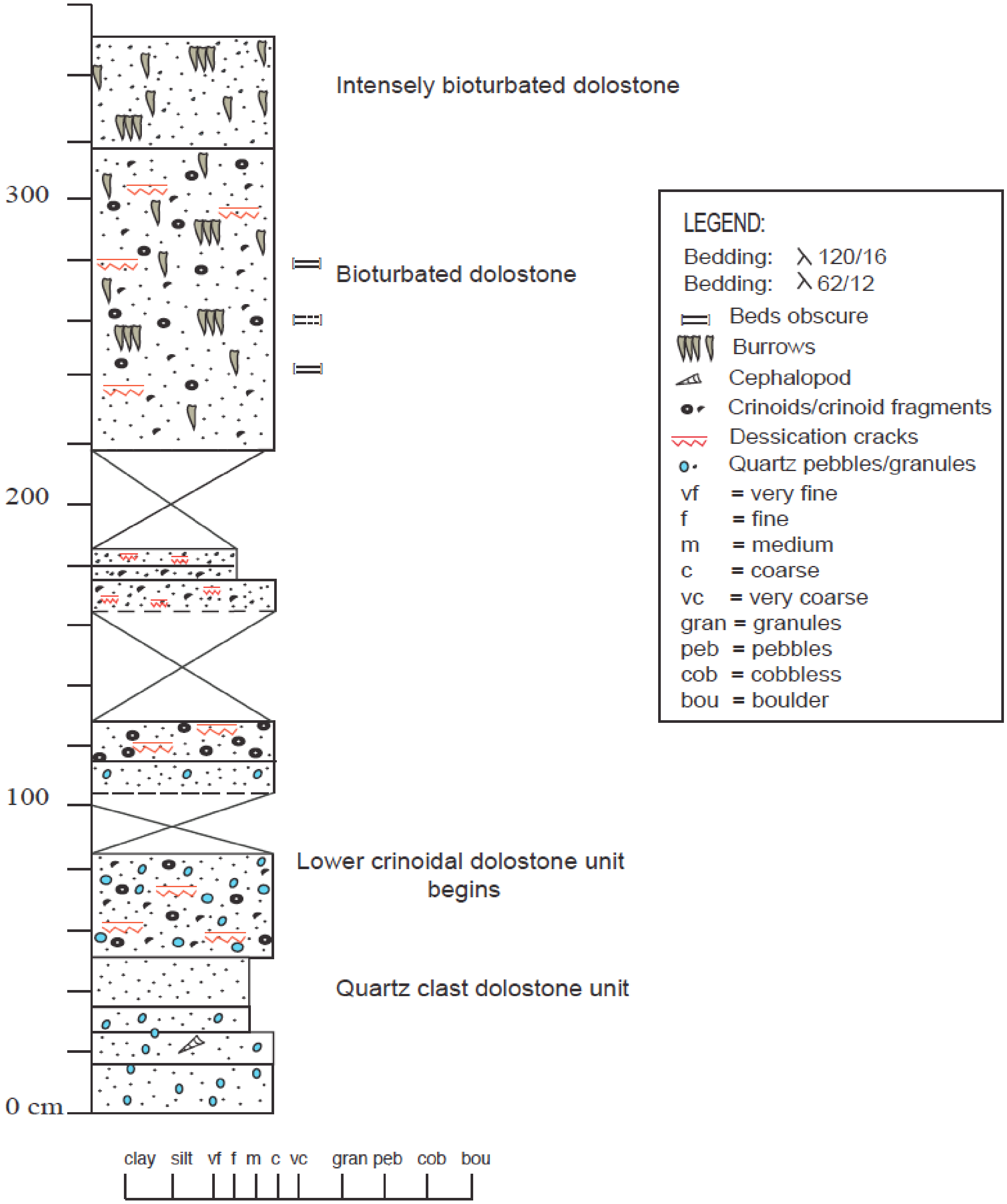

Figure 3.10: Stratigraphic section showing the lower crinoidal dolostone unit on Partridge Island. Note the decrease in abundance and eventual disappearance of quartz clasts up-section.

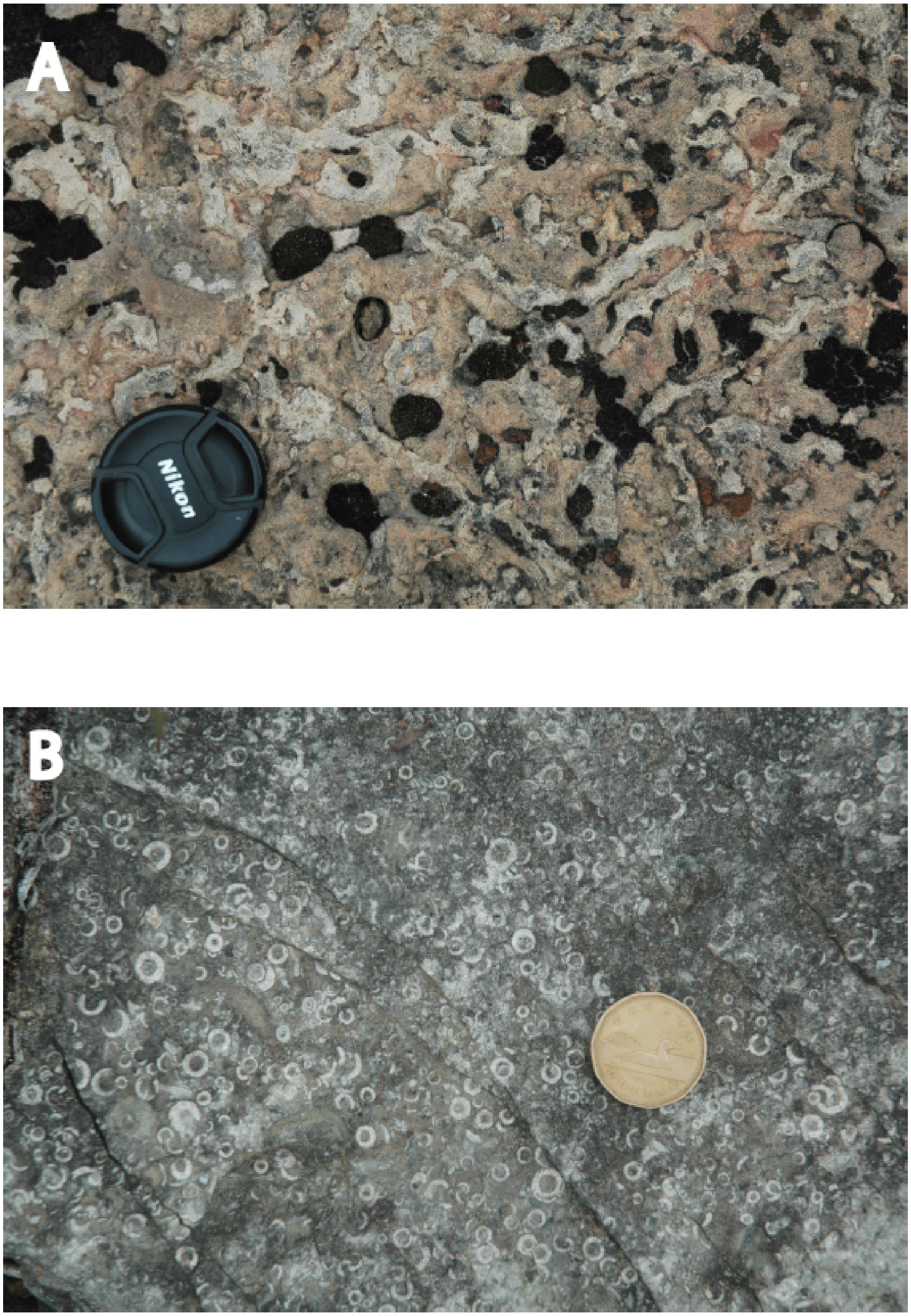

Figure 3.11: The lower crinoidal dolostone unit on Heywood and Partridge islands. A) Abundant horizontal and vertical burrows (5 cm lens cap for scale). B) Grainstone bed with crinoid ossicles (2.5 cm coin for scale). Photo courtesy of P.L. Corcoran.

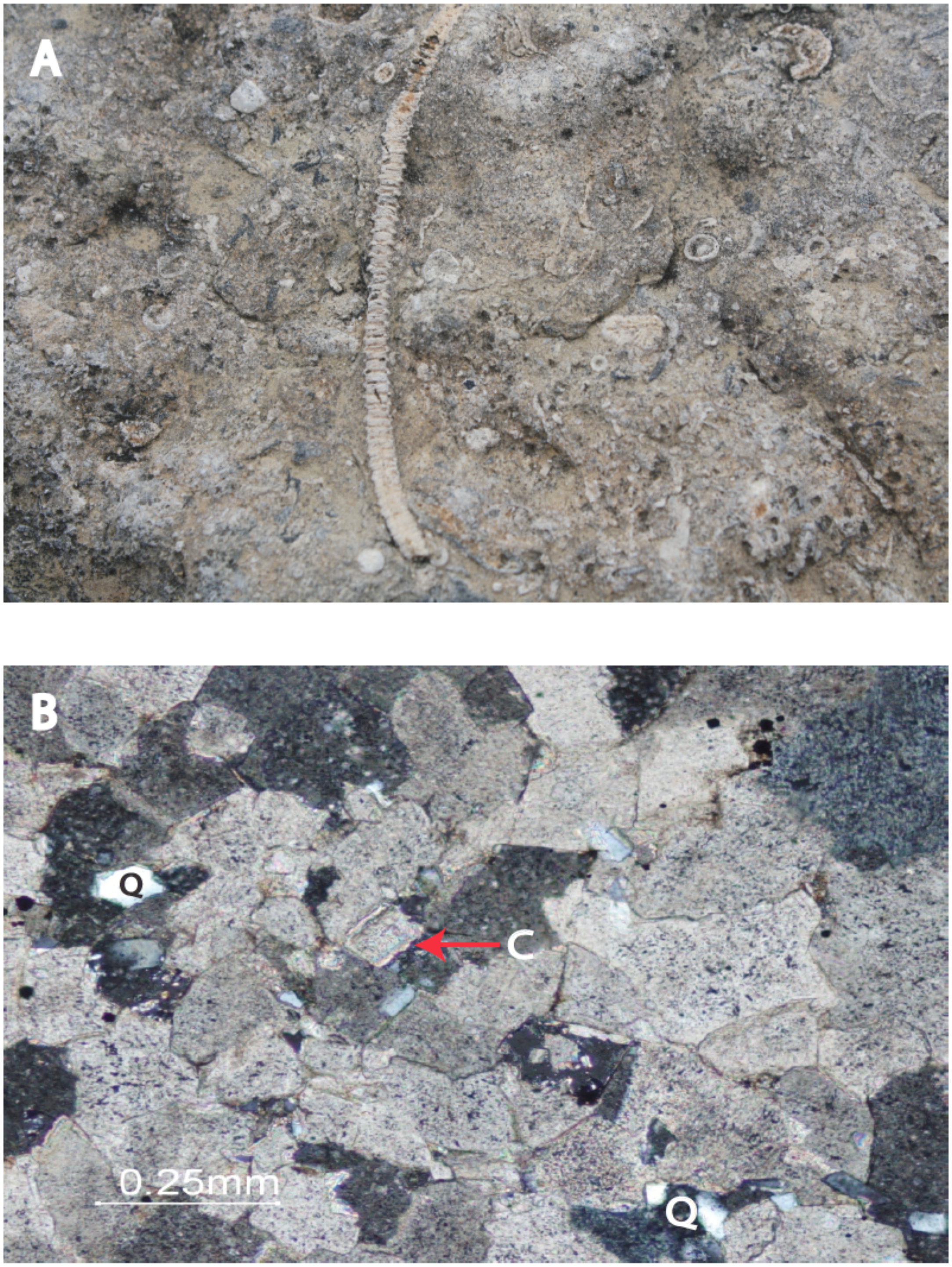

Figure 3.12: The lower crinoidal dolostone unit on Heywood and Partridge islands. A) Crinoid stem (field view of photo is 30 cm across). B) Thin section photo exhibiting broken crinoid fragment (C) and angular quartz grains (Q) surrounded by dolomite crystals.

Lithofacies	**Sample**	**Qtz**	**Qtz (%)**	**Dolomite**	**Dolomite (%)**	**Fossil fragments**	**Fossil Fragments (%)**	**Total**
Quartz Clast Dolostone	MG-08-04	14	3.5%	386	96.5%	0	0%	400
	MG-08-11	3	0.8%	397	99.3%	0	0%	400
	MG-09-12	6	1.5%	394	98.5%	0	0%	400
	MG-09-12A	4	1%	394	98.5%	2	0.5%	400
	MG-09-12B	2	0.5%	395	98.8%	3	0.8%	400
	MG-09-12C	1	0.3%	398	99.5%	1	0.3%	400
Lower Crinoidal Dolostone	MG-08-02	2	0.5%	398	99.5%	0	0%	400
	MG-08-05	3	0.8%	397	99.3%	0	0%	400
	MG-08-06A	9	2.3%	391	99.8%	0	0%	400
	MG-09-06B	1	0.3%	399	99.8%	0	0%	400
	MG-08-10	1	0.2%	399	99.8%	0	0%	400
	MG-08-13	38	9.5%	362	90.5%	0	0%	400
	MG-08-21	6	1.5%	394	98.5%	0	0%	400
	MG-08-22	1	0.3%	399	99.8%	0	0%	400
	MG-09-03	0	0%	400	100%	0	0%	400
	MG-09-52	1	0.3%	398	99.5%	1	0.3%	400
Stromatoporoid Dolostone	MG-08-15	1	0.3%	399	99.8%	0	0%	400
	MG-09-22	1	0.3%	398	99.5%	1	0.3%	400

Table 2: Point count data from the six main lithofacies on Heywood Island.

Upper Crinoidal Dolostone	MG-08-19	16	4%	384	96%	0	0%	400
	MG-08-20	27	6.8%	373	93.3%	0	0%	400
	MG-09-18	10	2.5%	389	97.3%	1	0.3%	400
	MG-09-18B	7	1.8%	391	97.8%	2	0.5%	400
	MG-09-28A	7	1.8%	392	98%	1	0.3%	400
	MG-09-28B	8	2%	392	98%	0	0%	400
	MG-09-28C	8	2%	390	97.5%	2	0.5%	400
	MG-09-29	6	1.5%	393	98.3%	1	0.3%	400
	MG-09-29A	4	1%	395	98.8%	1	0.3%	400
	MG-09-29B	5	1.3%	393	98.3%	2	0.5%	400
	MG-09-30A	0	0%	398	99.5%	2	0.5%	400
	MG-09-30B	0	0%	397	99.3%	3	0.8%	400
	MG-09-31	7	1.8%	393	98.3%	0	0%	400
	MG-09-57	0	0%	400	100%	0	0%	400
Shale	MG-08-16	0	0%	400	100%	0	0%	400
	MG-08-17A	7	1.8%	392	98%	1	0.3%	400
	MG-08-17B	10	2.5%	390	97.5%	0	0%	400
	MG-08-17C	14	3.5%	386	96.5%	0	0%	400

Table 2: Continued.

3.2.5 Brachiopod Dolostone Unit

The brachiopod dolostone unit is 1-1.5 m thick and contains planar to undulatory beds ranging in thickness from 5-30 cm (Figure 3.13) (Grifi, 2009). The beds are largely grainstone-dominated. The fossil assemblage is dominated by the brachiopods *Strophomena* and *Rafinesquina* that are 2-3 cm in diameter (Figure 3.13). Locally, 0.25-1 cm size crinoid ossicles, 1-5 cm long broken crinoid stem segments, algal fragments up to 4 mm long, and 2-5 cm long bryozoans were also identified by Grifi (2009) in the field and in thin section (Figure 3.14a, b). Gastropods, 2-4 cm in size, and rugose corals ranging in length from 3 to 7 cm long were noted to be common towards the top of the section. Quartz pebbles were observed to be uniformly distributed throughout the unit, except in the upper 30 cm where no quartz was visible on outcrop scale.

A bed of wave-rippled grainstone was observed in the lower brachiopod dolostone unit. Average dimensions of the ripples were determined to be 72 cm in wavelength and 5.5 cm in height (Figure 3.15) (Grifi, 2009).

Dolomite crystals account for >98% of the samples, whereas quartz grains and bioclasts compose <1.8% and <0.2%, respectively (Table 2). The rocks are fine to coarse crystalline with dolomite crystals that are mainly subhedral. Quartz grains range from 1-3 cm and are predominantly monocrystalline and subangular. Fossil fragments were difficult to recognize petrographically as a result of dolomite recrystallization. In contrast to Heywood Island samples, rocks sampled from Shoal Island (Figure 3.3) display abundant brachiopod fragments and minor crinoid and coral fragments in thin section. Most of the fossils are disarticulated, with minor fragmentation. Kerogen characterizes the Shoal Island samples in thin-section.

3.2.6 Interpretation

The low proportion of fragmented fossils and the uniform distribution of quartz pebbles indicate a relatively quiet setting and supports fair weather conditions. The disappearance of quartz towards the upper part of the brachiopod dolostone unit indicates low erosive energy of the depositional environment. The brachiopod dolostone unit may have been deposited on a mid carbonate ramp setting (Burchette & Wright, 1992).

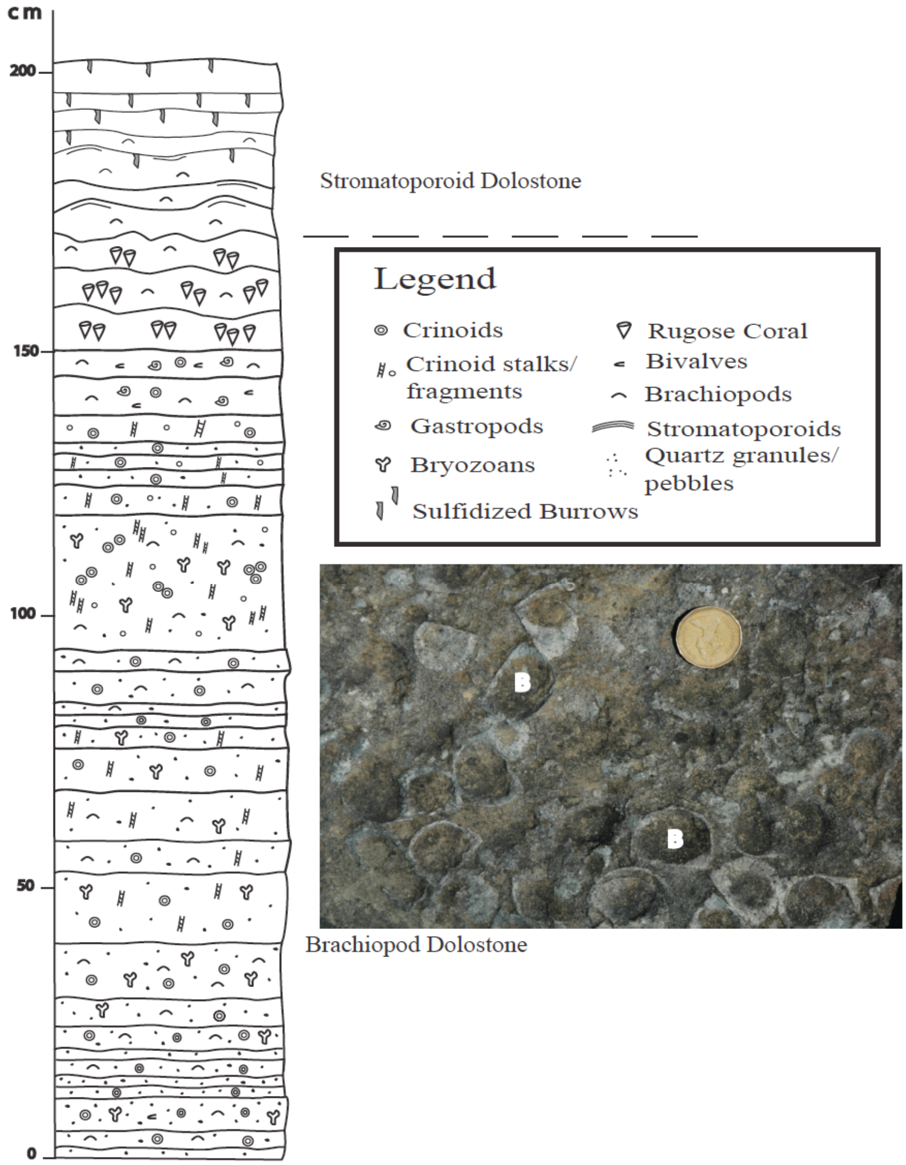

Figure 3.13: Middle section showing the brachiopod and stromatoporoid dolostone units. The presence of some articulated brachiopods and inarticulaed brachiopods suggests that they were preserved in life position (concave upward) indicating low energy conditions and high-energy burial (storm). Note the disappearance of quartz grains up section. The outcrop photo illustrates large strophomenid brachiopods (B) in the brachiopod dolostone unit. Photo courtesy of P.L. Corcoran. Diagram from Grifi (2009).

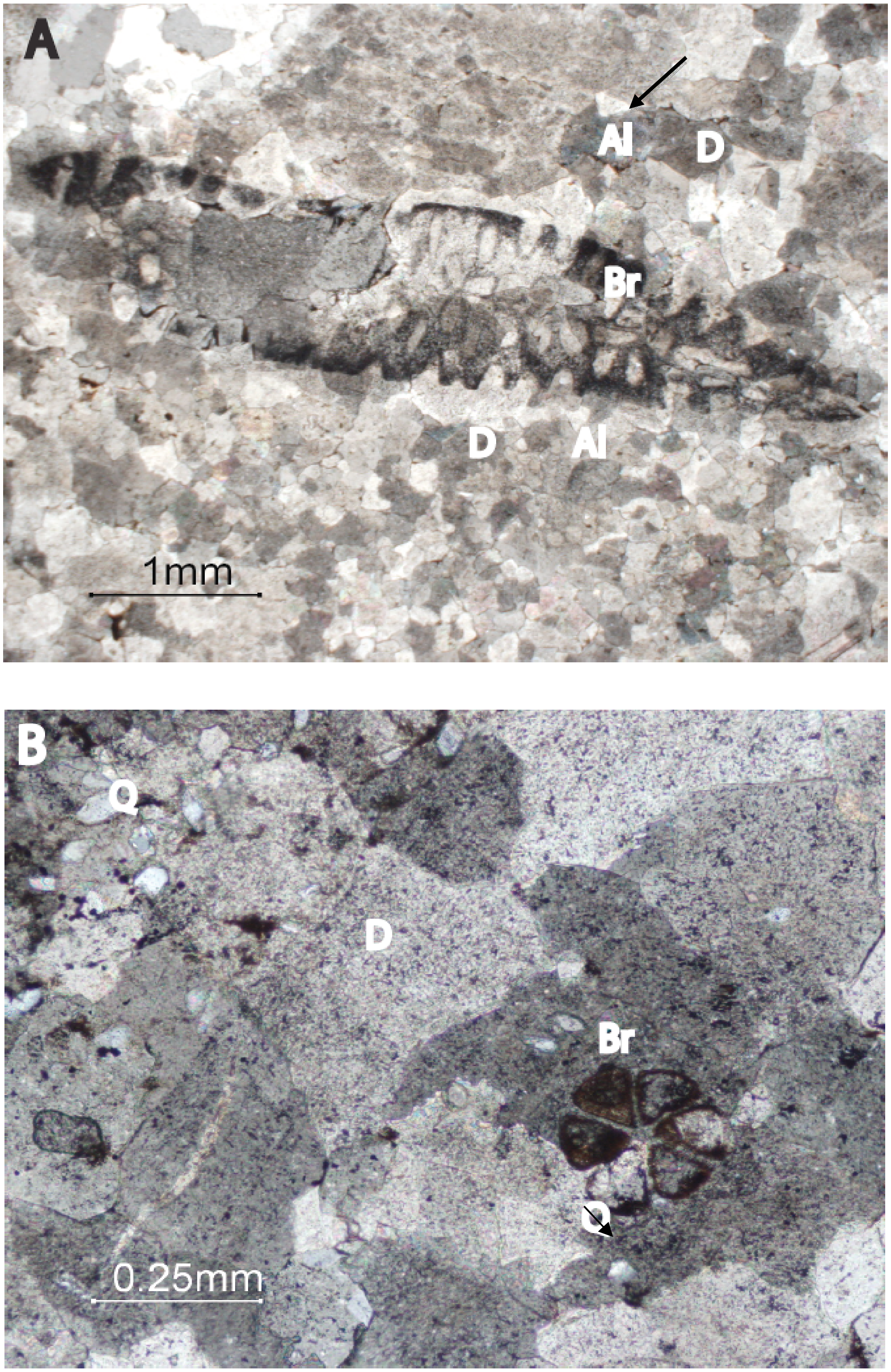

Figure 3.14: Thin section photos of the brachiopod dolostone unit. A) A bryozoan (Br) and algal fragment (Al) in a dolomite matrix (D). B) A bryozoan fossil (Br) and quartz (Q) in a dolomite matrix (D).

Figure 3.15: Wave ripples in the brachiopod dolostone unit. Scale is person, 160 cm. Photo courtesy of P.L. Corcoran.

This unit was probably deposited in slightly deeper water than the quartz clast dolostone and the lower crinoidal dolostone units. The local disarticulated and fragmented fossils, in addition to local large scale wave ripples are consistent with sporadic high wave energy associated with storm activity (Flugel, 2010). The presence of kerogen in the Shoal Island dolostones signals the earliest appearance of potential oil-forming material, which characterizes the shales of the upper Lindsay Formation (see Section 3.2.11 for more details).

3.2.7 Stromatoporoid Dolostone Unit

The stromatoporoid dolostone unit overlies the brachiopod dolostone unit, is 5-100 cm thick, and is largely bindstone with some packstone beds up-section (Figure 3.13) (Grifi, 2009). The strata are wavy and bedding planes display hummocky cross stratification in some packstone beds. Although dominated by stromatoporoids that are

30-90 cm in diameter (Figure 3.16a), minor 2-3 cm brachiopods, and 2-3 cm sized tabulate and rugose corals also comprise the fossil assemblage. Sulfidized *Thallasinoides* burrows, 2-7 cm long are common in packstone beds towards the top of the section (Figure 3.13) (Grifi, 2009). Quartz pebbles and granules were not identified on outcrop scale.

Petrographic analysis revealed that dolomite crystals account for >99.5% of the rock, whereas quartz grains and fossil fragments account for <0.5% (Table 2). The matrix is fine to medium grained with dolomite crystals that are mainly subhedral (Figure 3.16b). Quartz grains are 2.5-4 cm in size and are mainly monocrystalline and subangular. Fossil fragments were not identifiable in thin section.

3.2.8 Interpretation

The stromatoporoid dolostone unit may have been deposited in a mid-ramp setting between fair-weather wave base and storm wave base. Stromatoporoids were common components of carbonate ramp build-ups during the Ordovician and Silurian periods (Burchette & Wright, 1992). In the mid-ramp environment, bottom sediment is frequently reworked and transported away by storm waves and swells, which may account for the low abundance of fossil debris (Flugel, 2010). Hummocky cross bedding in packstone beds is consistent with storm activity (Dott & Bourgeois, 1982). The fair-weather phase is represented by well preserved fossils such as stromatoporoids and burrows, which are common in this unit. Sulfidized burrows towards the top of the section may reflect localized dysoxic conditions during deposition. These conditions may reflect stratification of the water column (Harris, 1984) (see Section 3.2.11 for more details).

3.2.9 Upper Crinoidal Dolostone Unit

The 0.5-1 m thick upper crinoidal dolostone unit contains planar, wavy and hummocky cross stratified beds ranging from 3-17 cm thick (Grifi, 2009). The beds are largely grainstone-dominated and become packstone-dominated up-section. The fossil assemblage in outcrop is predominantly characterized by fragmented and articulated crinoid stems up to 3-7 cm long, however, 2-3 cm size brachiopods, and 2-4 cm long bryozoans were also identified (Figures 3.17, 3.18a,b) (Grifi, 2009). Pockets of sulfidization and sulfidized *Thalassinoides* burrows, 3-6 cm long are also common in the upper crinoidal dolostone unit (Fig. 3.19a) and tabulate corals of the genus *Tetradium* were identified on Heywood Island (Figure 3.19b).

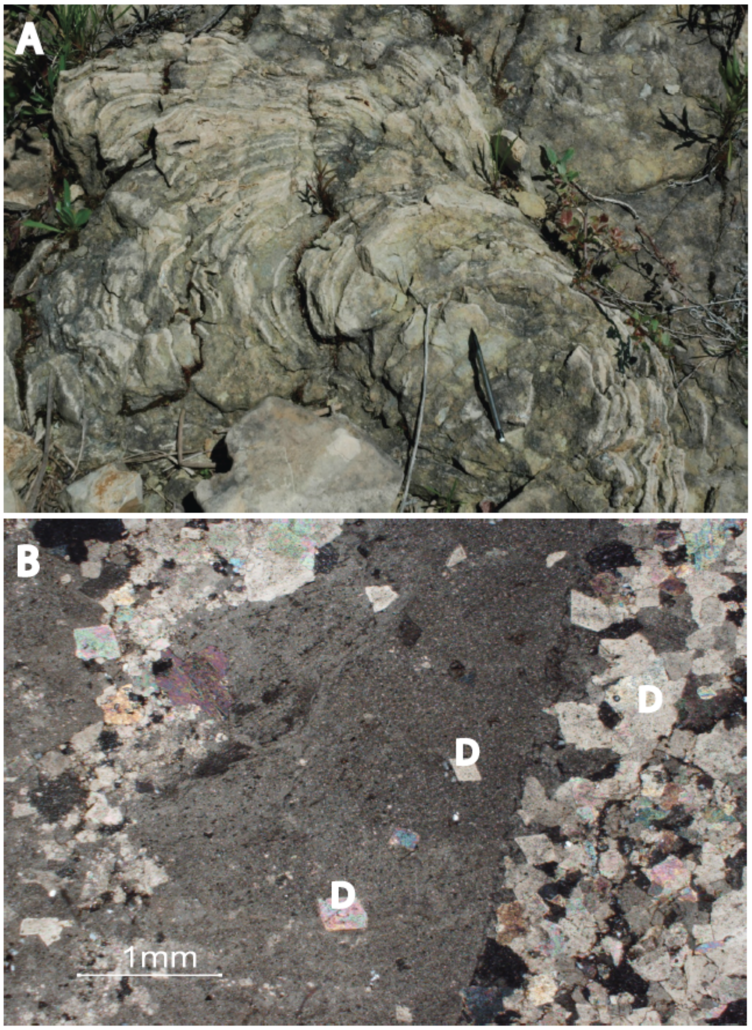

Figure 3.16: The stromatoporoid dolostone composed mainly of stromatoporoids with minor tabulate and rugose corals, as well as sulfidized burrows. A) A well preserved stromatoporoid. Scale: Pencil 2 cm. B) Thin section photo illustrating replacement of calcite with dolomite (D). Photo (A) courtesy of P.L. Corcoran.

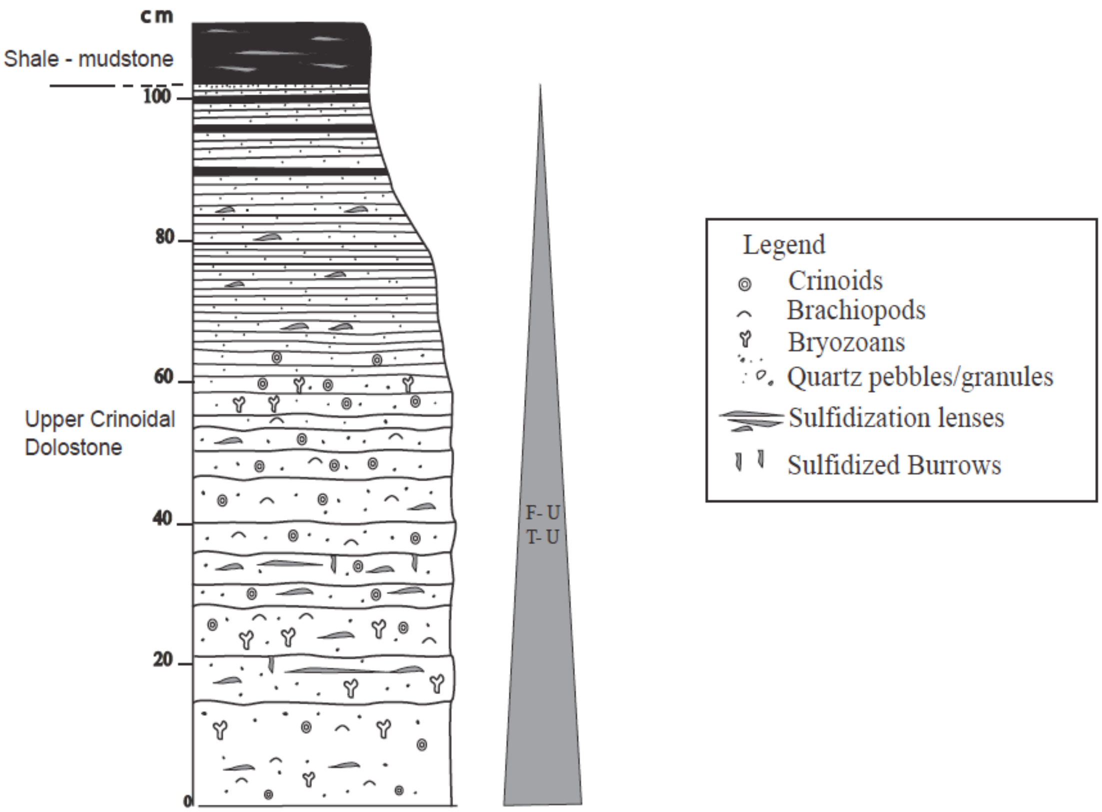

Figure 3.17: Fining and thinning upward succession of the upper crinoidal dolostone and shale units (From Grifi, 2009). Note how quartz clast size decreases up-section.

Rocks of the upper crinoidal dolostone are composed of dolomite crystals (>93.25%), quartz grains (<5.75%) and fossil fragments (<1%) (Table 2). Dolomite crystals are anhedral to subhedral. In thin section, alternating laminae of fine crystalline dolomite and coarse crystalline dolomite were observed, as well as muddy dolomite. Quartz grains are 0.5-3.5 mm in size, are monocrystalline, and subangular to subrounded. The upper crinoidal dolostone unit contains the greatest percentage of quartz relative to the lower units, except the quartz clast dolostone. The quartz grains are visible in thin section up to the contact with the shale at the top of the Lindsay Formation, although quartz grain size decreases up-section (Figure 3.17) (Grifi, 2009). In thin section, the quartz grains are interspersed evenly throughout the dolomite. Most of the quartz grains contain bubble trains and/or fluid inclusions. Some samples contain quartz arenite rock fragments. Rounded and flat kerogen pellets become more common up-section, and disarticulated and articulated crinoid fragments are predominant. Brachiopods, gastropods, bryozoans, bivalves, rugose corals and trilobites characterize this unit. These bioclasts are fragmented, disarticulated, articulated and whole. Iron oxide is abundant and coats all grains. Rapid deposition of sediment over very fine grained saturated sediment results in microflame textures of mudstone protruding into dolostone due to dewatering. The rapid deposition of sediment may also explain the flattened kerogen pellets.

3.2.10 Interpretation

The up-section decrease in quartz clast size from the upper crinoidal to shale units represents a decrease in flow energy. The upper crinoidal dolostone unit may have been deposited on a mid- to outer ramp setting between fair-weather wave base and storm wave base. Low energy carbonates and normal marine benthos organisms such as brachiopods, trilobites, bryozoans, sponges and crinoids are also found in this zone (Flugel, 2010). Episodic storm events may have brought in the higher flow energy required to fragment and disarticulate the fossils, transport and deposit fossils between the inner and mid-ramp (mollusks and rugose coral), and to transport the larger quartz grains (Flugel, 2010). Storm activity is supported by the presence of hummocky cross stratification (Dott & Bourgeois, 1982). The fair-weather phase is represented by burrows and articulated and whole fossils, such as crinoid stems. Burrows in this unit are mainly horizontal and are predominantly found in muddy dolostone, which may indicate deepening of water across the shelf (Boggs, 2006). The presence of autochthonous fossils suggests that the upper crinoidal dolostone unit was deposited in slightly deeper waters than the underlying dolostone units. The mid- to outer ramp environment also allows for the settling of mud and finer-grained limestone, which was identified towards the top of this unit as muddy dolostone.

Abundant iron oxide (mainly hematite at the expense of pyrite) coating grains and within burrows reflects local reducing conditions. These conditions may reflect anoxic conditions just below the sediment-water interface (Harris, 1984) (see Section 3.2.11 for more details).

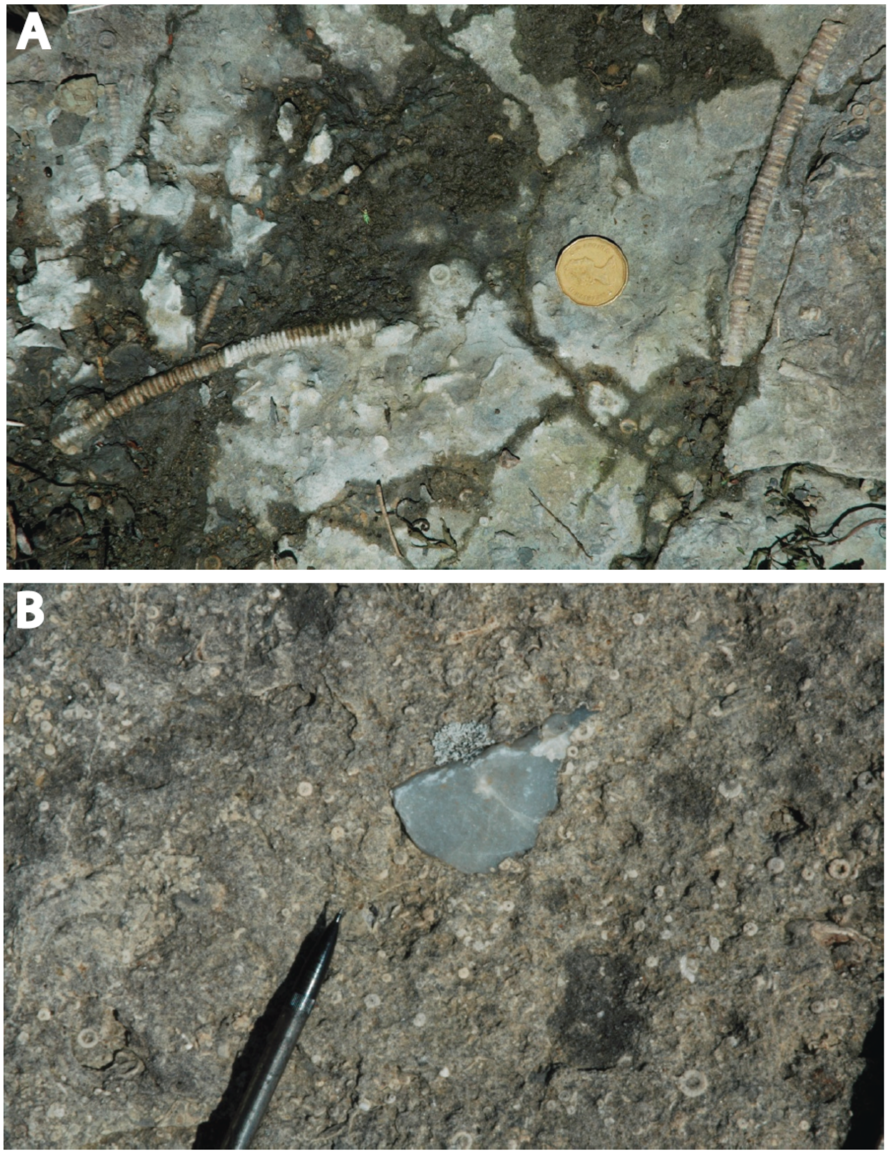

Figure 3.18: The upper crinoidal dolostone unit is mainly composed of crinoidal debris, brachiopods, and bryozoans. A) Fragmented and whole crinoid stems in a bed of packstone. Scale: coin, 2.5 cm. B) Crinoid ossicles and fragmented shelly debris surrounding a subangular quartz pebble. Scale, pen 3 cm. Photo courtesy of P.L. Corcoran.

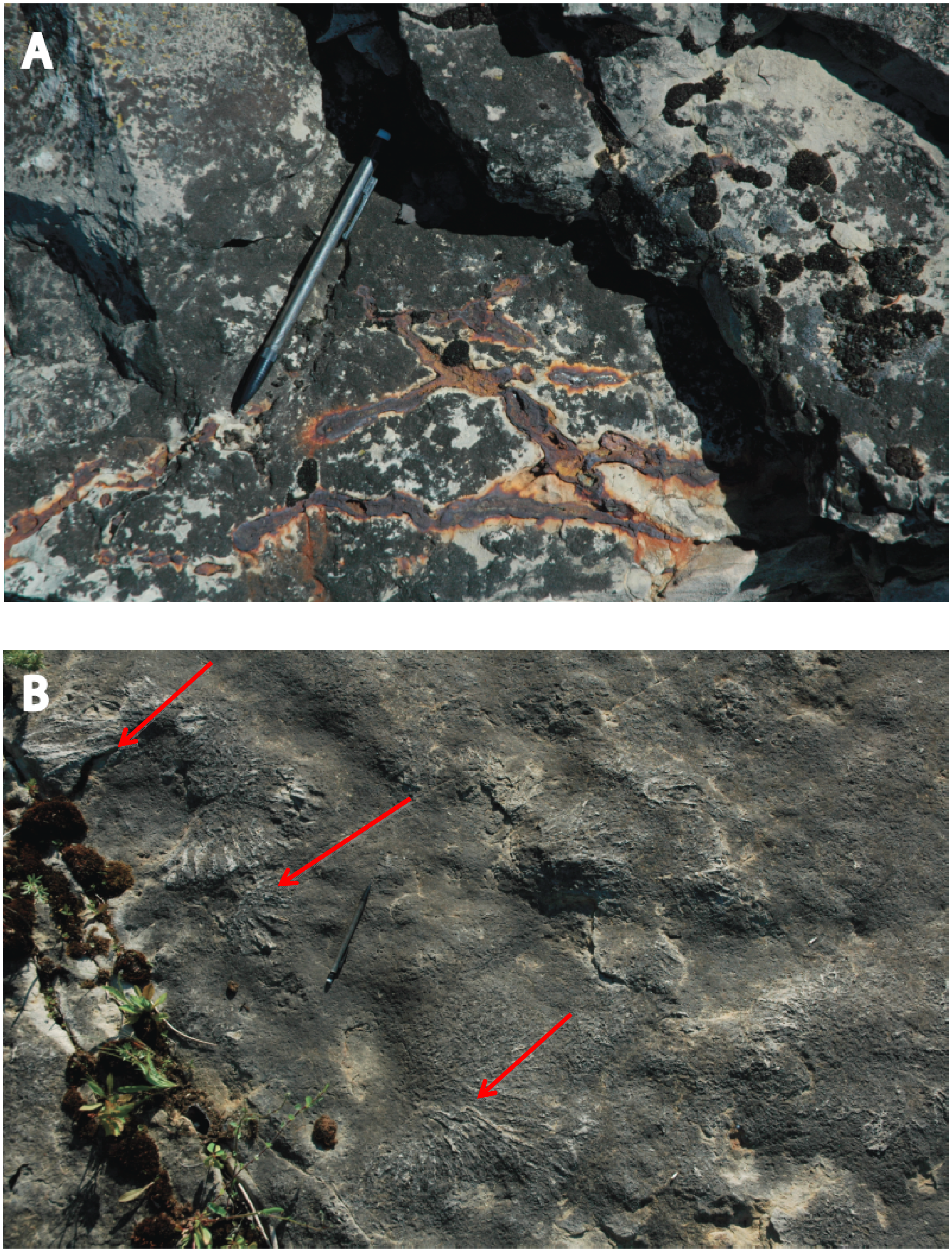

Figure 3.19: Field photos of the upper crinoidal dolostone unit. A) Sulfidized *Thalassinoides* burrows. B) *Tetradium* coral. Scale, pencil 14 cm. Photo courtesy of P.L. Corcoran.

3.2.11 Shale-Mudstone Unit

The gradational contact between the upper crinoidal dolostone and shale-mudstone units on Heywood Island is marked by a grey, siltstone subunit (Figures 3.17, 3.20a). The siltstone ranges from 20-40 cm thick, and contains thin, planar beds, very minor rippled horizons, and small quartz granules (Figure 3.20a and b). Fossils are uncommon in the siltstone, although minor disarticulated brachiopods were identified (Grifi, 2009). The shale-mudstone unit contains planar bedded and planar laminated black shale. Fossils are uncommon in the shale on Heywood Island, except for the presence of graptolites (Figure 3.21). Sulfidized burrows 4-8 cm long and sulfide lenses cover approximately 15-20% of the outcrop (Grifi, 2009). When broken, the shale has a distinct petroliferous odor.

Thin section analysis of the siltstone revealed dolomite crystals comprise >96%, quartz granules account for <3.8%, and fossil fragments represent <0.2% of the rock. The dolomite matrix is very fine to medium grained with crystals that are mainly subhedral to anhedral. Quartz grains are 0.25-0.75 mm in size and are monocrystalline, and mainly subangular. Bioclasts identified in thin section include disarticulated brachiopods. Minor quartz arenite rock fragments were identified in addition to kerogen and hematite. In addition to planar laminae, microflames and mini-ripples were identified in thin section.

3.2.12 Interpretation

The presence of quartz clasts at the contact between the underlying dolostone and siltstone subunit may indicate a brief episode of intense basement erosion. The quartz detritus need not have travelled far given the proximity of quartz arenite outcrops <1 km away. In addition, the 10^{o} dip and southwest-facing strike of the shale beds suggests that an unexposed quartz arenite outcrop is located within 200 m northeast of the area (Figure 3.1). The presence of minor amounts of brachiopods may be a result of transport from shallow to deeper environments post-mortem. The graptolites, which are pelagic organisms, would have fallen to the seafloor post-mortem. Under anoxic/dysoxic conditions, graptolite fossils are preserved because scavengers are rare in this type of environment (Copper et al., 1991).

The shale may have been deposited on an outer ramp, below normal storm wave base. The deep water in the outer ramp environment allows for the settling of silts and muds. However, Harland & Pickerill (1984) suggest that the deposition of very fine-grained material directly off the flanks of basement highs could also be due to the presence of a protected embayment or a lagoonal environment. Storm currents could have been redirected as the quartz arenite outcrops acted as rocky barriers (Corcoran, 2008).

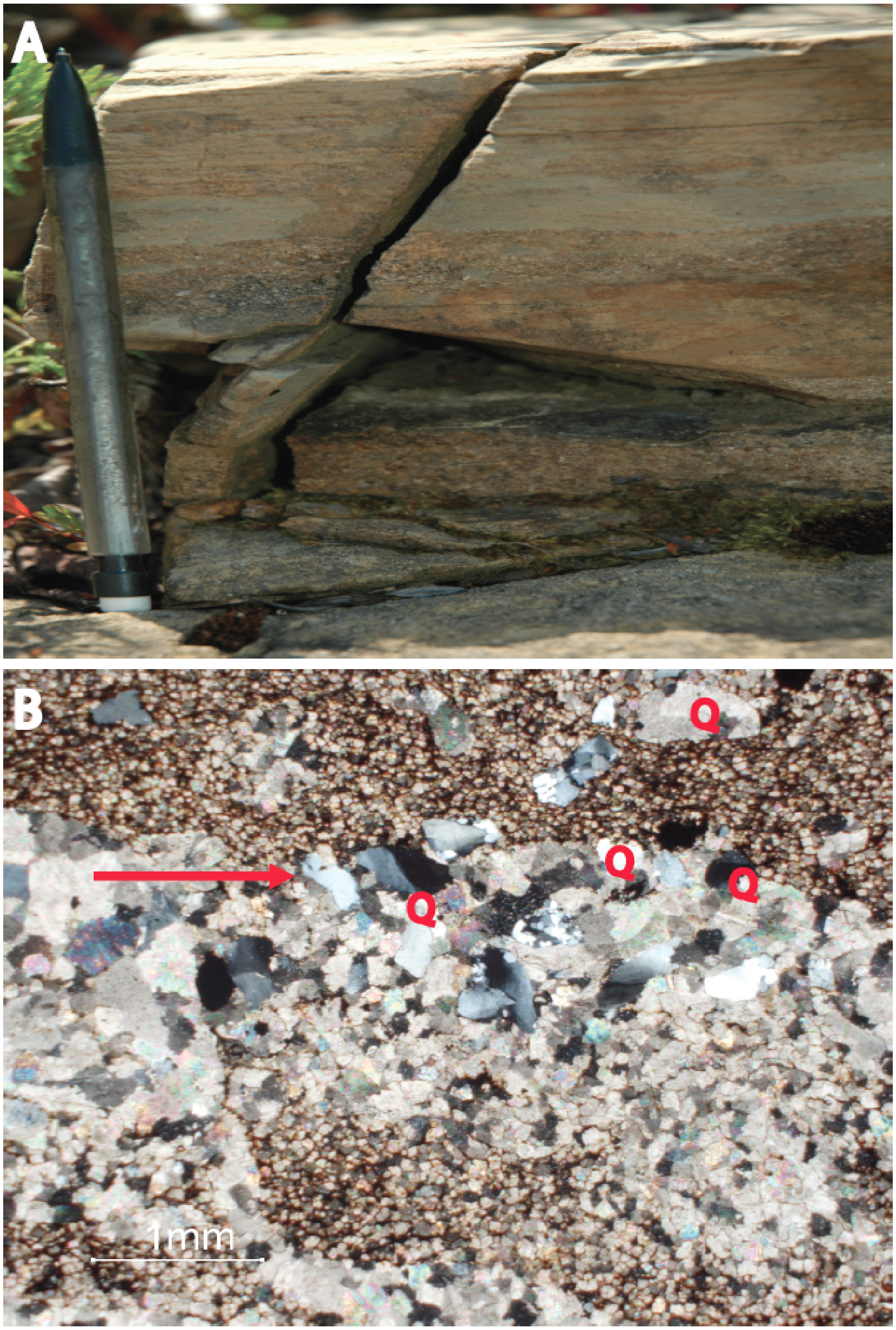

Figure 3.20: A) Field photo exhibiting the contact between the upper crinoidal dolostone unit and siltstone of the shale-mudstone unit. B) Contact between dolostone and siltstone in thin section (indicated by arrow). Q, quartz grains. Photo (A) courtesy of P.L. Corcoran.

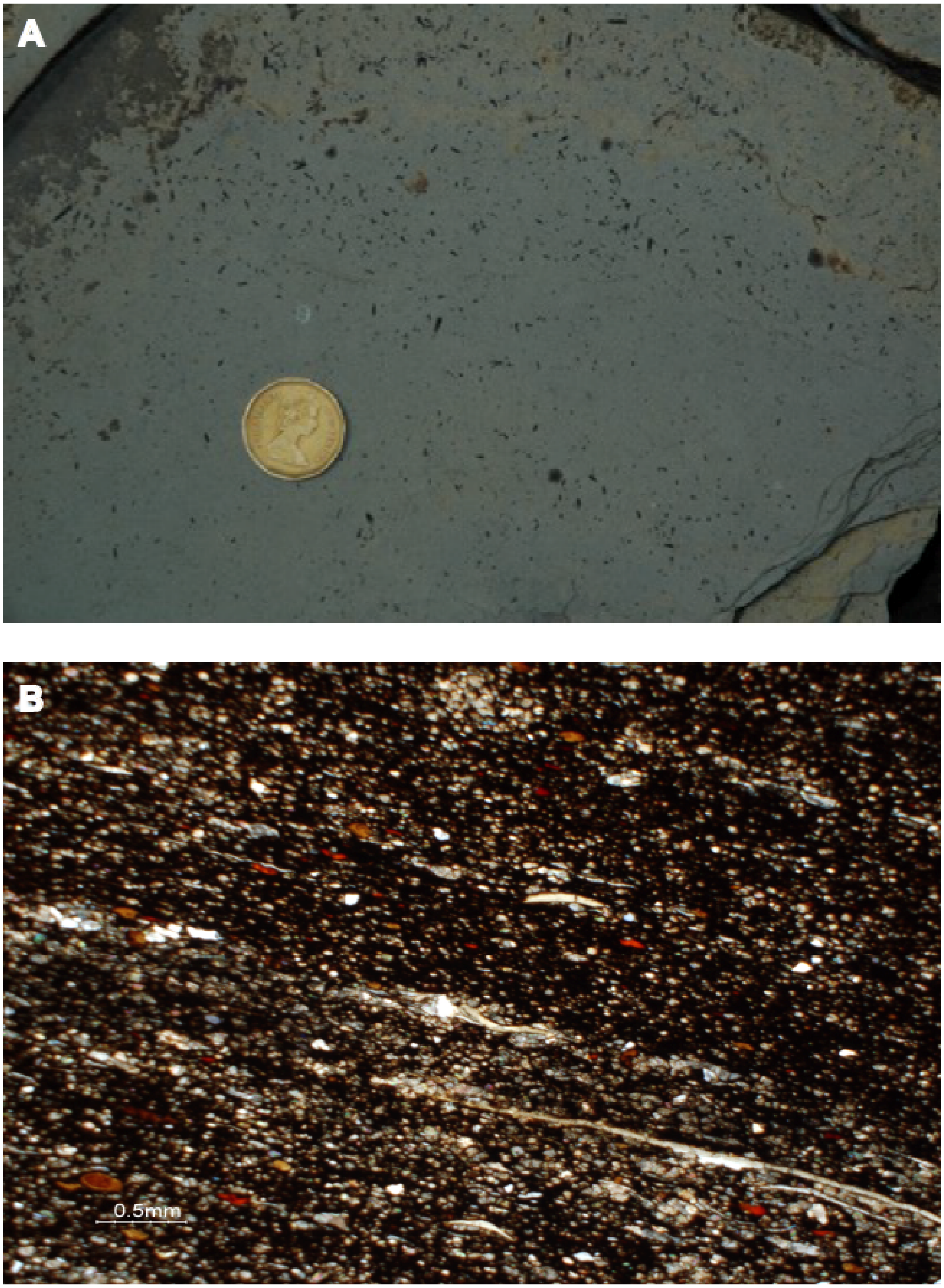

Figure 3.21: A) Field photograph displaying graptolite fossils in shale of the shale-mudstone unit on Heywood Island. B) Thin section photo exhibiting kerogen pellets in the shale-mudstone unit. Photo (A) courtesy of P.L. Corcoran.

3.3 Overview of OGSR Core Stratigraphy

Two cores were studied at the Oil, Gas and Salt Resources (OGSR) Library in London, Ontario in order to compare the stratigraphy and lithology of the Lindsay Formation at Bidwell and Albemarle townships, and Heywood and Partridge islands. One core was drilled from Township Albemarle in Bruce County (OGS 82-4) and the second core log was derived from Township Bidwell in Manitoulin County (Imperial # 644) (Figure 3.22). The stratigraphic units are composed of limestone and were classified using the scheme of Dunham (1962), which could not be as readily applied to the Heywood and Partridge Island units due to the dolomitization.

Figure 3.22: Map of Bruce Peninsula and Manitoulin Island displaying the locations of the two OGSR cores that were logged (Modified from Ontario Oil, Gas and Salt Resources Corporation, 2001).

3.3.1 Wackestone-Packstone Unit

This 4 m thick unit represents the bottom of the Lindsay Formation in core Imperial #644 (Figure 3.23). The wackestone component is heavily bioturbated, and contains *Planolites* trace fossils, in addition to sparse planar to low-angle laminated beds with discrete mudstone layers, vugs, and minor iron oxidation. The moderately fossiliferous beds contain trilobite, crinoid, brachiopod, bivalve, and rugose coral fossil fragments (Figure 3.24) (Figure 3.25). The fossil assemblage is disarticulated and fragmented with faunal diversity decreasing up-section. Packstone interbeds are massive to cross laminated and contain minor burrows. The interbeds are highly fossiliferous and contain trilobite, crinoid, brachiopod, and bivalve fragments.

3.3.2 Interpretation

The up-section change from a wackestone-dominated to packstone-dominated lithology in this unit suggests an overall increase in flow energy. Low sedimentation rates near the bottom are supported by the abundance of burrows, whereas higher flow energy toward the top of the unit is evidenced in disarticulated and fragmented fossils (Choi & Simo, 1998; Flugel, 2010). This unit is inferred to have been deposited on an upper mid-ramp setting. In the mid-ramp, the bottom sediment is frequently reworked by storm waves and swells, which causes disarticulation and fragmentation of the fossils. The intruding marine currents and episodic storm events bring in the higher energy required to move and deposit fossils, such as rugose corals, from the inner ramp to the mid-ramp. The planar laminae in the lower wackestone component are consistent with waning current flow, whereas minor cross-laminae in the packstone interbeds are consistent with wave ripple development.

3.3.3 Wackestone Unit

This unit is approximately 2.4 m thick and represents the bottom of the Lindsay Formation in core OGS 84-2 (Figure 3.26). The wackestone is highly bioturbated with abundant *Chondrites* and *Planolites* trace fossils, and is also bioeroded. Minor planar beds are preserved. Sparse fossil fragments include brachiopod, bivalve and other unidentifiable fragments. The fossil assemblage is disarticulated and highly fragmented.

3.3.4 Interpretation

Abundant burrows and low fossil abundance in this unit indicates a low energy environment that was conducive to bioturbation. The wackestone unit may have been deposited on a mid ramp setting between the upper shoreface and fair weather base (Burchette & Wright, 1992).

3.3.5 Crinoidal Wackestone-Packstone Unit

The approximately 24.6 m thick crinoidal wackestone-packstone unit gradationally overlies the wackestone unit in core OGS 84-2 (Figure 3.25). This unit mainly appears massive as a result of bioturbation, but minor planar laminations are preserved. The beds are moderately fossiliferous with local highly fossiliferous interbeds. The fossils are mainly crinoids, however, other bioclasts such as brachiopods, trilobites and cephalopods were also identified. The fossil assemblage is predominantly disarticulated and fragmented, but some beds contain whole crinoid ossicles and crinoid stems.

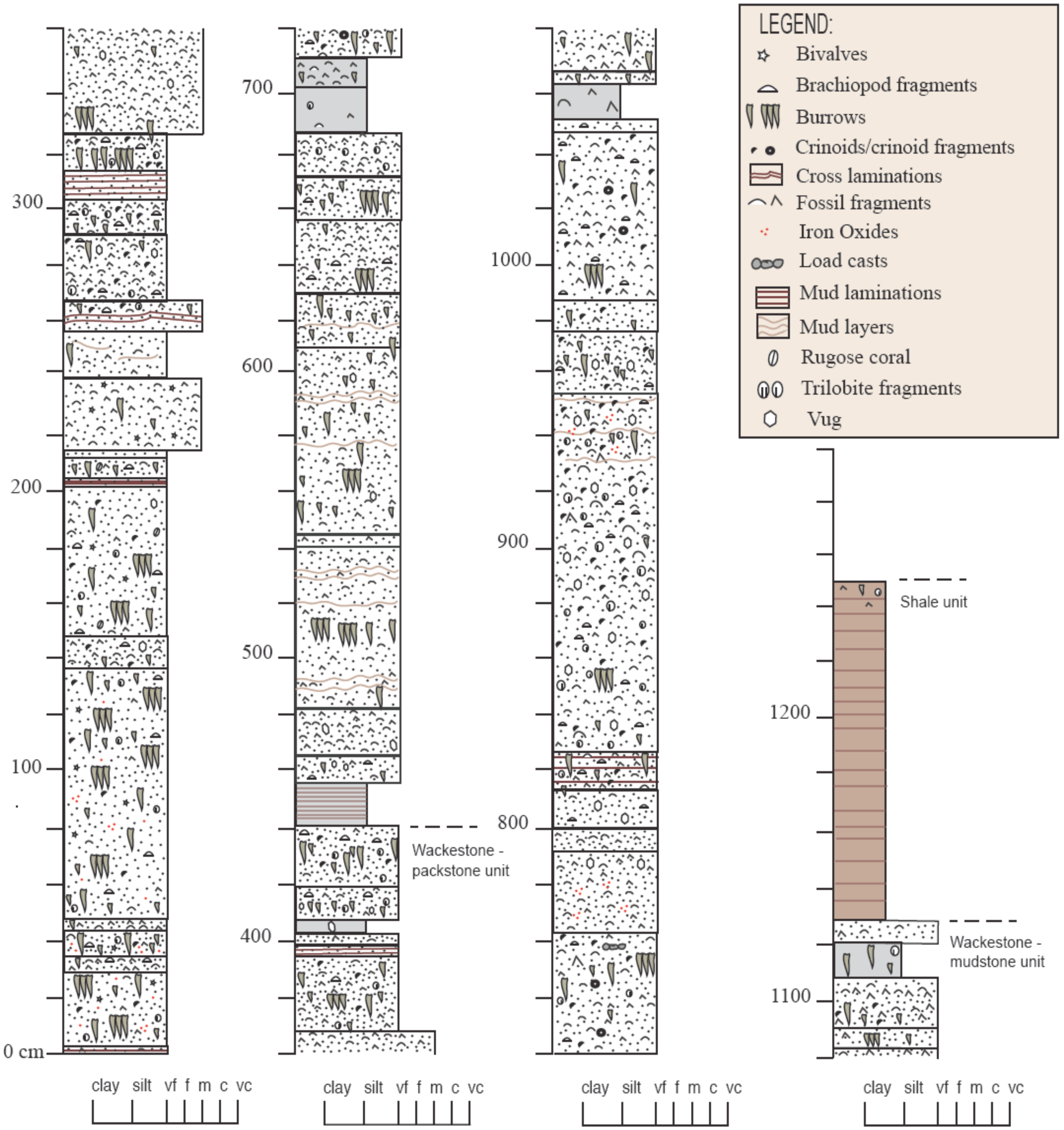

Figure 3.23: Stratigraphic section of the Lindsay Formation at Bidwell, Ontario.

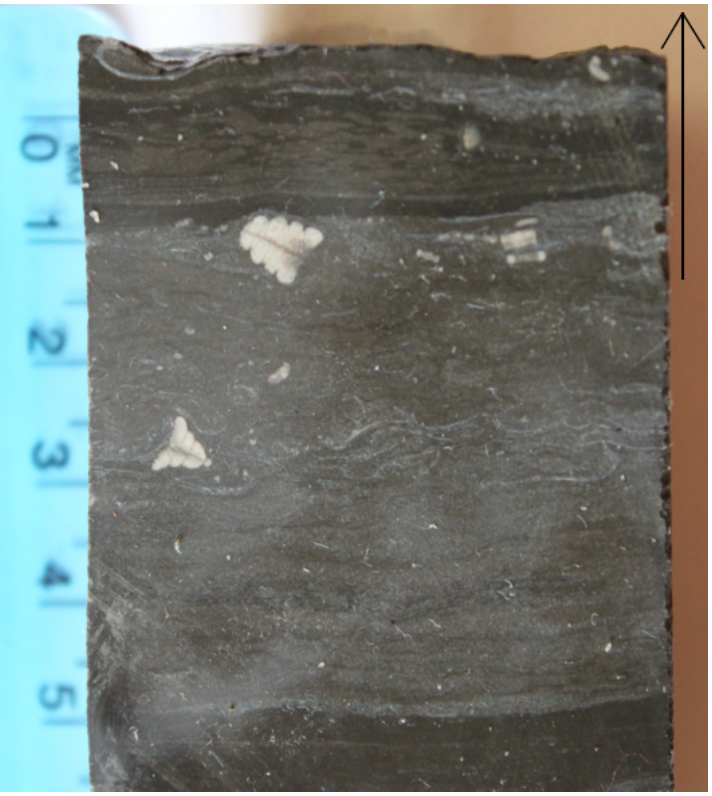

Figure 3.24: Oblique cut views of Ordovician crinoid stems found in the wackestone-packstone unit in Imperial #644 core.

Figure 3.25: Nodular limestone containing *Planolites* in the wackestone-packstone unit of core OGS 84-2.

3.3.6 Interpretation

The presence of disarticulated and fragmented fossils indicates transport of fossil fragments during increased wave activity. This unit is inferred to have been deposited on a mid-ramp setting between fair-weather base and storm wave base. The increase in burrows up-section suggests a change to a relatively calmer environment that was conducive to bioturbation. Articulated and whole fossils, such as the crinoid stems and crinoid ossicles are suggestive of deposition under fair weather conditions (Flugel, 2010). The planar laminae are consistent with waning current flow, which possibly occurred following storm wave activity.

3.3.7 Wackestone-Mudstone Unit

This approximately 1.5-7 m thick unit overlies the wackestone-packstone unit in core Imperial #644, and overlies the crinoidal wackestone-packstone unit in core OGS 84-2 (Figures 3.23 and 3.25). The wackestone component contains massive, wavy to planar laminated beds. The majority of massive beds contain burrows. The moderately to highly fossiliferous beds are characterized by brachiopod, crinoid, and trilobite fragments. The fossil assemblage is disarticulated and fragmented with faunal diversity decreasing up-section. Mudstone interbeds are 4-20 cm thick, and are planar to wavy laminated, planar cross-laminated, rippled and normally graded (Figures 3.26, 3.27). Fossils are uncommon in the mudstone, however, minor crinoid ossicles were identified. Pyrite is also a local component of the mudstone interbeds.

Figure 3.26: Stratigraphic section of the Lindsay Formation at Albemarle, Ontario.

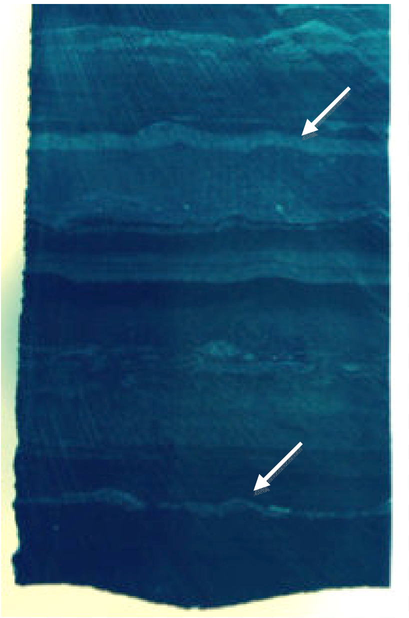

Figure 3.27: Planar to wavy laminations in the wackestone-mudstone unit in core OGS 84-2. Note the rippled base.

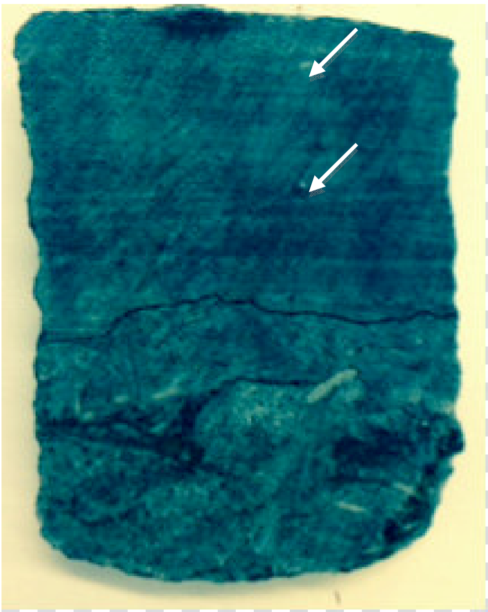

Figure 3.28: Planar cross-laminae in the wackestone-mudstone unit in OGS 84-2 core.

3.3.8 Interpretation

The fragmented and disarticulated fossils in combination with minor articulated crinoid ossicles are consistent with reworking and transport during storm activity, with sporadic low energy periods. These conditions of low wave energy favored the development of burrows, as well as deposition of suspended muds (Flugel, 2010). The well sorted moderately to highly fossiliferous beds are consistent with storm reworking. The rippled to wavy laminated beds in the wackestone indicate regular wave activity. Planar laminated and graded bedded mudstone is consistent with waning current flow, following storm events (Reineck & Singh, 1975). This unit was probably deposited in an upper mid-ramp setting between fair-weather base and storm wave base.

3.3.9 Mudstone-Siltstone Unit

This unit is approximately 1.8 m thick and overlies the wackestone-mudstone unit in core OGS 84-2 (Figure 3.25). The mudstone beds are composed of planar laminations and ripples. Fossil fragments are sparse, with only one bed being moderately fossiliferous. The fossil assemblage is mainly composed of unidentifiable fossil fragments, however, crinoid, brachiopod and trilobite fragments were identified. Brachiopod and trilobite stringers also characterize this unit (Figure 3.28). Siltstone interbeds are <5 cm thick and contain stringers of brachiopod and trilobite debris.

3.3.10 Interpretation

The lack of bioturbation and minor fossil fragments in the mudstone-siltstone unit indicate a relatively low energy environment (Choi and Simo, 1998). Wave processes were operational, as supported by symmetrical ripples, and planar laminae support waning flow conditions following storm events. Discrete <5 cm thick fossil stringers are interpreted as storm deposits (tempestites) (Witzke and Bunker, 1997). These tempestites are characterized by variably arranged, diarticulated and fragmented fossils. The preserved features indicate a lower mid-ramp to outer ramp setting for the mudstone-siltstone unit.

3.3.11 Mudstone-Wackestone Unit

The approximately 1.1 m thick mudstone-wackestone unit overlies the mudstone-siltstone unit in core OGS 84-2 (Figure 3.25). The mudstone beds are planar laminated and are mainly characterized by brachiopod and trilobite stringers. Wackestone interbeds are 5-10 cm thick and contain trilobite, crinoid, and brachiopod fragments. These interbeds are bioturbated, with burrows decreasing in abundance and ultimately disappearing up-section.

3.3.12 Interpretation

The mudstone-wackestone unit shares similar characteristics to the mudstone-siltstone unit, however, the former contains a relatively greater abundance of fossil debris. Interbedded wackestone and mudstone containing stringers suggests the interaction of wave and storm activity in the mid- to outer-ramp setting.

3.3.13 Shale Unit

The shale unit in core Imperial #644 is faintly laminated, fissile, black to dark brown and is approximately 1.2 m thick (Figure 3.23). Faunal abundance and diversity in the shale unit is extremely difficult to identify in core. The only fossils unequivocally identified were trilobite remains at the top of the unit.

Figure 3.29: Brachiopod and trilobite stringers in the mudstone-siltstone unit in core OGS 84-2.

3.3.14 Interpretation

The black to dark brown colour of the shale indicates that it is rich in organic matter (Figure 3.21). The lack of bioturbation and minor fossil fragments suggest a deep water environment where organisms could not survive. The shale unit is consistent with a relatively quiet depositional environment where settling of fines prevailed. The rocks are inferred to have been deposited in the lower mid- to outer ramp environment. Although a lagoonal interpretation could be made based on the nature of the unit, its stratigraphic position above the mudstone-wackestone unit and underlying mudstone-siltstone unit suggests gradual transgression over time.

3.3.15 Mudstone Unit

The upper mudstone unit in core OGS 84-2 is approximately 80 cm thick, is black to dark grey, and contains planar- to wavy-laminated beds (Figure 3.25). Faunal abundance and diversity within the mudstone is difficult to identify in core. However, stringers of brachiopods and trilobites were identified throughout the mudstone unit.

3.3.16 Interpretation

The black to dark grey colour of the mudstone indicates that it is rich in organic matter. The lack of bioturbation and minor fossil fragments suggest a quiet water environment, but the presence of fossil stringers indicate deposition above storm wave base where storm reworking takes place. Planar, irregular and wavy laminae indicate subtle fluctuations in water energy. The mudstone is interpreted as having been deposited in a lower mid-ramp to outer ramp environment. The primary distinction between the shale unit and mudstone unit is the fissility and dark brown to black colour of the former.

3.3.17 Summary

The characteristics of the Lindsay Formation units in drill core and on Heywood and Partridge islands point to a predominantly mid-ramp to outer ramp depositional environment. The quartz-clast dolostone, lower crinoidal dolostone and brachiopod dolostone are the only units containing evidence of deposition in an inner ramp setting. Although carbonate ramp models are often applied to ancient epeiric sea deposits, the typical facies of the inner ramp along gently sloping continental margins may differ where the shoreline is rocky. This issue will be further addressed in Chapter 5.

Chapter 4 – Geochemistry of the Lindsay Formation Shale-Mudstone

4 Collingwood Member of the Lindsay Formation

The petroliferous shale in the upper part of the Lindsay Formation was formerly assigned to the lower member (Craigleith Member) of the Whitby Formation (Liberty, 1969) and has a long and complicated nomenclatural history (see reviews by Russell & Telford, 1983; Hamblin, 1999). This unit, which is now considered the Collingwood member of the Lindsay Formation (Russell & Telford, 1983) is up to 10 m thick (Johnson et al., 1992) and is composed of mudrock and limestone exposed in southern Ontario, Canada (Brett et al., 2006). The deposits are considered equivalent to part of the widespread Utica Shale of eastern North America (Brunton et al., 2009). Rocks of the Collingwood member extend southwest from Port Elgin on Lake Huron to Port Colborne on Lake Erie (Hamblin, 1999), and extend north to south from the type area along Georgian Bay near Collingwood, Ontario to the shore of Lake Ontario, east of Toronto (Brett et al., 2006). With the exception of local exposures on Manitoulin Island and Heywood Island (i.e. described above as the shale-mudstone unit), the Collingwood Member pinches out either due to post-depositional erosion (Churcher et al., 1991) or to non-deposition during the time of maximum transgression (Melchin et al., 1994). The upper Lindsay Formation shales and mudstones are organic-rich and represent one of the earliest oil-shale units that was commerically exploited (Liberty, 1969; Snowdon, 1984; Melchin et al., 1994).

In the Craigleith area of Georgian Bay the Collingwood Member gradationally overlie fine-grained, nodular limestones of the Lindsay Formation (Brunton et al., 2009). However, Brett et al. (2006) and Hiatt (1985) reported sharp basal and erosional contacts. The shale-dominated unit contains cyclic packages approximately 50-150 cm thick composed of: 1) dark grey to black, organic-rich, laminated shales that grade upsection into: 2) dark to light grey calcaerous shales and mudstones, 3) lenticular to tabular concretionary argillaceous limestones, and 4) light grey calcareous, fossiliferous mudstones, shales and marls (Brett et al., 2006). Very thin, fossiliferous bioclastic interbeds contain mainly brachiopods and trilobites with lesser amounts of conularids, bivalves, and nautiloids (Rudkin et al., 1998; Brett et al., 2006). The fossils are predominantly preserved as pavements or stringers (Brett et al., 2006). According to previous studies, the total organic carbon (TOC) in the black to dark grey, petroliferous shale is mainly between 2% to 8% (Snowdon, 1984). However, according to Obermajer et al. (1999) the Collingwood Member at Georgian Bay has TOC values between 0.92% to 11.26%, whereas, the Collingwood Member at Toronto has TOC values between 0.67% to 4.31%.

4.1 Collingwood Member Geochemistry

There are two advantages of using a geochemical approach toward understanding the upper Lindsay Formation: 1) geochemical methods are equally applicable to coarse- and fine-grained sedimentary rocks, whereas, using petrography is difficult for very fine-grained deposits (McLennan et al., 1993), and 2) the provenance of sedimentary deposits can be determined using geochemical discrimination diagrams (McLennan et al., 1993).

Ten representative mudrock samples were analyzed for major element chemistry at Geoscience Laboratories of the Ministry of Northern Development and Mines in Sudbury, Ontario. Major elements in addition to Ba, Co, Rb, Sc, Sr, Th, U and Zr were determined using fused-disc X-ray fluorescence (XRF), and loss on ignition (LOI) values, as determined by gravimetric methods, range from 32.7-40 (Table 3). The high LOI values produced by heating the Lindsay Formation samples are a function of the high carbonate and organic matter content in the mudrock. Five samples were collected from Heywood Island (45°56'08.54" N, 81°45'05.23" W), three from Manitoulin Island (45°53'31.260" N, 81°55'24.420" W), and two were collected from Delphi Point (44°32'17.26"N, 80°23'03.25" W) in Collingwood, Ontario (Figure 3.7), in order to compare Lindsay Formation shale-mudstone compositions from three different localities.

Heywood Island calcareous shale and mudstone samples contain 11.96-16.89 wt% SiO_2, and 12.61-14.87 wt% MgO. In addition, the proportions of Al_2O_3 and TiO_2 are similar for all samples, with values between 2.18 and 3.89 wt%, and 0.12 and 0.23 wt%, respectively. The amount of CaO in the samples is relatively high compared with the average sandstone, and ranges from 21.53-25.93 wt%. Aluminum is often used as a representative of detrital influx due to its immobile nature. Bivariate plots using Al_2O_3 versus other oxides indicate which elements are strongly controlled by the detrital fraction. There are strong negative correlations between Al_2O_3 and MgO (correlation coefficient n = -0.875), and Al_2O_3 and MnO (n = -0.764), which suggests that these oxides are associated with the authigenic fraction (Figure 4.1). Sharma et al. (2003), in their investigation of the Lindsay Formation shales in eastern Ontario and on Manitoulin Island, found that the main clay mineral components are illite and chlorite, the latter of which contains appreciable MgO. In contrast, the strong positive correlations between Al_2O_3 and SiO_2 (n = 0.968), K_2O (n = 0.841), and TiO_2 (n = 0.968) indicate a strong association with detrital phases (Figure 4.1). The presence of MnO and its negative correlation with Al_2O_3 may be a function of its trace occurrence in pyrite, or its concentration near the anoxic/oxic boundary (Wignall, 1994). There is no correlation between CaO and Al_2O_3. The samples contain minor amounts of trace elements with values <100 ppm, except for Ba, which ranges between 100 and 151 ppm.

In contrast to the Heywood Island samples, calcareous shales and mudstones collected from Manitoulin Island and Delphi Point contain greater amounts of SiO_2 (17.97-24.13 wt%), Al_2O_3 (3.99-5.74 wt%), TiO_2 (0.27-0.37 wt%), CaO (22.98-32.55 wt%) and K_2O (2.11-2.56) (Table 3; Figure 4.1). The MgO and MnO contents are much lower than those of the Heywood Island samples, with 1.5-11.2 wt% and 0.06-1.3 wt%, respectively. Similar correlations between Al_2O_3 wt% and the other oxides were identified in the Heywood, Manitoulin and Delphi Point samples (Figure 4.1).

There are greater proportions of all analyzed trace elements in the Manitoulin Island and Delphi Point samples compared with those from Heywood Island (Table 3; Figure 4.2). Most trace elements in all samples are less abundant than NASC, except for Sc and U. The element Sr is enriched in the Delphi Point and Manitoulin Island samples compared with NASC. In contrast, the average Sr value for the Heywood Island samples is almost 4 times lower than for that of the samples from the two other localities. (Figure

Location	**Heywood**	**Heywood**	**Heywood**	**Heywood**	**Heywood**	**Manitoulin**	**Manitoulin**	**Manitoulin**	**Delphi**	**Delphi**
Sample	MG-09-29	MG-09-31	MG-08-16	MG-08-17	MG-08-18	MG-09-66	MG-09-68	MG-09-69	CO-2010	Craigleith
Units	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
SiO_2	14.31	14.71	16.89	13.18	11.96	20.47	17.97	20.53	18.03	24.13
Al_2O_3	3.19	2.36	3.89	2.96	2.18	4.77	3.99	4.72	4.02	5.74
TiO_2	0.17	0.13	0.23	0.17	0.12	0.29	0.27	0.28	0.27	0.37
Fe_2O_3	2.76	2.48	3.39	2.49	2.76	1.6	2.74	2.97	2.6	2.57
MnO	0.15	0.35	0.24	0.37	0.26	0.06	0.13	0.09	0.06	0.1
MgO	13.85	14.4	12.61	14.36	14.87	2.65	11.2	5.81	3.14	1.5
CaO	23.7	24.56	21.53	24.34	25.93	32.55	22.98	25.68	32.26	28.07
Na_2O	< 0.01	< 0.01	< 0.03	< 0.04	< 0.05	< 0.02	< 0.06	< 0.07	< 0.08	0.15
K_2O	1.8	1.23	2.07	1.73	1.18	2.54	2.21	2.56	2.3	2.11
P_2O_5	0.13	0.3	0.16	0.18	0.18	0.18	0.23	0.23	0.23	0.38
LOI	37.53	38.08	36.22	38.92	39.99	33.42	35.91	33.27	32.9	32.66
Total	97.55	98.52	97.18	98.61	99.33	98.53	97.53	96.07	95.73	97.77
Ba	138	100	151	141	102	181	144	171	159	254
Co	6	< 6	6	< 6	< 6	8	7	13	6	9
Rb	32	24	39	31	23	50	40	48	43	60
Sc	43	45	40	44	46	62	41	50	62	56
Sr	84	61	71	61	80	295	104	177	300	451
Th	< 4	< 4	< 4	< 4	< 4	5	< 4	< 4	4	6
U	3	< 3	4	< 3	< 3	3	4	9	4	3
Zr	34	32	45	36	28	53	46	53	47	71

Table 3: Major and trace element compositions of shale-mudstone samples from Heywood Island, Manitoulin Island and Delphi Point.

4.2). Using the SandClass system (Figure 4.3) of Herron (1988) all samples plot as calcareous wackes (Ca >15%). Six of the 10 samples were determined to have Th values of <4 ppm, whereas the other 4 samples contain 4-6 ppm Th (Table 3). The 4 samples plot in the "andesite compositional variations" and mixed mafic-felsic provenance fields on the Th/Sc vs. Zr/Sc plot (Figure 4.4). Substituting any value lower than 4 for Th in the samples containing <4 ppm Th would result in the same determination.

4.2 Geochemistry Discussion

The mudrock samples from the upper Lindsay Formation include shales, claystones and mudstones based on petrography (Table 3). The mudstones and claystones are dark grey to dark brownish-grey and are mainly parallel-laminated, whereas the shales are black to dark brown, fissile, have a distinct petroliferous odor, and contain appreciable amounts of pyrite. According to the SandClass system diagram (Figure 4.3), all samples plot as wackes, rather than shales, as a result of the SiO_2/Al_2O_3 ratios being lower than those of shales analyzed by Herron (1988). However, the obvious fissility in three Lindsay Formation samples indicates that at least some deposits can be positively classified as shale. The low to intermediate $\log(Fe_2O_3/K_2O)$ values are consistent with a moderate degree of mineral assemblage stability. This can be corroborated by the petrographic data provided in Chapter 3, which show that the mudrocks mainly contain quartz, muscovite and feldspar in the detrital fraction, as opposed to less stable lithic fragments and other Fe-rich grains. The low $\log(SiO_2/Al_2O_3)$ values are commensurate with poor mineralogical maturity (Herron, 1988), as supported by angular to subrounded grains.

The least mobile trace elements include the rare earth elements (REE), Th, Zr, Ti, and Sc, as they are less sensitive to weathering and metamorphism than the large ion lithophile elements (LILE) (Holland, 1978). Although the REE were not analyzed in this study, other immobile trace elements reflect the controls of mineral composition, provenance and paleoredox conditions. The influence of an andesitic source rock for the

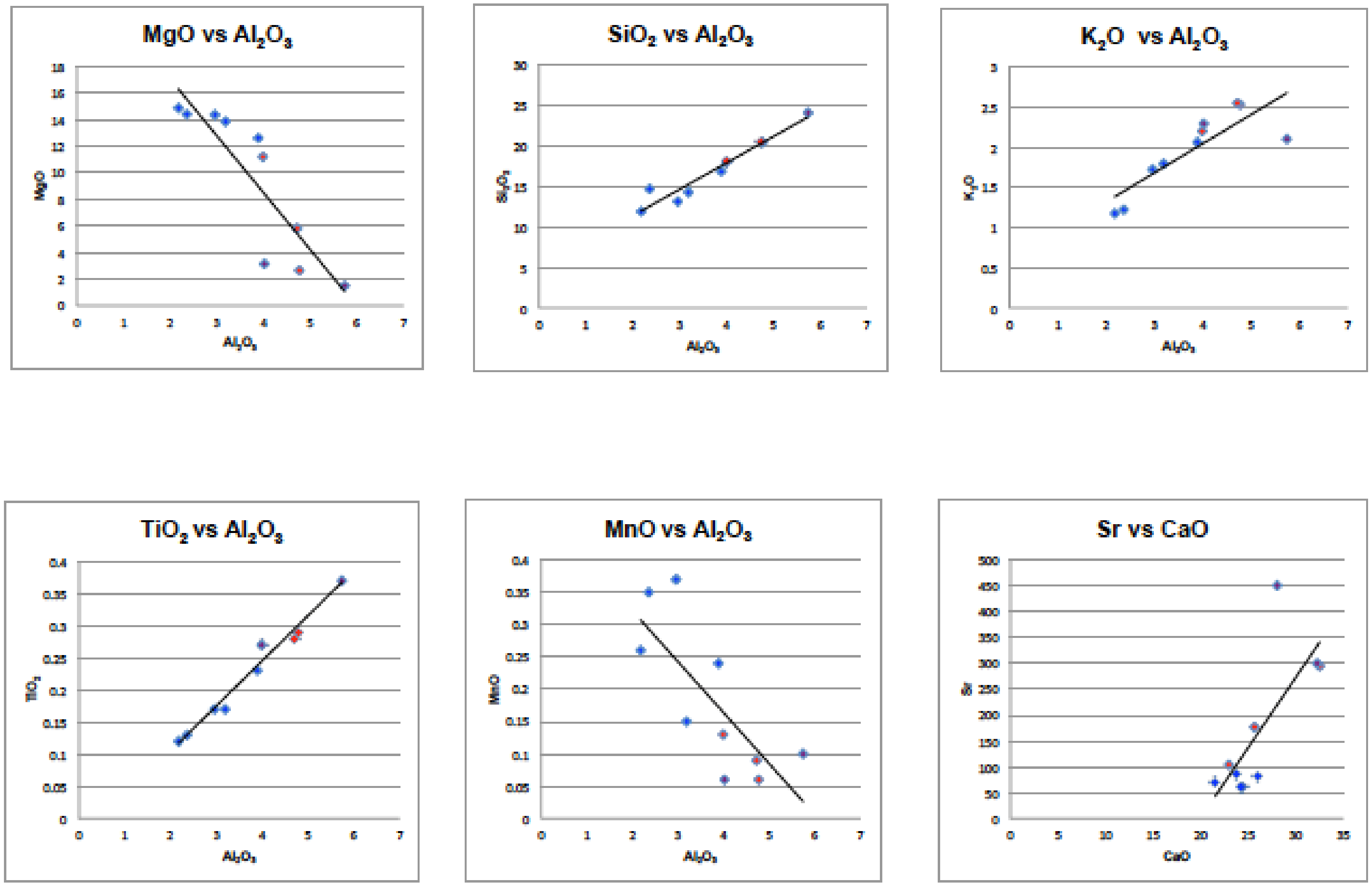

Figure 4.1: Major and trace element trends of mudrock samples from Heywood Island, Manitoulin Island and Delphi Point (The blue dots represent Heywood samples, the red dots represent Manitoulin samples and the purple dots represent Delphi point samples).

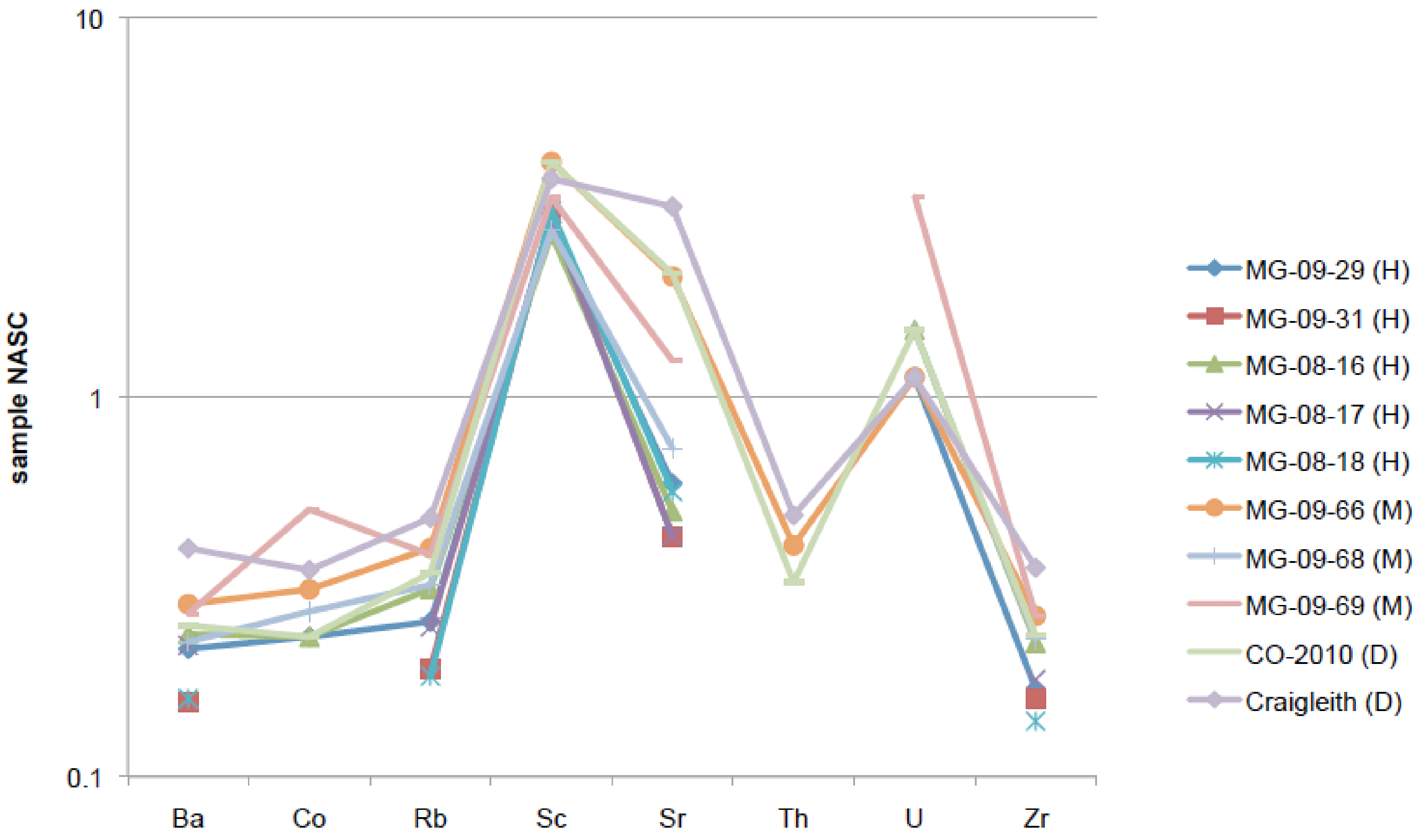

Figure 4.2: NASC-normalized trace element plot of shale samples from Heywood Island, Manitoulin Island and Delphi Point (Gromet et al., 1984).

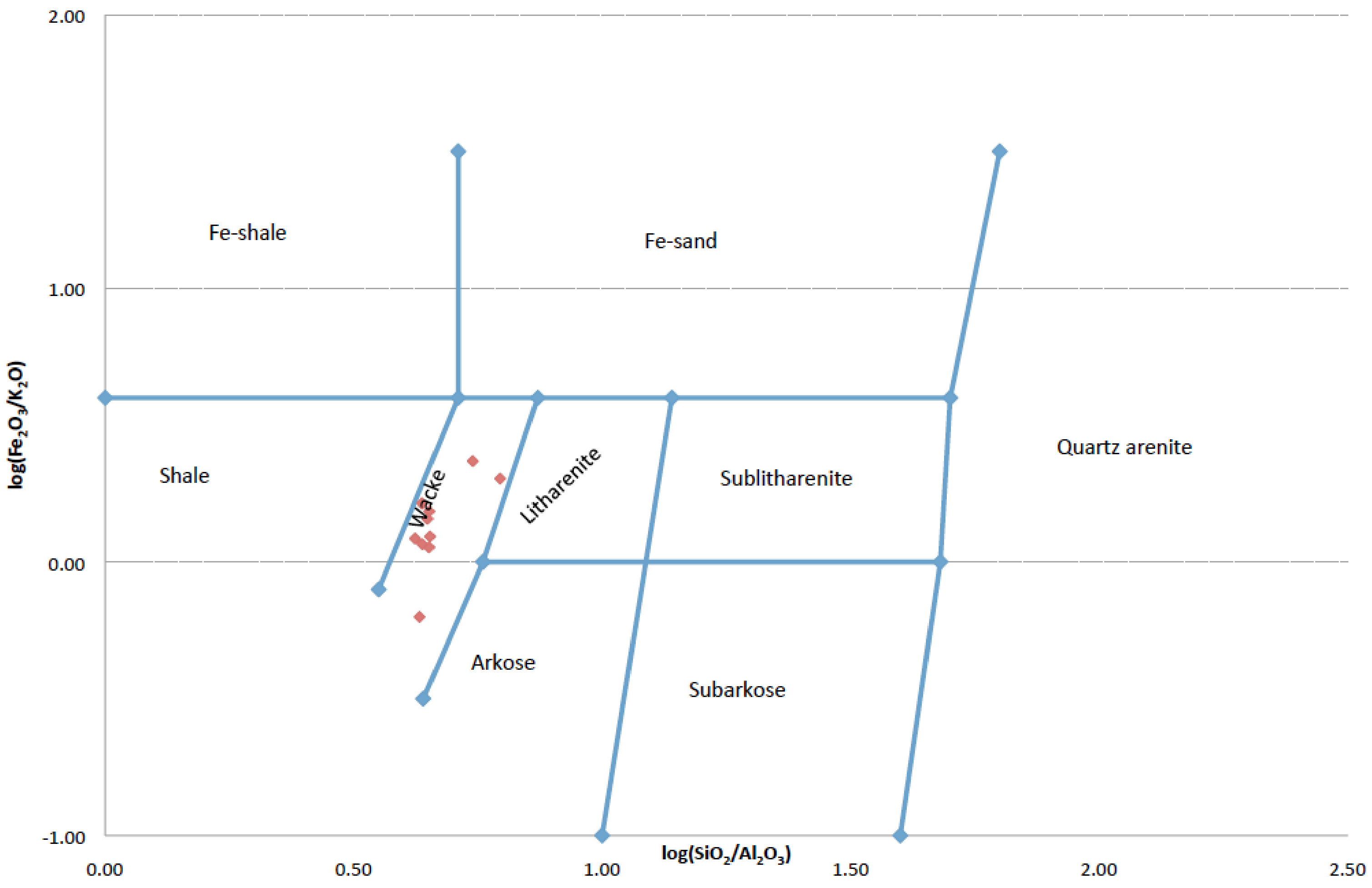

Figure 4.3: The SandClass system for geochemical classification of terrigenous sands and shales (Modified from Herron, 1988).

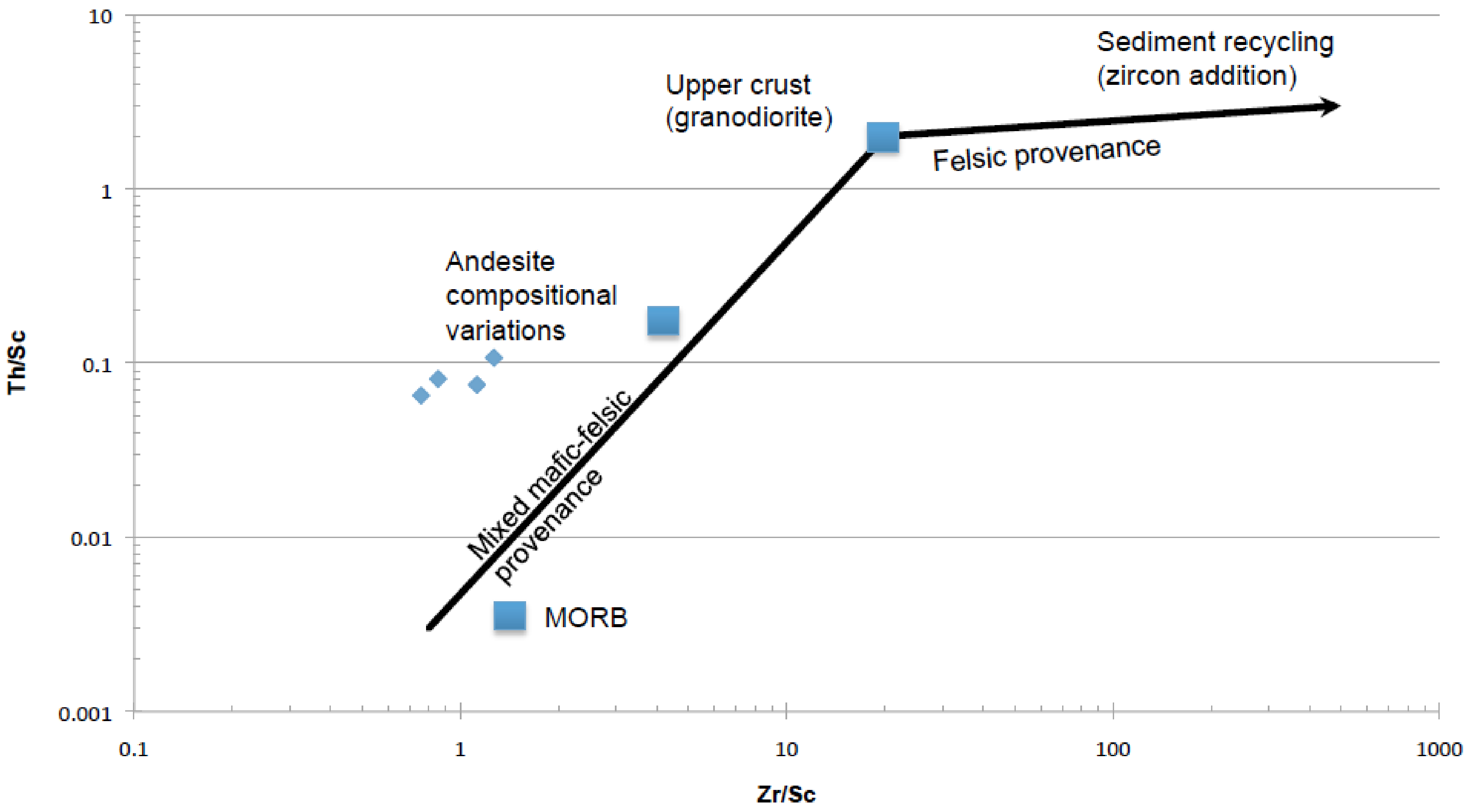

Figure 4.4: Plot of Th/Sc versus Zr/Sc for samples from Heywood Island, Manitoulin Island and Delphi Point (Modified from McLennan et al., 1993).

Lindsay Formation samples, as indicated by the Fe_2O_3/K_2O vs. SiO_2/Al_2O_3 plot, is supported by Sc values greater than NASC. Enriched Sc is often associated with a mafic volcanic source (Bhatia & Crook, 1986). The enriched Sr values for the Delphi Point and Manitoulin Island samples appear to be influenced by the proportion of CaO in the samples, as there is a positive correlation between Sr and CaO ($n = 0.747$) (Figure 4.1).

The controls on Th/U ratios are complex in sedimentary rocks. This ratio is typically 3.5-4.0 in most upper crustal rocks (McLennan et al., 1993), but highly reduced sedimentary environments can have enriched U values leading to low Th/U ratios (McLennan & Taylor, 1984). The Th/U ratios in the Lindsay Formation samples are <3, which may reflect low Th/U ratios in island arc and mid-ocean basalt igneous provenances (McLennan et al., 1990). Sharma et al. (2003) attributed high mafic/felsic ratios, as determined from relative proportions of Cr, Ni, Ti and Nb, and low La/Sm_n ratios in the Lindsay Formation shale to mafic-derived sediment. Alternatively, the high U values in black shales can be attributed to the precipitation of authigenic U under anoxic conditions (Wignall, 1994). Anoxia during diagenesis of the Lindsay Formation mudrocks is supported by the presence of pyrite. The production of iron sulfide occurs under anoxic conditions and is controlled by organic matter availability, which was identified in the samples in the form of kerogen.

In comparing the geochemical samples from the three different localities, the Manitoulin and Delphi Point mudrocks are more chemically similar than the Heywood Island samples. The latter have greater LOI values and contain more MgO and MnO, which, suggests greater organic matter content in the Heywood Island samples and a slightly stronger mafic component. Corcoran (2008) and Grifi (2009) suggested that the easternmost shales on Manitoulin Island and the shales on Heywood Island may have been deposited in a lagoonal setting, which may have accounted for greater organic matter preservation. Notwithstanding, all samples analyzed are consistent with a mixed mafic-felsic provenance, with a stronger mafic component than that of NASC, as indicated by elevated Sc values. Therefore, felsic detritus was probably derived from the proximal Canadian Shield rocks, as supported by the presence of quartz granules and pebbles in the shales of Heywood Island, but the mafic detritus may have been derived from the Taconic arc rocks, as suggested by Sharma et al. (2003).

Chapter 5 - Discussion

5 Introduction

Field work forms the basis for studying ancient depositional environments, which are reconstructed by identifying lithology, sedimentary structures and textures, diagenetic features, fossils, and biogenic structures (Flugel, 2010). A vertical stratigraphic section is subdivided into different rock units with varying thicknesses and characteristics. A facies refers to a distinct part of a rock that contains similar lithology, sedimentary structures and biological features that differ from units above, below and laterally adjacent. Facies analysis helps to re-create ancient paleoenvironments through comparison with modern and other previously studied ancient examples (Walker, 2006). In addition, each facies displays well-defined petrography, which can help differentiate the properties of other facies in the same stratigraphic section (Flugel, 2010). Combining stratigraphy, facies analysis and petrography leads to the development of depositional models.

5.1 Paleogeography

The epeiric sea covering much of the Canadian Shield during the Middle Ordovician to Early Devonian is recorded in the stratigraphy throughout southern Ontario, which contains extensive limestone and dolostone deposits. These units were deposited during the Tippecanoe marine transgression, which followed deposition of regressive units during the Sauk sequence (Sloss, 1963). Due to significant surface relief of exposed Precambrian quartz arenites prior to Trenton Group deposition, evidence of this transgression is especially dramatic in the Manitoulin area, as observed on both Heywood and Partridge islands. Evidence that the islands were skirted by rocky shoreline is provided by quartz arenite inliers and quartz clasts in basal carbonate beds throughout the study area (Johnson & Rong, 1989).

The depositional dynamics preserved in Paleozoic rocks throughout most of the interior of North America appears to reveal fluctuations in relative sea level, resulting from both eustatic and tectonic controls. In eastern North America the latter included lithospheric flexure that accompanied the Taconic Orogeny and development of the Appalachian Foreland Basin, and subsidence of the Michigan Intracratonic Basin. Pulses of alluvial sediments (i.e. from streams) would have extended into the Ontario-Michigan area at times of more rapid erosion and uplift of the Taconic Highlands, (Coniglio et al., 2006). The deposition of clay and silt-sized sediment followed erosion of the weathered Taconic mountains (Holland, 1993). Some of this sediment was re-suspended and moved by tropical storms or tsunami waves, however, the mud supply to the area was intermittent and shell-bearing organisms colonized the sea bed as the muddy bottoms became firm. Following the death of the organisms, their shells accumulated at the bottom of the sea floor where storms and tsunami waves re-suspended, mixed and redeposited the shelly material (Holland, 1993). These beds are preserved as fossiliferous limestone or dolostone. The alternating layers of limestone and shale reflect periods of clear water alternating with periods of heavy sediment influx from the Taconic Mountains (Holland, 1993).

During the Late Ordovician (Blackriverian – Edenian) marine carbonates were deposited on the flanks of Manitoulin, Heywood and Partridge islands (Brunton et al., 2009). Evidence of erosion which was attributed to regression (Sproule, 1936), was followed by the deposition of carbonates and siliciclastic muds of the Lindsay Formation (Johnson & Rong, 1989 are visible on the outcrops of these islands. Erosion has reduced the areal extent of the Paleozoic strata were once continuous for thousands of square kilometres and covered all of the islands in the present study (Coniglio et al., 2006).

During the Ordovician the Manitoulin area was situated on the northeast margin of the Michigan Basin, south of the paleoequator (Coniglio et al., 2006). However, the exact latitude is still under debate. Torsvik et al. (2012) placed southern Ontario in a tropical setting, approximately 15° south of the paleoequator. The warm tropical sea provided favorable living conditions for relatively diverse marine communities dominated by corals, bryozoans, brachiopods, and crinoids (Coniglio et al., 2006).

5.2 Paleoenvironmental Reconstruction of a Rocky Shoreline Complex

The lowest Late Ordovician (Trenton) strata in the Manitoulin area record two distinct transgressive periods. As discussed in Chapter 3, detailed field and petrographic analyses of outcrops has allowed for the division of the Lindsay Formation on Heywood Island into six distinct units: (1) quartz clast dolostone, (2) lower crinoidal dolostone, (3) brachiopod dolostone, (4) stromatoporoid dolostone, (5) upper crinoidal dolostone, and (6) shale-mudstone. These units are considered as facies and are summarized in Table 4. These strata can be grouped into three facies associations that represent deposition in a tropical paleoenvionment along a homoclinal ramp passing seaward from a rocky shoreline that was frequently influenced by storms (Figure 5.1). The three lithofacies associations are: (1) Inner ramp (2) Mid-ramp, and (3) Outer ramp. The Lindsay Formation strata in the Manitoulin area illustrate an overall deepening-upward trend.

The fossil occurrences observed on Heywood and Partridge islands are similar to those observed in other rocky shoreline deposits. For example, tabulate corals, brachiopods and trilobites were found on Precambrian quartzite boulders that are buried in coarse carbonate debris of a late Ordovician to Early Silurian rocky shoreline succession in southwest Hudson Bay, Manitoba (Johnson & Baarli, 1987). Similarly, brachiopods, bryozoans and corals are common in Middle Ordovician rocky shoreline deposits preserved around Quebec City (Harland & Pickerill, 1984). In these deposits, the Precambrian gneiss basement is overlain by arkosic sandstone, and skeletal and shelly conglomerate. Fine-grained limestone fills in cracks and joints between cobbles and boulders, indicating the influence of high energy storms and wave currents (Harland & Pickerill, 1984). A study from Sweden indicates the presence of bivales, brachiopods and rudists on boulders of all sizes and in dense numbers (Surlyk & Christensen, 1974). This detritus was deposited when a shallow sea onlapped the Precambrian gneiss basement and resulted in the formation of an archipelago of islands during Campanian times (Surlyk & Christensen, 1974).

5.2.1 Platformal Setting

The Lindsay Formation is relatively thin on Heywood and Partridge islands, in contrast to the units exposed on the Bruce Peninsula. Thickening of these sediments to the south as observed through the Albemarle core and as reported by Liberty (1969) and Noor (1989) suggest a southward-deepening ramp; a pattern that was clearly maintained throughout most of the Ordovician (Brookfield & Brett, 1988). The facies and facies associations suggest that these sediments were deposited between upper shoreface and below normal storm wave base, on a shallow homoclinal ramp as water levels rose. Two distinct sea level events are recorded by the Upper Ordovician succession on Heywood Island. The initial transgression is marked by the quartz clast dolostone and the second transgressive pulse is clearly marked by the appearance of shale-mudstone (Johnson & Rong, 1989). The conformable succession of strata between the two units represents a long phase of shallow carbonate deposition (Copper, 1978). On Heywood and Partridge islands, the quartz clast dolostone, lower crinoidal dolostone, brachiopod dolostone, stromatoporoid dolostone and upper crinoidal dolostone were deposited on shallow, inner to mid parts of the ramp during the first Ordovician transgression (Table 4). Deeper ramp facies, like the shale-mudstone were deposited in the outer ramp as water levels rose during the second Ordovician transgression (Table 4). The gradational contact between the upper crinoidal dolostone and shale-mudstone unit is marked by a siltstone subunit. The presence of quartz clasts at this contact indicates a brief episode of proximal, intense erosion of a quartzite island during transgression and the associated change to anoxic/dysoxic conditions of the outer ramp environment. The deep water in the outer ramp setting allows for settling of silts and muds out of suspension and is only affected by the heaviest storms (Burchette & Wright, 1992). Stratification of the water column and deep, anoxic conditions helped preserve the graptolites that characterize the shale. The lack of other organisms (except for a few post-mortem transported brachiopods) and bioturbation in the shale-mudstone unit suggests that water levels rose relatively quickly and were not conducive to organism growth.

Facies	Lithology	Sedimentary structures	Biota	Interpretation
1. Quartz clast dolostone	Present on Heywood and Partridge islands and is 0.5-3.0 m thick. Characterized by rounded to subangular boulders up to 3.2 m in diameter. Proportion of quartz relative to dolostone in high, with number of quartz clasts decreasing up-section. Facies is mainly composed of dolomite crystals (>96.5%), which are fine to medium grained with euhedral, subhedral and anhedral crystal forms. Quartz grains compose 1.5% - 3.5% of the sample volume and are mainly monocrystalline, subangular, and measure 0.25-0.5 mm. Fossil fragments comprise 2% of the sample volume. Two rounded quartz arenite rock fragments are polycrystalline. Patches of iron oxide and magnetite coat the grains.	Massive to weakly planar bedded.	Abundant bioclasts include orthoconic cephalopods, crinoids, brachiopods, bryozoans, rugose corals and tabulate corals.	Very shallow, near-shore environment commensurate with a rocky shoreline setting.
2. Lower crinoidal dolostone	Present on Heywood and Partridge islands and is 1.0-3.5 m thick. Subangular to subrounded quartz arenite clasts with the number and size of clasts decreasing up-section. Facies is mainly composed of dolomite crystals (>98%), which are fine to coarse grained with subhedral crystal forms. Quartz grains compose <1.5% of the sample and are mainly monocrystalline, and subrounded to subangular. Rare fossil fragments. One sample contained a rock fragment composed of monocrystalline quartz in a dolomite matrix. Hematite is locally present.	Beds are mainly planar to low-angle and are 10-20 cm thick.	Abundant burrows. Bioclastic debris largely consists of crinoid stems and crinoid ossicles. A small number of bryozoans, cephalopods, brachiopods and stromatoporoids were also identified.	Shallow, inner carbonate ramp.
3. Brachiopod dolostone	Present on Heywood Island only and is 1.0-1.5 m thick. Quartz pebbles are uniformly distributed throughout this unit except in the upper 30 cm of the outcrop where no quartz is visible. This facies is largely composed of dolomite crystals (>98%), which are fine to coarse grained with mainly subhedral crystal forms. Quartz grains compose <1.8% of the sample volume and are monocrystalline, subangular, and measure 1-3 cm. Fossil fragments comprise <0.2% of the sample. Abundant fossil fragments on Shoal Island. Kerogen was identified in the Shoal Island thin sections.	Planar to wavy beds, 5-30 cm thick.	Bioclastic debris largely consists of brachiopods (*Strophomena & Rafinesquina)*. Bryozoans, long broken crinoid stems and crinoid ossicles, algae, gastropods and rugose corals were also identified.	Inner to mid carbonate ramp.
4. Stromatoporoid dolostone	Present on Heywood Island only and is 5.0-100 cm thick. This facies is largely composed of dolomite crystals (>99.5%), which are fine to medium grained with mainly subhedral crystal forms. Quartz grains and fossil fragments compose <0.5% of the sample volume. The quartz grains are 2.5-4 cm in size and are mainly monocrystalline and subangular.	Wavy beds and local hummocky cross stratification.	Sulfidized burrows common towards the top of the unit. Dominated by stromatoporoids, but also consist of minor brachiopods, tabulate and rugose corals.	Mid-carbonate ramp between fair-weather wave base and storm wave base.

5. Upper crinoidal dolostone	Present on Heywood Island only and is 0.5-1.0 m thick. This facies is largely composed of dolomite crystals (>93.25%), which alternate between fine to coarse grained with anhedral and subhedral crystal forms. Muddy dolomite also exists in this unit. Quartz grains compose <5.75% of the sample volume and are monocrystalline, subangular to subrounded, and measure 0.5-3.5 mm. Quartz grains are interspersed evenly, however, the quartz grain size decreases up-section. Some samples contain quartz arenite fragments and rounded and flat kerogen pellets become more common up-section. Disarticulated and articulated fossils characterize this unit. Iron oxide is abundant and coats all grains. Compaction is evident as evidenced by microflames of mudstone protruding into dolostone.	Planar, wavy and hummocky cross stratified beds, 3-17 cm thick.	Pockets of sulfidization and sulfidized burrows. Fossil assemblage consists of fragmented and articulated stems of crinoids, however, some brachiopods, bryozoans and tabulate corals (*Tetradium*) were also identified.	Mid-carbonate ramp between fair-weather wave base and storm wave base.
6. Shale-mudstone	The gradational contact between the upper crinoidal dolostone and shale-mudstone facies on Heywood island is marked by a grey, siltstone subunit, which is 20-40 cm thick. Siltstone subunit contains dolomite crystals comprising >96% and are fine to medium grained with subhedral to anhedral crystal forms. Quartz granules comprise <3.8% of the sample and are monocrystalline, subangular, and measure 0.25-0.75 mm. Fossil fragments represent <0.2% of the rock and are disarticulated. Minor quartz arenite fragments, kerogen, hematite, planar laminae, microflames and mini-ripples were also identified.	Siltstone consists of thin, planar beds, very minor rippled horizons, and small quartz granules. Shale-mudstone facies contains planar bedded and planar laminated black shale.	Sulfidized burrows and sulfidized lenses cover 15-20% of the outcrop. Siltstone subunit consists of minor disarticulated brachiopods. Shale-mudstone facies contains graptolites.	Outer carbonate ramp below normal storm wave base. Possibly in a protected embayment or a lagoonal environment.

Table 4: Description and interpretation of Lindsay facies in the Manitoulin area.

Initially, the carbonate ramp experienced considerable local bathymetric control because of the underlying, irregular Precambrian quartz arenite basement, however, over time, this relief was progressively masked (Grimwood et al., 1999). Deposition of the Lindsay Formation in the Manitoulin area was also affected by a complicated shoreline configuration, with numerous rocky shores, rocky headlands and islands, and sheltered bays. The older strata (quartz clast dolostone, lower crinoidal dolostone) show the basement influence most clearly. Due to the lack of detrital siliciclastics, the ramp became carbonate-dominated (Grimwood et al., 1999).

5.3 Tropical versus Temperate - Water Origin of Trenton Carbonates

Several studies of the Trenton Group and correlative sediments indicate that there was a shift from tropical to temperate conditions in parts of eastern North America during the upper Mohawkian and Cincinnatian (e.g. Patzkowsky & Holland, 1993; Lavoie, 1995; Pope and Read, 1997; Lavoie & Asselin, 1998). The brachiopod-bryozoan-echinoderm dominated strata of the Trenton Group in the Manitoulin area resembles modern cool-water sediments according to Brookfield (1988), where red algae, forams, bivalves and bryozoans are the dominant carbonate particles (James, 1997). This thesis does not support this inference. The strata of the Trenton Group, and especially the Lindsay Formation, represents inner to outer parts of a homoclinal ramp in a warm, shallow, tropical environment. These rocks, including those from the subsurface (Bidwell and Albemarle cores) and from outcrop studies (Heywood and Partridge islands) are characterized by fragmented, articulated and disarticulated cephalopods, gastropods, algae, trilobites, tabulate corals, rugose corals, and stromatoporoids. These components are typical of tropical-water carbonates, and their presence refutes the cool-water carbonate interpretation. In addition, paleogeographic reconstruction of the Upper Ordovician strata place southern Ontario in a tropical setting (Torsvik et al., 2012). The cool-water Heterozoan interpretation of Brookfield (1988) for the Upper Ordovician carbonates of Manitoulin Island could be explained by upwelling. During the Tippecanoe transgression, cool, nutrient-rich upwelling waters may have mixed with near-surface, tropical waters (Grimwood et al., 1999). Prevailing northwesterly winds would have intensified this mixing (Pope & Read, 1997), allowing for the development of the Heterozoan association of bryozoans, echinoderms, bivalves and brachiopods (Grimwood et al., 1999). The Photozoan association survived, but eventually the water conditions may have become too cool for abundant coral and stromatoporoid growth, as observed in the Manitoulin area facies. Patzkowsky & Holland (1993) and Lavoie & Asselin (1998) provided a similar explanation for the deposition of temperate-type carbonates in Cincinnatian time across eastern Laurentia. Future studies need to assess the Trenton strata for evidence of upwelling, such as increases in phosphate content (e.g. Lavoie & Asselin, 1998).

5.4 Provenance of Detritus

The Lindsay Formation mudstones and shales analyzed in this study indicate an andesitic-like source composition based on the ratio of Fe_2O_3/K_2O vs. SiO_2/Al_2O_3. A mafic component is also supported by elevated Sc values compared to NASC. Combined with the high mafic/felsic ratios determined from the study by Sharma et al. (2003), the data indicate that the Lindsay Formation detritus was sourced at least in part by erosion of mafic rock. However, the localized abundance of quartz granules in the sampled mudrocks and the lack of a clearly defined basalt provenance on the Fe_2O_3/K_2O vs. SiO_2/Al_2O_3 plot suggest that the deposits were derived from mixing of both mafic and felsic sources.

A felsic provenance for the Lindsay Formation shales is supported by quartz arenite clasts in the mudrocks, which would have been supplied locally by erosion of the Paleoproterozoic quartz arenite islands breaching the Ordovician sea surface. Additional felsic detritus could have been contributed by erosion of slightly more distal Archean rocks of the Canadian Shield (Johnston et al., 1991). The mafic provenance may be represented by a distal volcanic arc that formed part of the Taconic continental-oceanic arc collision, as proposed by Sharma et al. (2003). The Taconic Orogeny affected the nature and spatial distribution of sediments in the Appalachian foreland basin and intracratonic Michigan Basin. Loading of thrust sheets to form mountains increased erosion and transport of detritus onto the Michigan carbonate platform. Continued loading eventually led to subsidence in the foreland basin, resulting in oversteepening of the carbonate ramp and deposition of shallow water mudstones and siltstones over carbonate strata (Lehmann et al., 1995). The result in the Manitoulin area is the siliciclastic-dominated Blue Mountain shale overlying the Lindsay Formation petroliferous shales and mudstones. However, it is generally accepted that the Lindsay Formation shales were part of the carbonate platform prior to oversteepening and sediment influx (Harris 1984; Hiatt 1985; Macauley et al. 1990). Although the influx of siliciclastic material has been associated with deposition of the overlying Blue Mountain Formation (see Johnson et al., 1992), the Lindsay Formation shale may contain some detritus derived from the Taconic arc rocks. Alternatively, the mafic detritus may simply have come from erosion of more mafic source rocks of the shield.

5.5 Depositional Model

The Ordovician carbonate ramps in southern Ontario formed in a foreland basin setting due to siliciclastic sediment starvation from the Taconic Orogeny. Gentle flexural subsidence and relatively shallow seas along a passive margin were conducive to the growth of these carbonate ramps (Burchette & Wright, 1992). Thick carbonate ramp successions represent “stacks” or “sets” composed of several ramp sequences or parasequences and indicate change in hydraulic, paleoenvironmental and biological conditions during the period of ramp development (Burchette & Wright, 1992). Evidence of ramp successions can be observed in the Manitoulin area and on the Bruce Peninsula (in the Albermarle core) wherein lithofacies are stacked on top of each other and represent inner ramp to outer ramp conditions. The ramp successions during the Upper Ordovician were heavily influenced by two major transgressions that are recorded in the Heywood Island strata.

According to Corcoran (2008) and Grifi (2009), paleohighs were exposed during the early stages of Ordovician transgression based on strike and dip measurements in the field. During the end of the Middle Ordovician, the epeiric sea covered the basement and the lowest lying areas of the quartz arenite inliers (paleohighs). Basement erosion occurred as water onlapped onto quartz arenite inliers during the first transgressive pulse (Corcoran, 2008) (Figure 5.1). As water levels rose, deposition of quartz clast dolostone occurred in near-shore regions and a thick unit of carbonate was also deposited along inner to mid ramp environments. These settings were affected by tropical storms that were able to erode the paleoislands and transport large boulders of quartz arenite along the windward side of the shoreline. Relatively high frequencies of storm events have been inferred for ramp sequences (e.g. Aigner, 1984; Handford, 1986; Calvet & Tucker, 1988; Faulkner, 1988) during carbonate platforms evolution (Burchette & Wright, 1992). According to Burchette & Wright (1992) windward ramps are more frequently affected by storms and have abundant grainstone lithofacies (as observed on Heywood and Partridge islands).

The Bidwell and Albemarle muddy limestone lithofacies were also deposited during the first transgressive pulse between the inner to outer parts of a carbonate ramp, however, they formed on the leeward side of the quartz arenite archipelago. According to Burchette & Wright (1992) leeward ramps have less abundant grainstone facies, are likely to have tabular geometries and show stronger progradation (seaward) or even lower slope angles than the windward ramps. The leeward side of a ramp usually forms a protected embayment setting and is not exposed to high energy waves (Burchette & Wright, 1992) and therefore the deposits usually represent calmer water facies. These facies include packstone, wackestone and mudstone (Burchette & Wright, 1992). The Bidwell and Albemarle units represent the deeper water facies of a seaward – facing ramp.

During the second stage of transgression, sea level rose significantly quickly around the Manitoulin area and eventually drowned some of the paleohighs (Grifi, 2009). Finer grained material in the upper crinoidal dolostone and the shale-mudstone lithofacies on Heywood Island as well as in the cores were deposited during the second pulse of transgression (Figure 5.1). The upper crinoidal dolostone and shale-mudstone unit were deposited close to the subaerially exposed basement, which allowed for erosion of quartz arenite to occur. The presence of quartz grains in the siltstone subunit is likely due to local erosion and reworking of the islands during a particularly stormy season.

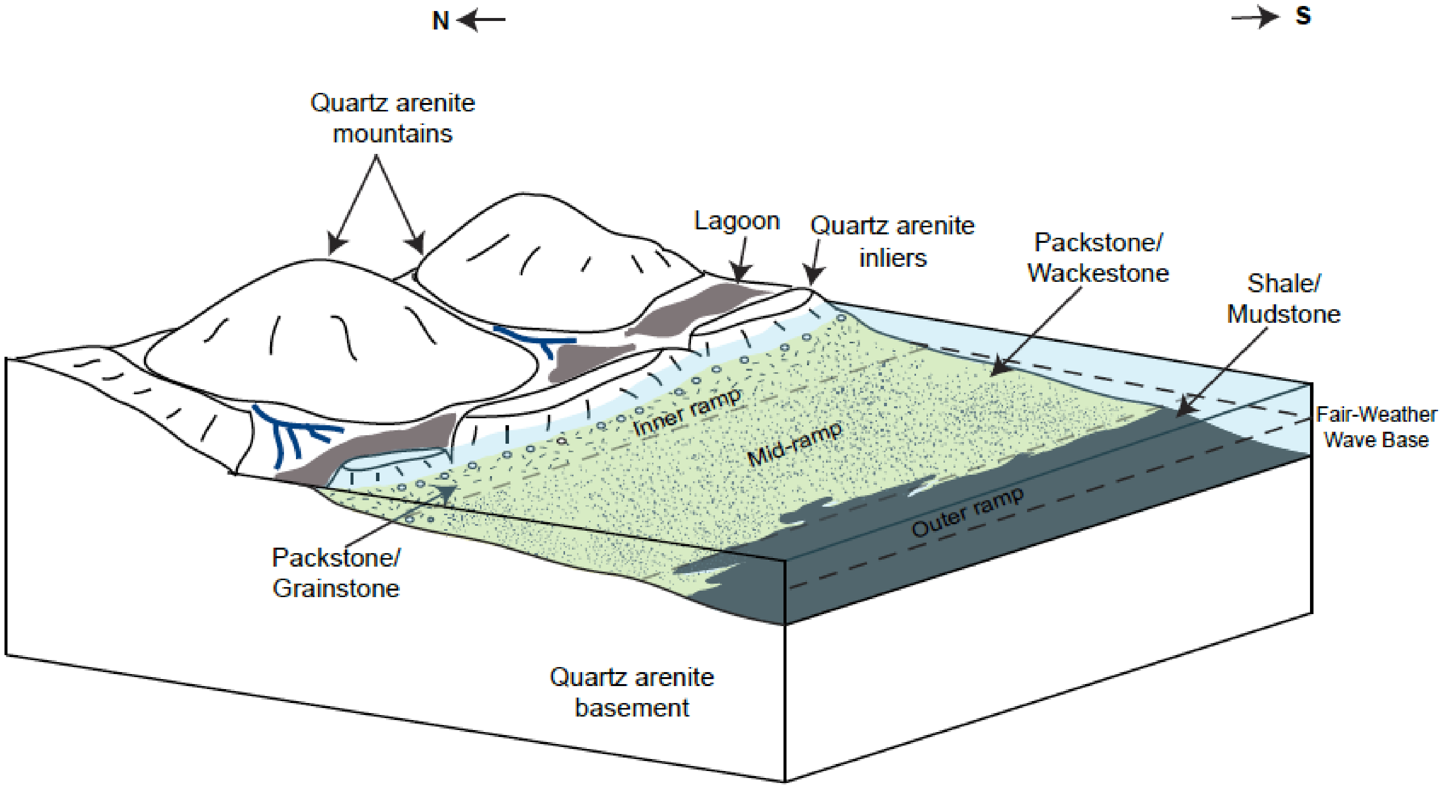

Figure 5.1: A rocky shoreline depositional model for the Manitoulin Island area. The following facies/units were deposited in 1) the nearshore to shallow inner ramp: quartz clast dolostone, lower crinoidal dolostone; 2) inner to mid-ramp: brachiopod dolostone, wackestone; 3) mid-ramp: stromatoporoid dolostone, upper crinoidal dolostone, wackestone-mudstone, crinoidal wackestone-packstone, wackestone-packstone; 4) mid- to outer ramp: mudstone-wackestone, mudstone-siltstone; 5) outer ramp: shale-mudstone, shale, mudstone.

The lack of muddy dolostone units and other organisms on Heywood Island suggests that the shale-mudstone facies in this area was not deposited in a lagoonal environment, but on the windward ramp of the island. In transgressive environments, drowning of high ramp sequences entails a strong retrogradation shift, which may be reflected in thin condensed sections of distinctive facies such as black shales, phosphatic mudstones, or glauconitic or chamositic ironstones (Burchette, 1992). However, the Bidwell and Albemarle cores consist of muddy limestone units, which indicate that the ramp was deepening southwards. The presence of brachiopod and trilobite in the mudstone and shale lithofacies near the Bruce Peninsula suggests that this environment was not as heavily influenced by storm activity as the windward Manitoulin side.

The missing units on Partridge Island may be a result of the inherent nature of self-destructiveness of rocky shoreline environments. This environment results in the non-preservation of sediments due to constant erosional processes that rework material and transport it into deeper water (Harland & Pickerill, 1984).

As a whole, the facies associations exhibit a very broad upward-fining succession from coarse-grained, basal, clastic dolostone to fine-grained organic-rich mudstone. The stratigraphy and sedimentology of the Ordovician ramp in the Manitoulin area reflect the accumulation of sediments in predominantly low-energy environments punctuated by periods of high energy, episodic storm events (Grimwood et al., 1999).

Chapter 6 - Conclusions

The purpose of this thesis was mainly to provide a detailed study of an Ordovician rocky shoreline deposit and its association with overlying carbonate strata exposed on Heywood and Partridge islands in the Manitoulin area of Ontario. The thesis reveals the stratigraphy of the Lindsay Formation on Heywood and Partridge islands, and compares it to the stratigraphy provided from cores of Bidwell Township and Albermarle County. This investigation identifies the faunal characteristics of an Upper Orovician rocky shoreline and characterizes the major and trace element geochemistry of the topmost mudrocks of the Lindsay Formation. The petrographic, stratigraphic, geochemical and sedimentological results are then used to construct a paleodepositional model for the Lindsay Formation in the Manitoulin area.

Heywood and Partridge islands are two localities where a major unconformity between Paleoproterozoic and Upper Ordovician strata is well preserved. Quartz arenite (basement rocks) of the Paleoproterozoic Bar River and Lorrain formations is abruptly overlain by an onlapping succession of Upper Ordovician to Lower Silurian carbonates and shales that record two transgressive pulses of an epeiric sea during that interval of time.

The initial transgression is marked by the quartz clast dolostone facies and the second transgressive pulse is clearly marked by the appearance of the shale-mudstone facies of the Lindsay Formation. The conformable strata between the bottom-most and top-most facies represent a long phase of shallow carbonate deposition. The Lindsay Formation on Heywood and Partridge islands is divided into six distinct facies: (1) quartz clast dolostone, (2) lower crinoidal dolostone, (3) brachiopod dolostone, (4) stromatoporoid dolostone, (5) upper crinoidal dolostone, and (6) shale-mudstone. The Lindsay Formation in cores from Albermarle County and Bidwell Township was divided into 8 facies, all of which have not been dolomitized: i) wackestone-packstone, ii) wackestone, iii) crinoidal wackestone-packstone, iv) wackestone-mudstone, v) mudstone-siltstone, vi) mudstone-wackestone, vii) shale, and viii) mudstone. These strata are grouped into inner ramp, mid-ramp, and outer ramp facies associations that represent deposition in a tropical, homoclinal ramp passing seaward from a rocky shoreline that was frequently influenced by storms. This Ordovician carbonate ramp formed as a result of subsidence associated with the Appalachian Orogen, as well as sediment starvation, which enabled the accumulation of carbonate-rich detritus. The Lindsay Formation strata in the Manitoulin area illustrates an overall deepening-upward trend. The fossils observed on Heywood and Partridge islands are similar to those observed in other rocky shoreline settings.

Major and trace element geochemistry of the Lindsay Formation mudrocks suggests that the detritus was derived from the mixing of both mafic and felsic sources. Felsic provenance of the Lindsay Formation is supported by quartz arenite clasts in mudrock strata that were supplied locally from erosion of Paleoproterozoic quartz arenite islands and distally through erosion of Archean rocks of the Canadian Shield. A distal volcanic arc that formed part of the Taconic continental-oceanic arc collision may have provided the mafic detritus. Alternatively, the mafic component may have originated from the shield rocks to the present north.

The proposed depositional model for the Manitoulin area involves deposition in nearshore-inner ramp to outer ramp settings. The strata show evidence of storm influence near Manitoulin Island and calmer deposition near the Bruce Peninsula area.

This project provides further insight into the conditions that characterize rocky shoreline environments of Late Ordovician age. Future investigations of the carbonate strata flanking quartz arenite islands northeast of Partridge Island to Killarney will provide additional information concerning past rocky shoreline dynamics.

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Curriculum Vitae

Name:	Hiba-tul Naseer Maheen
Post-secondary Education and Degrees:	Western University London, Ontario, Canada June 2015 Masters of Science in Geology
	McMaster University Hamilton, Ontario, Canada 2005-2010 Honors Bachelor of Science in Life Sciences
	McMaster University Hamilton, Ontario, Canada 2005-2010 Bachelor of Science in Earth and Environmental Sciences
Honours and Awards:	Dean's Honors in Science 2004
	Entrance Scholarship at Western University 2010-2012

Related Work Experience

Senior Program Assistant for Aboriginal and Outreach Education
Prospectors and Developers Association of Canada, Mining Matters, 2013-2014
Designed and delivered Mining Matters' Aboriginal and Outreach Education that teaches important geological concepts. Designed mineral posters promoting Canadian minerals and their usage, and geology-based activity books for children between the ages of 5-18. Co-designed educational materials on Ontario rocks and fossils with the Ontario Geological Survey and the Royal Ontario Museum.

Teaching Assistant
Western University 2010-2012
Assisted students in lab sessions, graded exams and essays for first year and third year courses.

Outreach Assistant
Western University 2012
Supervised undergraduate students to gain field knowledge by studying rocks in their field context and using essential background skills to do subsequent analysis in the lab.