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**LITHOSTRATIGRAPHY, SEDIMENTOLOGY AND DIAGENESIS
OF THE UPPER ORDOVICIAN HULL BEDS AND VERULAM
FORMATION, UPPER OTTAWA GROUP, EASTERN ONTARIO**

Jeffrey P. Kiernan

**A thesis presented to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for
the degree of**

Master of Science

**Department of Earth Sciences, Carleton University
Ottawa-Carleton Geoscience Centre**

February 1999

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acceptance of the thesis

**Lithostratigraphy, Sedimentology and Diagenesis of The Upper Ordovician Hull
Beds and Verulam Formation, Upper Ottawa Group, Eastern Ontario**

Submitted by Jeffrey P. Kiernan, B.Sc.
in partial fulfillment of the requirements for the degree of
Master of Science

Thesis Supervisor

Chair, Department of Earth Sciences

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Ottawa-Carleton Geoscience Centre

February 1999

ABSTRACT

The Upper Ordovician Ottawa Group in eastern Ontario is equivalent to the Black River and Trenton groups of adjacent areas and records shallow-marine, epicontinental carbonate sedimentation at the margin of the Taconic foreland basin. Previous studies of the upper Ottawa Group have defined four formations: Bobcaygeon, Hull, Verulam and Lindsay. This present study examines the middle portion of the upper Ottawa Group in detail, and reveals that, although the Bobcaygeon, Verulam and Lindsay formations are regionally mappable lithostratigraphic units, the Hull strata are of local extent and are here redefined as the *Hull Beds*. Lithostratigraphic and biostratigraphic data suggest that the Hull Beds are laterally equivalent to Upper Bobcaygeon strata in eastern Ontario. The Verulam Formation sharply overlies the Hull Beds; their boundary represents a potentially important marine flooding surface. The Verulam Formation is conformably and gradationally overlain by the Lindsay Formation.

Sedimentological analyses of the middle Ottawa Group suggest that the Hull Beds represent inner-ramp barrier-and-lagoon facies, whereas the Verulam strata represent deposition under significantly deeper-water, storm-dominated conditions. The Hull Beds contains six major lithofacies comprising three lithofacies associations, each representing a different depositional setting. Lagoonal environments are represented by micritic mudstone to packstone interbedded with bioclastic grainstone-rudstone washover deposits, and marginal, peloidal sands with minor synsedimentary dolomite. Barrier-top environments included beach to upper shoreface bioclastic and oncolitic sands and gravels, backbarrier calcareous silt flats, and associated sandy/gravelly washover channel fill deposits. The barrier-front environment is represented by wave- and storm-influenced upper to lower shoreface bioclastic sand deposits. The Verulam Formation is characterized by interbedded bioclastic limestone and calcareous shales. Five lithofacies are defined for the Verulam Formation: four of these represent different types of carbonate storm

deposits, and the fifth represents fairweather calcareous shale deposition. Storm bed types include intraclastic, lenticular rudstones; reworked, rippled grainstone; graded grainstone-packstone and very fine packstone to calcisiltite. Hardgrounds, lenticular to wavy bedding and a variety of current- and wave-formed sedimentary structures are preserved in the Verulam tempestites.

The lagoon and barrier-top environments in the Hull Beds are characterized by a *chlorozoan* grain type association (green algae, colonial corals, oncoids, ooids, micrite, etc.) whereas the remainder of the Upper Ottawa Group (including the barrier-front deposits of the Hull Beds) is characterized by a *bryonoderm* grain type association (brachiopods, crinoids, bryozoans, molluscs, solenoporacean algae, etc.). This may suggest that the open marine, middle- to outer-ramp environment was similar to modern temperate carbonate settings, while the contemporary innermost portion of the ramp (barrier-top and lagoon environments of the Hull Beds) was similar to modern tropical carbonate-producing areas. The lack of supporting evidence for cool-water carbonate deposition (e.g., dropstones, high paleolatitude, etc.) suggests that other environmental factors (e.g., salinity, seasonality, etc.) may have played a more important role in determining the distribution of grain type associations.

Burial diagenesis, expressed as sparry cements and pressure-dissolution fabrics, appears to be the predominant agent of alteration of the Hull and Verulam lithofacies. Only the lagoonal deposits appear to contain well-preserved early diagenetic features (e.g., fringing cements and micrite envelopes). Based on geochemical and field characteristics, dolostone bands in lagoon-margin peloidal grainstones are interpreted as the product of overgrowth and replacement of small, syngedimentary, metastable dolomite crystals.

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Chapter 1: INTRODUCTION

1.1 Purpose of study

This thesis examines the stratigraphy, sedimentology, diagenesis and geochemistry of Ordovician inner- to outer-ramp marine carbonate facies preserved in the Upper Ordovician Verulam Formation and Hull Beds of eastern Ontario.

The study has four objectives: (1) to describe the lithofacies of the Hull Beds and Verulam Formation in eastern Ontario and adjacent areas of Quebec; (2) to clarify the lithostratigraphy of the Upper Ottawa Group in eastern Ontario; (3) to propose depositional environments and models for the Hull Beds and Verulam Formation in this region; and (4) describe and discuss general attributes of their diagenesis and geochemistry.

1.2 Study area

The study area is located in southeastern Ontario and adjacent areas of Quebec (Fig. 1.1). A total of forty-one sections were measured from thirty-six localities (Table

1. Klock Quarry	13. Behind Supreme Court Bldg.	25. Beechwood Cemetery
2. Stittsville Roadcut, Hwy. 7	14. Behind Parliament	26. Francon Quarry south
3. Lac des Fees	15. Nepean Point	27. McCarthey Road
4. Pharand & St. Louis	16. Lady Jane Grey Dr.	28. Russell Core
5. Baker Park	17 a & b. Ottawa Rowing Club	29. Castor River
6. Boul. de Maisonneuve	18. Rideau Falls	30. Crysler dam
7a, b & c. Hull Promontory	19. Governor's Bay	31. Laflyshe Farm Quarry
8. Victoria Island	20a & b. Aviation Parkway	32. McLean Quarry
9. Primrose & Lorne	21. Quarry Rd.	33. Plumadore Quarry
10. Lebreton Core	22. Brittany Rd.	34. St. Isadore Quarry
11. Lebreton Street	23. St. Laurent Blvd	35. Clifftondale Quarry
12. Kippewa & Bronson	24. Montreal Rd.	36. L'Orignal Quarry

Table 1.1: Numeric codes for study locations as used on Figures 1.1, 1.2 and 1.3

Figure 1.1: Location of study area and study locations (*marked by asterisks) in eastern Ontario. Dashed box denotes area shown in Figure 1.2. Location numbers listed on Table 1.1 and in Appendix 1.

Figure 1.2: study locations within the city of Ottawa. Dashed box marks area shown in Figure 1.3

1.1, Fig. 1.1, 1.2 and 1.3; Appendix I). Two sections were measured from drill cores of the GSC Lebreton (Loc. 10) and GSC Russell (Loc. 28) wells. Data for a few other locations has been taken from the literature, and is cited where appropriate. Most of the outcrop examined in the course of this study occurs in and around the cities of Ottawa and Hull.

1.3 Geologic setting

1.3.1 The St. Lawrence Platform

The St. Lawrence platform extends from western Newfoundland to the central Great Lakes. It makes up the northern marginal portions of, from west to east the Michigan, Allegheny, Quebec and Anticosti basins (Sanford 1993a). During the late Ordovician, the two western basins were intracratonic (Sanford 1993a), while the two eastern basins (Quebec and Anticosti) are divisions of the Taconic foreland basin (Quinlan and Beumont 1984). Sanford (1993a, 1993b) divides the St. Lawrence platform into three lateral divisions: western (Michigan and Allegheny basins), central (Quebec basin) and eastern (Anticosti basin). The divisions are based both on major structural divides (e.g., the Frontenac and Saguenay arches) and tectonostratigraphic considerations. The present study area lies in the westernmost part of the Quebec basin, in the Ottawa Embayment (Fig. 1.4). The Ottawa Embayment shares tectonostratigraphic characteristics with the Quebec basin, but the Upper Ordovician section is lithostratigraphically similar to the equivalent strata of the Lake Simcoe region (see Melchin *et al.* 1994, Dix *et al.* 1997a and Lavoie *et al.* 1998).

Figure 1.4: Regional geologic setting of the study area. (A) The Ottawa Embayment, and location of major basinal divides. (B) Faults of the Ottawa Bonnachère Graben in the Ottawa Embayment. After Dix *et al.* 1997a, b; Sanford 1993a, b.

(facing page 6)

1.3.2 The Ottawa Embayment

The Ottawa Embayment (Fig. 1.4) is a “closed structural depression” (Sanford 1993a, p. 714) at the westernmost end of the central portion of the St. Lawrence Platform as defined by Sanford (1993a, 1993b). The “embayment” is bounded by three major Precambrian highlands: the Frontenac Arch to the southwest, the Laurentian Arch to the northwest, and the Adirondack dome to the south. The Beauharnois Arch, which completes the structural closure on the east of the “embayment”, is supposed by Sanford (1993b) to be a post-Ordovician uplift although recent studies by Salad Hersi *et al.* (1998) suggest subtle, periodic uplift of this feature during Blackriveran time.

Although Frontenac, Laurentian and Adirondack uplifts are currently expressed as Precambrian exposures, only the Adirondack dome is supposed to have been periodically emergent during the late Ordovician (Kay 1942; Titus 1986). The presence of major outliers of the Ottawa Group (e.g., the area around Braeside, Ontario) demonstrates contemporary submergence of the southern flank of the Laurentian Arch to the northwest of the “embayment”. Although not necessarily emergent, the Frontenac and Laurentian arches, and possibly the Beauharnois arch were important basinal divides during the Ordovician (Sanford 1993a, b; Salad Hersi *et al.* 1998).

A major system of major normal faults runs approximately parallel to the Ottawa River Valley in the study area (Fig. 1.4). Within the study area, the fault systems are the main control on bedrock patterns (Fig. 1.5). Faults are deep-seated (Mereu *et al.* 1986) and define the Ottawa-Bonnechère Graben (Kay 1947), which continues across the Canadian Shield to the northwest as far as the northern shores of Georgian Bay (Sanford 1993a, Kumerapelli 1985). The Timmiskaming Graben, a portion of which contains a

Figure 1.5: Bedrock geology of the study area. After Dix *et al.* (1997)

thick Ordovician-Silurian sedimentary succession, branches off from the Ottawa-Bonnechère Graben near Pettawawa, Ontario to form a triple-point junction. The Ottawa-Bonnechère Graben itself branches off from the St. Lawrence paleo-rift system at another triple-point junction near the confluence Ottawa and St. Lawrence Rivers (Kumerapelli 1985).

The Precambrian exposure of the Gatineau Hills forms the northern boundary of Paleozoic strata in the study area and have been interpreted as a post-Ordovician uplift by Kay (1942). The extent of the late Ordovician sea over the craton to the north and northeast of the study area is unknown. Outliers of approximately Ottawa Group-equivalent rocks occur far into the craton in northern Ontario and Quebec (e.g., Timmiskaming, Lake Waniswipi, Lac St. Jean, Lac Manicougan; see Sanford 1993a). Whether these outliers reflect a complete inundation of the Canadian Shield is unknown. Although Kay (1937) suggested a set of relatively narrow, interconnecting seaways around large island landmasses, it is possible that the shield outliers do reflect extensions of the St. Lawrence or Hudson's Bay platforms, and that the amount of shield exposed during the Ordovician was restricted to a few, rather small islands. The presence of rocky shorelines developed at the contact between Precambrian rocks and upper Trenton-equivalent strata around the northern rim of the Michigan basin (Johnson & Jia-yu 1989) demonstrate that the Upper Ordovician succession does progressively onlap the basement in at least some of the present outcrop belt in Ontario.

1.3.3 Stratigraphic setting

The regional stratigraphic framework used in this study (Fig. 1.6) was recently defined by Williams (1991) and Salad Hersi (1998, reviewed by Dix *et al.* 1997a). The Hull and Verulam formations of eastern Ontario are two of seven formations of the Ottawa Group (see generalized stratigraphic column, Fig. 1.6). The lower three, the Pamela, Lowville and Chaumont formations are of Blackriveran age, and correlative with the Black River Group of Quebec and New York State; they are also equivalent to the lower part of the Simcoe Group in central Ontario. The upper four formations are Rocklandian to Maysvillian in age (see Melchin *et al.* 1994, p. 23 and references therein): the Bobcaygeon, Hull, Verulam and Lindsay formations. These are correlative with the Trenton Group of New York State and Quebec, and the upper part of the Simcoe Group in central Ontario (Melchin *et al.* 1994, Dix *et al.* 1997a, Salad Hersi 1998). The present stratigraphic nomenclature is based on precedents set in the Black River Group of New York State (for the Lower Ottawa Group) and on Liberty's (1967) lithostratigraphic scheme for the Trenton-equivalent Upper Simcoe Group (Salad Hersi 1998, Dix *et al.* 1997a). The term "Hull Formation" is currently in popular use (see Salad Hersi 1998, Salad Hersi & Dix 1997b, Dix *et al.* 1997a). Data presented in this thesis, however, suggests that it is not a regionally extensive, mappable unit and thus does not warrant the rank of formation (NACSN, 1983). For the remainder of this thesis, the strata referred to by Salad Hersi (1998), Dix *et al.* (1997) and Uyeno (1974) as the Hull Formation will be referred to as the **Hull Beds**.

Figure 1.6: Stratigraphic setting. Right-hand column shows the entire Lower Paleozoic succession in the Ottawa Embayment (after Williams 1991, Salad Hersi & Dix 1997a and Dix *et al.* 1997a). The stratigraphy of the Ottawa Group (after Dix *et al.* 1997a, Salad Hersi, 1998 and this study) is shown on the left. In the “Stage” column, R=Rocklandian, K=Kirfieldian, and S=Shermanian.

1.4 Previous work

1.4.1 Stratigraphy and Biostratigraphy

Several stratigraphic schemes have been applied to the Ordovician of the Ottawa Embayment over the past hundred years. Figure 1.7 summarizes the terms used by various workers in eastern Ontario over the past century. Early stratigraphic schemes are impractical to the lithostratigrapher because they are largely based on biostratigraphic divisions. These include the work of Raymond (1912, 1914), Kay (1937) and Wilson (1946a). Raymond (1914) introduced the Hull Formation to describe a unit in the Ottawa area “which...carry the well-known crinoid fauna”. Kay (1937) described this unit as “limestone with shaley partings”, and noted grey, thick, coarse-grained beds in upstate New York. Kay (1937) also described the “Sherman Fall” Formation (equivalent to the Verulam of this study), named from Sherman Falls in the Trenton Gorge of New York. The Sherman Fall Formation was defined by a generally higher content of shale and the abundance of the bryozoan *Prasopora orientalis*. He divided the formation into the Shorenham and Denmark members based on shale content (the lower, Shorenham Member being the more shaley). The upper contact with the overlying Cobourg Formation was noted to be gradational. Most of the formation definitions provided by Kay and his contemporaries rely heavily on the identification of fossil components, and gave only scant lithological descriptions.

Lithostratigraphic formations should not be based on biostratigraphic principles (NACSN, 1986). This problem was recognized by Wilson (1946a), Uyeno (1974) and Salad Hersi (1998). Wilson (1946a) established the Ottawa Formation in eastern Ontario to include the Black-River- and Trenton-equivalent strata situated between the distinctive

Figure 1.7: History of stratigraphic nomenclature for Upper Ordovician rocks in the Ottawa Embayment. X indicates parts of the section not studied.

(facing page 13)

Raymond 1914	Kay, 1942	Wilson, 1946a	Liberty, 1967	Uyeno 1974	Williams 1991	Saadat Herat 1998, Din <i>et al.</i> 1997	THIS STUDY					
Colingwood	Gloucester	Billings	<div></div>	<div></div>	Billings	<div></div>	<div></div>					
	Colingwood	Eastview						<div></div>				
	Picton	Hillier mbr Cobourg							Cobourg FZ	Lindsay	Lindsay	Lindsay
		Hallowell mbr							Sherman Fall FZ	Verulam	Verulam	Verulam
	Trenton	Dennart mbr Sherman Fall							Hull FZ	Bobcay- geon	Hull	Verulam
	Hull	Shore- ham mbr							Rockland FZ	Gull River	Chaumont	Hull Beds Bobcay- geon
	Rockland	Rockland							Lowville FZ	Shadow Lake	Lowville	Lowville
Aylmer	Black River Gp.	Black River Gp.	<div></div>	<div></div>	St. Martin	Hog's Back	<div></div>					
								Leray	Pamelia	Pamelia	Pamelia	Rockcliffe

lithologies of the Chazyan Rockcliffe Formation (a sandstone-dominated unit) and the calcareous, organic-rich mudrocks that cap the section in eastern Ontario (Billings, Carlsbad and Russell formations of Wilson 1946a). Formational names applied by Kay (1937) were re-defined by Wilson (1946a) as informal, faunal zones.

Liberty (1967) attempted to apply lithostratigraphic nomenclature developed in central Ontario (the Simcoe Group of Liberty, 1955) to the present study area. In Liberty's interpretation, the Blackriveran faunal zones of Wilson (1946a) are replaced by the Shadow Lake and Gull River formations. Each of the Trenton-equivalent faunal zones, with the exception of the Hull, are replaced by an equivalent formation. Liberty did not apply the term "Hull", assigning it and Wilson's (1946a) Rockland beds to the Bobcaygeon Formation. The "Sherman Fall" and "Cobourg" faunal zones were replaced by the Verulam and Lindsay formations respectively. Essentially ignoring Liberty's (1967) suggestions, Uyeno (1974) elevated Wilson's (1946a) Ottawa Formation to group status, and the faunal zones thereof to formations. Uyeno (1974) defined only one formation within the Ottawa Group - the Hull Formation. Unfortunately, the definition is based on contacts with completely undefined units: the "Rockland Formation" below and "Sherman Fall Formation" above. Uyeno divided the Hull Formation into two members. His upper member is equivalent to the Wilson's (1946a) Hull and Raymond's (1912) "Crinoid Beds". Uyeno's lower member, which is no longer well exposed, is either equivalent to the Upper Bobcaygeon Formation (Salad Hersi 1998) or is composed of lithofacies H4, H5 and H6 of this study (see Chapters Two and Three). Uyeno (1974) was among the first workers to note the distinctly shale-free nature of the Hull Beds. Williams (1991) did not use term

“Hull Formation”, because Uyeno’s type section (the former Canada Cement Quarry in downtown Hull; now flooded) exposed neither the upper nor lower boundary of the Hull Formation. Williams (1991) used Liberty’s (1967) formation names with redefined boundaries. Sanford (1993b) used a combination of older New York State terminology and a few of Liberty’s (1959, 1967) formation names.

More recently, Salad Hersi & Dix (1997a) have defined the base of the Ottawa Group and proposed a new unit, the Hog’s Back Formation, as representative of the Chazyan to Blackriveran transition. Dix *et al.* (1997a) and Salad Hersi (1998), provided a purely lithostratigraphic framework for the Ottawa Group. These studies contain a revised Blackriveran stratigraphy based on precedents set in New York State, suggesting that the Lower Ottawa Group is lithologically similar to the Parnelia, Lowville and Chaumont formations (see Walker 1973), rather than the Shadow Lake and Gull River formations of central Ontario (see Liberty 1955, 1967). Salad Hersi (1998), Dix *et al.* (1997a) and Salad Hersi & Dix (1997b) recognized the Hull “Formation” as a discrete lithostratigraphic unit and suggested two possible stratigraphic models for the middle part of the Upper Ottawa Group: (1) an interfingering relationship between the Hull and Verulam formations; or (2) Verulam lapping onto a paleotopographic surface at the top of the Hull Beds.

1.4.2 Paleontology

The macrofaunal and conodont paleontology of the Ottawa Group has been extensively studied. The literature is summarized in Table 1.2.

Reference	Study interval	Taxonomic groups
Wilson 1946b	Ottawa "Formation"	Brachiopods
Wilson 1947	Ottawa "Formation"	Trilobites
Wilson 1948	Ottawa "Formation"	Miscellania
Wilson 1951	Ottawa "Formation"	Gastropods, Conularids
Wilson 1956	Ottawa "Formation"	Pelecypods
Fritz 1958	Ottawa "Formation"	Bryozoans
Barnes, 1967	Lower Ottawa Group	Conodonts
Uyeno 1974	Hull "Formation"	Conodonts
Steele-Petrovich 1984	Lower Ottawa Group	All
Mamet & Shalaby 1995	Ordovician	Algae

Table 1.2: Paleontological literature for Ordovician strata of eastern Ontario.

1.4.3 Sedimentology

Compared to the volume of stratigraphic and paleontological literature, little work has been published on the sedimentology of the Ottawa Group. Equivalent strata in New York, central Ontario, and Quebec have received more attention. Dissertations by Sawford (1972), Steele-Petrovich (1984) and Salad Hersi (1998) provided some details of sedimentology and depositional environments, but have dealt primarily with the lower Ottawa Group. Wilson (1946a), Uyeno (1974) and Williams (1991) briefly mentioned that the formations of the upper Ottawa Group were most likely deposited in a relatively shallow, frequently agitated, open marine environment. Latramouille (1971) provided a detailed description of an outcrop of the Hull Beds, with sedimentological interpretations limited by small study area. Dix *et al.* (1997a) pointed out the apparent storm-dominated nature of the Verulam Formation. Kiernan *et al.* (1998) suggested a set of coeval warm- and cool-water environments for the upper Hull Beds.

Sedimentary attributes of equivalent strata outside the study area are worth noting. Brookfield and Brett (1988) described a shoal- and intershoal model for Trentonian

sedimentation in central Ontario, and suggest an overall ramp-like morphology for the Ordovician platform. Brookfield (1988) further suggested that despite paleomagnetic data identifying tropical latitudes (Van der Voo 1988), central Ontario was the site of cool-water carbonate deposition. In southern Quebec, Lavoie (1994) elaborated on this idea as it applies to the Deschambault Formation, a unit equivalent to the Bobcaygeon Formation and Hull Beds. In the south-eastern United States, Patzkowsky & Holland (1993) and Pope & Read (1997) have also noted possible temperate-water affinities of Trenton-equivalent carbonates. Titus (1982, 1986) and Titus & Cameron (1976) have provided sedimentological and biofacies analysis of the Trenton Group of northwestern New York State. The volume edited by Keith (1988) provided numerous small stratigraphic, sedimentologic, diagenetic and petroleum-related studies of Trentonian strata throughout eastern North America. McFarland (1997) has recently described storm-related features in the Verulam Formation of central Ontario.

1.5 Statement of Problem

1.5.1 Lithological descriptions

To date, few studies have provided detailed lithological descriptions of the Upper Ottawa Group. The four major lithostratigraphic units of the Upper Ottawa Group (Bobcaygeon, Verulam and Lindsay formations and the Hull Beds) will each be described using modern terminology.

1.5.2 Depositional environments

More detailed lithofacies descriptions of the Hull Beds and Verulam Formation will be used to reconstruct their environments of deposition. Studies of equivalent strata in Central Ontario (Brookfield 1988, Armstrong 1997, Grimwood *et al.* 1998), Quebec (Lavoie 1995, Lavoie *et al.* 1998) and the eastern United States (e.g., Pope & Read 1998, Patzkowsky & Holland 1993) have suggested that Ordovician carbonate-producing environments in the Appalachian foreland basin may have resembled modern temperate carbonate settings. This possibility is assessed for the Upper Ottawa Group of eastern Ontario.

1.5.3 Lithostratigraphy

Using the lithological characteristics of the four major units, the lithostratigraphy of the Upper Ottawa Group will be revised. Two particular problems will be addressed:

(1) The position of the Hull Beds (Fig. 1.8): The Hull Beds appear to lie between the Bobcaygeon and Verulam formations in the Ottawa area (Wilson 1946a, Uyeno 1974, Salad Hersi 1998), but are not recognizable in the Russell core (loc. 28) (Fig. 1.8). The relationship of the Hull Beds to the Bobcaygeon and Verulam Formations has not been determined, although Salad Hersi & Dix (1997b) have suggested that they may interfinger with the Verulam Formation. Furthermore, the usefulness of the term "Hull Formation" in the formal nomenclature is re-assessed.

(2) The definition and nature of the Verulam-Lindsay transition: Williams (1991) defines the base of the Lindsay Formation as the last (i.e., uppermost) shale bed of greater than 5

Figure 1.8: Placement of the Hull Beds in the Upper Ottawa Group. Two complete sections of the Upper Ottawa Group were measured: LB= Lebreton (core and outcrop, locs. 10 and 11) and RC= Russell core (loc. 28). The Hull Beds are present in the Ottawa-Hull area (represented by Lebreton), but are absent in the eastern parts of the study area (represented by the Russell core). The position of the Hull Beds and the interfingering, gradational relationship between the Verulam and Lindsay formations are fully discussed in Chapter Four.

cm thickness. This definition is difficult to use in the field, and does not appear to correspond to a real lithological change.

1.5.4 Diagenesis and geochemistry

The diagenesis of the Hull Beds and Verulam Formations have never been described. The general diagenetic features are described and discussed in Chapter Five of this thesis. A brief geochemical investigation of dolomite found in two lithofacies of the Hull Beds (H4 and H6) and in burrows in the Verulam Formation is also included. A limited geochemical investigation of shaley beds in the upper Ottawa Group is employed to elucidate their provenance.

1.6 Methodology

1.6.1 Stratigraphy

Stratigraphic sections were measured in a bed-by-bed fashion. Attributes such as colour, texture, grain-size, sorting, grain types, sedimentary structures and bedding style were recorded for each bed along with information about their upper and lower boundaries. Lateral changes in bedding were noted, but not described quantitatively. Paleocurrent measurements were taken from appropriate sedimentary structures when observed (mostly dip azimuths of cross-strata). Paleocurrent measurements were corrected (using a stereonet) for structural dip if greater than 10° from the horizontal. At two locations (Chaudière Bridge and the Laffyshe Farm Quarry; Figs. 1.1 and 1.3), sections were too small to warrant detailed measurement but yielded paleocurrent data,

along with general lithologic attributes. The Francon Quarry (loc. 25) was visited in order to supplement stratigraphic data from Salad Hersi (1998).

The stratigraphic attributes of the two cores are described in much less detailed because bedding was difficult to consistently distinguish (Hull Beds) or too thin (Verulam Formation) to allow detailed measurement in the time available.

1.6.2 Petrography

Samples of limestone and shale were taken from outcrops. Over 270 thin sections were cut from selected samples. Most of the thin sections were stained with a solution of Alizarin Red S and Potassium Ferricyanide in order to distinguish among carbonate minerals (Dickson 1965). A standard petrographic microscope was used to examine the thin sections. Shale samples and cut slabs of limestone were examined under a binocular microscope.

Most of the thin sections were also examined using cathodoluminescence microscopy, with particular attention paid to those thin sections with well-developed cements or dolomite. A Nuclide Luminascope ® was operated at a voltage of 10-12 kV, a 0.4-0.6 milliamperes beam current and at less than 30 millitorr vacuum. A few shale samples and thin sections were also examined under ultraviolet light, but no fluorescence of either carbonate or organic matter was observed.

Several thin sections were polished with 1000-grade grit and lightly etched (0.1% acetic acid for 10-20 seconds) and coated with gold-palladium alloy for examination by scanning electron microscopy (SEM). Carbonate mud, peloids, calcareous algae and

oids were examined in detail. A JSM 6400 SEM, located at Carleton University, was operated at 20 kV with a 0.8 nannoampere beam current. Qualitative geochemical data was obtained during SEM work via a Link EXZ energy-dispersive X-ray spectroscopic system (EDX). Further petrographic images were obtained from the microprobe by electron backscattering (see below).

1.6.3 Mineralogy and Geochemistry

Bulk mineralogy of selected samples was determined by powder X-ray diffractometry (XRD). Samples were crushed in distilled water or acetone and the resulting suspensions poured onto a glass slide and allowed to dry. Qualitative XRD scans were made of about 130 shale samples and about 20 limestones and dolostones using a Phillips PW1710 automated diffractometer. Scans were made between three and seventy degrees 2θ at 0.15 degrees per second with a sample interval time was 0.5 seconds. Copper $K\alpha$ x-rays were produced at 30 keV and 50 mA. Insoluble residues of five limestone samples, obtained by repeated leaching of carbonate from samples with 20% HCl through filter paper, were also scanned in the same manner. Selected samples (both shale and carbonate) were scanned slowly (0.02 degrees 2θ per second) between 28.5 and 32 degrees 2θ in order to examine the position and shape of dolomite peaks.

Carbonate content of selected shale and limestone samples was determined using a carbonate bomb (Müller & Gastner 1971). This provides a fairly accurate determination of total carbonate (within about 5 wt.%), and a good estimate of the relative proportion of slow- and fast-reacting carbonates (i.e., calcite and dolomite).

Ten shale samples, taken from exposures of the upper Bobcaygeon Formation, Hull Beds and Verulam Formation were analyzed for whole-rock geochemistry using X-ray fluorescence (XRF) spectrographic techniques. X-RAL Laboratories in Toronto, Ontario provided analyses for major elements Si, Al, Ca, Mg, Na, K, Fe, Mn, Ti, P and L.O.I. as well as traces Ni, Nb and Cr.

Selected thin sections were polished and coated with carbon, then analyzed by electron microprobe for Ca, Mg, Na, Sr, Fe, Mn and Ba content of bioclasts, dolomites and possible early marine cements. A Camebax MBX automated electron microprobe with four wavelength-dispersive spectrometers and an EDX (energy-dispersive x-ray) spectrometer was used. Absorbed current was 15 nannoamps, measured in a Faraday cup. Counting time was 15 seconds for major elements (Ca, Mg) and 60 seconds for minors (Na, Sr, Fe, Mn and Ba). Electron backscatter images were obtained using a Lamont solid-state BSE system during microprobe analyses.

Chapter 2: LITHOFACIES OF THE HULL BEDS AND VERULAM FORMATION

2.1 Introduction

2.1.1 General statements

The Hull Beds and Verulam Formation are represented in general by eleven lithofacies: six define the Hull Beds, five define the Verulam Formation. In addition, a set of anomalous lithologies are described for the Hull Beds. Lithofacies are defined on the basis of grain types, texture (grain size, sorting, etc.), presence and nature of matrix, bedding style, nature of bed bounding surfaces and internal sedimentary structures. Each lithofacies is presented in this chapter with descriptions of their constituents, sedimentary features and a brief overview of depositional environment (depositional environments are discussed fully in Chapter Three). A graphic summary of the major grain types and their approximate relative abundance is shown in Figure 2.1.

The Hull Beds represent deposition in the innermost portions of a southeasterly-dipping carbonate ramp. Interpreted paleoenvironments include lagoon, barrier-top and barrier-crest. The Verulam Formation represents deeper-water, storm-dominated deposition. Its various lithofacies represent four different types of storm deposit (V1-V4) and interstorm, fairweather mud deposition (V5). The general lithological characteristics and interpretations of each lithofacies are summarized on Table 2.1.

2.1.2 Terminology

To avoid confusion in the lithofacies descriptions and discussion in the following chapters, it is necessary to clarify the meaning of several terms.

Figure 2.1: Distribution of grain-types in defined lithofacies.

Litho-facies	Texture & grain-size	Major constituents	Bedding style	Internal structures	Interp- retation
H1	<ul style="list-style-type: none"> • Rudstone • Bioclasts: 1 to 50 mm, Intraclasts up to 30 cm • Moderately- to poorly sorted 	<ul style="list-style-type: none"> • Bryozoans, brachiopods, echinoderms molluscs (esp. pelecypods), oncoids, Solenopora, green algae and intraclasts 	<ul style="list-style-type: none"> • Tabular when associated with H2 • Steep-sided channels when associated with H5 • Broad lenses when associated with H4 and H6 	<ul style="list-style-type: none"> • Scoured basal contact • Normal gradation • Crude parallel lamination • Cross-stratification 	<ul style="list-style-type: none"> • Gravelly beach (?) to upper shoreface deposits • Storm washover channels • Washover fans
H2	<ul style="list-style-type: none"> • Grainstone • Fine- to very coarse sand-sized • Generally well-sorted 	<ul style="list-style-type: none"> • Echinoderms, bryozoans, brachiopods, Solenopora, molluscs 	<ul style="list-style-type: none"> • Usually tabular • 10-100 cm thick • Thicker beds often result of amalgamation 	<ul style="list-style-type: none"> • Sharp basal contact • Planar-parallel lamination, often with low-angle truncation • 5 to 15 cm high sets of tabular- and trough lamination • <i>Skolithos</i> burrows 	<ul style="list-style-type: none"> • Beach (?) to upper shoreface deposits
H3	<ul style="list-style-type: none"> • Grainstone to packstone • Very fine to fine sand-sized • Moderately sorted 	<ul style="list-style-type: none"> • Irregular peloids, echinoderms, brachiopods, bryozoans, molluscs and minor calcareous silt 	<ul style="list-style-type: none"> • Tabular • 10 to 40 cm thick 	<ul style="list-style-type: none"> • Sharp-based • Planar to wavy parallel lamination • Tabular and trough cross-lamination • Rare HCS and SCS • <i>Skolithos</i>, <i>Helminthopsis</i>, <i>Chondrites</i> 	<ul style="list-style-type: none"> • Lower shoreface • Seaward of H1 & H2
H4	<ul style="list-style-type: none"> • Wackestone, Bafflestone, Packstone • Matrix < 4 μm (micrite) • locally abundant silt- to sand-sized allochems • Coral colonies up to 30 cm 	<ul style="list-style-type: none"> • Micrite, Tetrarium, ostracods, calcareous green algae, pelecypods, ooids (in packstone beds only), gastropods homogenous peloids. 	<ul style="list-style-type: none"> • Tabular • Wackestones & bafflestone: 3 to 100 cm thick • Packstone: <20 cm thick 	<ul style="list-style-type: none"> • Sharp or gradational base • Packstones normally graded with rare parallel- and cross-lamination • Wackestones and bafflestones typically massive. • Bioturbation very light to heavy 	<ul style="list-style-type: none"> • Wackestone & bafflestone: quiet lagoon deposits, located "landward" of barrier represented by H1, H2, H3 and H5. • Packstone: lagoonal storm deposits.
H5	<ul style="list-style-type: none"> • Calcisiltite • less than ~10% sand-sized bioclasts 	<ul style="list-style-type: none"> • Calcareous silt, ostracods, green algae, homogenous peloids (?), <i>Tetrarium</i> 	<ul style="list-style-type: none"> • Wavy and lenticular. • Lenses typically 3-25 cm thick and with up 10's of metres lateral continuity 	<ul style="list-style-type: none"> • Faint parallel lamination • Nodular chert • Sparse <i>Skolithos</i> burrows typical • Rare occurrences of heavy bioturbation 	<ul style="list-style-type: none"> • Deposition of fine abrasion products in slackwater areas on barrier crest
H6	<ul style="list-style-type: none"> • Grainstone to packstones • Well-sorted • Very fine- to fine sand sized 	<ul style="list-style-type: none"> • Homogenous peloids, ostracods, green algae • Minor micrite 	<ul style="list-style-type: none"> • Tabular • 5 to 30 cm thick 	<ul style="list-style-type: none"> • Massive • Occasionally parallel- or cross-laminated 	<ul style="list-style-type: none"> • Lagoon-margin sand accululation on small, wave-formed beaches

Table 2.1: Summary of depositional characteristics and interpretations of lithofacies for the Hull Beds and Verulam Formation. Continues next page.

Lithofacies	Texture & grain-size	Major constituents	Bedding style	Internal structures	Interpretation
V1	<ul style="list-style-type: none"> • Rudstone • 1 to 30 cm intraclasts, medium sand to cm-sized bioclasts • Poorly sorted 	<ul style="list-style-type: none"> • Intraclasts, usually of V3, V4 or V5 • Bioclasts include bryozoans, brachiopods, molluscs & rugose corals 	<ul style="list-style-type: none"> • Lenticular • 10-30 cm thick, up to 10 m long • may grade laterally into lithofacies V3 	<ul style="list-style-type: none"> • Scoured basal contact • Normal gradation • Imbrication of intraclasts 	<ul style="list-style-type: none"> • "Proximal" storm-bed
V2	<ul style="list-style-type: none"> • Grainstone • Medium- to very coarse sand-sized • Well-sorted 	<ul style="list-style-type: none"> • Echinoderms, bryozoans, brachiopods, molluscs, trilobites, intraclasts, broken oncoids 	<ul style="list-style-type: none"> • Lenticular • 5 to 25 cm thick • 5 to 15 m long • Major thickness variation due to large ripple-forms 	<ul style="list-style-type: none"> • Scoured basal contact • Normal gradation (intraclasts concentrated at base) • Coarse-grained ripples and associated cross-stratification • <i>Helminthopsis</i> 	<ul style="list-style-type: none"> • Re-worked tempestite
V3	<ul style="list-style-type: none"> • Grainstone to wackestone, typically packstone • Fine- to coarse-sand sized • Moderately sorted 	<ul style="list-style-type: none"> • Echinoderms, brachiopods, bryozoans, molluscs, trilobites, ostracods, calcispheres, rugose corals • Calcareous silt matrix 	<ul style="list-style-type: none"> • Lenticular, wavy and discontinuous • 0.5 to 40 cm thick • Abrupt lateral changes in thickness common 	<ul style="list-style-type: none"> • Sharp or scoured basal contact • Normal gradation • Planar and wavy parallel lamination • HCS • Low- to moderate angle cross-lamination • Symmetrical and asymmetrical ripples • SVF, <i>Chondrites</i>, <i>Helminthopsis</i> • Hardgrounds 	<ul style="list-style-type: none"> • "Proximal" to "distal" tempestites
V4	<ul style="list-style-type: none"> • Calcisiltite to packstone • silt- to very fine sand-sized • moderately to well-sorted 	<ul style="list-style-type: none"> • Calcareous silt, ostracods, calcispheres, echinoderms, brachiopods, trilobites, bryozoans 	<ul style="list-style-type: none"> • Lenticular and discontinuous • 0.5 to 30 cm thick 	<ul style="list-style-type: none"> • Sharp basal contact • Normal gradation • Wavy to planar lamination • HCS • Low-angle cross-lamination • Ripples • <i>Helminthopsis</i>, <i>Chondrites</i>, SVF 	<ul style="list-style-type: none"> • "Distal" tempestites
V5	<ul style="list-style-type: none"> • Calcareous shale • Clay to silt-sized 	<ul style="list-style-type: none"> • Terrigenous clay and calcareous silt with minor bioclasts (brachiopods, bryozoans, crinoids and ostracods) 	<ul style="list-style-type: none"> • Tabular, but distorted by compaction between early-cemented limestone beds • 0.5 to 10 cm thick, average ~2 cm. 	<ul style="list-style-type: none"> • Sharp basal contact (rarely graded from lithofacies H5) • Parallel laminatio • Carbonate-cemented burrow tubes (<i>Planolites</i>, <i>Chondrites</i>, <i>Phycodes</i>) 	<ul style="list-style-type: none"> • Interstorm, fairweather deposits.

Table 2.1 (continued).

Micrite, calcareous silt and microspar

For the purpose of this study, any material composed of *crystalline carbonate with a crystal size less than four microns* is micrite (Folk 1959). Any other mud-sized carbonate (4-62µm in size) is considered to be calcareous silt (if of apparent sedimentary origin) or microspar (if of apparent diagenetic origin). The term micrite is not used in a genetic sense; it is a grain-size term only.

Peloid types

Two distinct types of peloid are present within the Hull Beds. *Homogenous peloids* are silt- to fine sand-sized, structureless, semi-opaque, dark coloured, spheroid to ovoid grains composed of micrite-sized calcite crystals and exhibiting no internal structure. Homogenous peloids are characteristic of lithofacies H6 (Table 2.1, Fig. 2.1) and are interpreted as either fecal pellets or micritized allochems (ooids? - see Chapter Three). *Irregular peloids* are silt- to medium sand-sized particles with a rounded, but irregular shape composed of more coarsely crystalline calcite (~2 to 20µm crystalline). They display high roundness but only moderate sphericity. These are interpreted micritized bioclasts (see Chapter Three).

Bioturbation styles

Top-down bioturbation refers to a bioturbation pattern in which burrows appear to emanate from only the upper surface of the bed. *Pervasive bioturbation* implies that the bed is thoroughly bioturbated, and the burrows cannot be shown to emanate only from the

upper surface of the bed. Note that pervasive bioturbation need not be heavy. One of the most common, although rather non-descript ichnofossils observed in the study interval are simple, vertical to subvertical, occasionally branching burrows. These simple, vertical forms are referred to by the acronym SVF.

2.2 Lithofacies of the Hull Beds

2.2.1 (H1) Bioclastic and intraclastic rudstone to very coarse grainstone

Composition

Lithofacies H1 (Fig. 2.2 A to D) consists of gravel- to very coarse sand-sized particles. Fragments of bryozoans (ramose, domal and rarely fenestrate forms), brachiopods, echinoderms, pelecypods, *Solenopora*, spongiostromate oncoids (terminology of Peryt 1983a; Fig. 2.2 B, C) and green algae are the major grain types (Fig. 2.2 A, D). Intraclasts are locally abundant, especially in channelized and lenticular beds. Subrounded phosphatic fragments (up to 3 mm across) are present in a few beds. Proportions of major grain types vary from bed to bed. Two major associations are notable in these deposits: a pelecypod-dominated association, which includes bryozoans, oncoids, green algae; and a bryozoan-dominated association which includes brachiopods, echinoderm and *Solenopora* (an ancient equivalent of modern calcareous red algae; Stanley *et al.* 1983). Other grain types include orthocones, gastropods, rugose corals, ostracods, phosphatic brachiopods, tetraiid corals, stromatoporoids and tabulate corals. Homogenous peloids are commonly admixed with the pelecypod-dominated grain-type association (see Fig. 2.4 F). Tabular beds of the bryozoan-dominated association is commonly intergradational in composition (laterally or vertically) with lithofacies H2.

Figure 2.2: Characteristics of lithofacies H1, H2 and H3.

A - Scour surface (solid line) with ~20 cm of sharp relief overlain by intra- and bioclastic rudstone of lithofacies H1. Clasts derived from immediately underlying beds of lithofacies H6. Scour surface outlined in black. Dashed line traces large, almost *in-situ* intraclast. Loc. 1.

B - Rudstone to very coarse-grained bioclastic grainstone of lithofacies H1. Oncoid shown by arrow. Basal surface is a planar scour cutting into parallel laminated medium-grained bioclastic grainstone of lithofacies H2. Note intrusion of coarse-grained material into horizontal (lamination-parallel) crack immediately below the scour to the right of the finger. Is this an early-lithified lamina that has been "spalled off"? Loc. 3.

C - Photomicrograph (crossed polars) of bryozoan-cored oncolite in lithofacies H1. Note ill-defined concentric laminae and spongiostromate texture. Loc. 7c.

D - Photomicrograph (plane light) of lithofacies H1 admixed with homogenous peloids of lithofacies H6. Note well-rounded bryozoan fragment (upper left), green algal fragments (middle right), homogenous peloids and clear, sparry cements. Loc. 3.

E - Plane-parallel and medium-scale trough cross-lamination, lithofacies H2. Loc. 19. Compass dial is 4.5 cm across.

F - Larger-scale, tabular cross-bedding in lithofacies H2. Note half-centimetre wavy lamination in bed immediately above cross-set. Loc. 25. Hammer handle is 32 cm long.

G - Photomicrograph (crossed polars) of lithofacies H2. Note abundant crinoids and bryozoans. Gravel-sized *Solenopora* (s) fragment at top. Loc. 3.

H - Photomicrograph (plane light) of lithofacies H3. Note irregular peloids and partially micritized echinoderm fragments. Loc. 25.

Sedimentary features

Beds of lithofacies H1 occur either as tabular beds of ~20 to 100 cm thickness or as lenses up to 80 cm thick and several to tens of metres long. Beds invariably overlie scoured surfaces, which may be planar or irregular, with up to 30 cm of sharp relief undercutting the underlying beds (Fig.2.2 A, B). Normal gradation of grain-size, from gravel to very coarse sand, is commonly developed. Other structures are crude parallel lamination, tabular and trough cross-stratification. Cross-strata may be laminae (<1 cm thick) or cross-beds (1-3 cm thick). Sorting is generally poor to moderate. Intraclasts tend to be tabular, and are up to 40 cm in length (Fig. 2.2 A). Imbrication of gravel-sized fragments is uncommon. Bioturbation has not been observed in this lithofacies.

Interpretation

Lithofacies H1 was deposited in a high-energy, shallow, probably warm-water environment. It formed on the crest of a (subtidal?) barrier-shoal facies, filled channels incised into lower-energy backbarrier deposits of lithofacies H5 and formed sharp-based washover fans in the lagoon environments represented by lithofacies H4 and H6. See Chapter Three for details.

2.2.2 (H2) Bioclastic, fine- to coarse-grained, well-sorted grainstone

Composition

Lithofacies H2 is characterized by abundant crinoid debris with fragments of bryozoans and brachiopods (Fig.2.2 G). Trilobites, pelecypods and gastropods are locally

important. *Solenopora* is a major constituent of some beds. Ostracods, phosphatic brachiopods, small rugosan corals and orthocones are also common. Green algal fragments are present in some beds. Irregular peloids are locally abundant, especially where this lithofacies grades into lithofacies H3. Quartz silt to fine sand comprises up to 5% of rock volume.

Sedimentary features:

Beds are typically tabular and sharp-based, commonly overlying scours. Bed thickness ranges from 10 to 100 cm, with an average of 15-25 cm (Figs. 2.2 E, F, 2.7 E). Thicker beds commonly contain internal scours and less well-defined internal boundaries, indicating amalgamation of units on a scale of 5 to 20 cm. At some localities, bedding is lenticular and forms metre-thick packages of 10-20 cm thick by 1-5 m long amalgamated lenses. Beds may be normally graded. Physical structures are dominated by crude- to well-developed parallel, planar lamination (Fig. 2.2 E). Parallel laminae are commonly arranged in centimetre-scale sets that truncate one another at a low angle. Small- to medium-scale, trough- and tabular cross-lamination (Fig. 2.2 E) is also common, though less abundant than parallel lamination. Bidirectional pairs of cross-sets ("herringbone"-like) cross-lamination is rarely present. Tabular cross-bedding (cross strata 1-2 cm thick, sets up to 40 cm high) is uncommon (Fig. 2.2 F). Sorting is good to excellent. Trace fossils are common but rarely abundant. Small *Skolithos* burrows are common and may be abundant. *Helminthopsis* and *Chondrites* are rare.

Interpretation

Lithofacies H2 formed in a high-energy, shallow-water, warm- or cool-water environment. It represents a beach to upper shoreface environment on the crest and front of the barrier-shoal mentioned above. See Chapter Three for details.

2.2.3 (H3) Peloidal very fine-to medium-grained packstone-grainstone.

Composition

Dominated by irregular peloids, typically of very fine- to fine-sand size (Fig 2.2 H). Most of the identifiable bioclasts are small (very fine to fine sand, occasionally up to 2 mm) echinoderm plates and ossicles, with disarticulated ostracod valves and larger fragments (up to ~5 mm) of brachiopods, trilobites and ramose bryozoans. The matrix consists of 10 to 40 μ m-sized microspar and calcareous silt and constitutes up to about 10% of thin sections. This lithofacies is intergradational in composition with lithofacies H2.

Sedimentary features:

Beds are invariably tabular and 10 to 40 cm in thickness. Tabular- and trough cross-stratification are present, but not as common as in lithofacies H2. Planar to wavy parallel lamination are the most common sedimentary structures. Hummocky and swaley cross-stratification are rare. Asymmetrical (combined flow?) ripples are rarely present on top of some beds. Sorting is moderate to good. Bioturbation is sparse or not present.

Helminthopsis is commonly present but rarely abundant on the upper surfaces of beds.

Simple vertical burrow-forms (SVF) are also common, whereas *Chondrites* and *Skolithos* have been recorded from only a few beds. Burrowing is generally “top-down” in style.

Interpretation

Lithofacies H3 represents lower shoreface deposits located on the seaward flank of the barrier. See Chapter Three for details.

2.2.4 (H4) Micritic mudstone-wackestone to packstone

Composition:

Lithofacies H4 is characterized by the presence of a micritic matrix (Fig. 2.3). This matrix may have a vague peloidal fabric, with faint, irregular clots or mottles up to 200 µm across. The most important grain types are *Tetradium* corals (Fig 2.3 A, B), ostracods, green algae (both udotacean and dasycladacean; Fig.2.3 C, H), bryozoans (domal, ramose and fenestrate forms) and pelecypods. Other bioclast types include trilobites, gastropods, echinoderm ossicles, phosphatic and articulate brachiopods, serpulid worm tubes, tabulate corals and stromatoporoids. Ooids are present in some of the grainier beds (Fig. 2.3 D, E, G), and are a dominant grain type when present. Homogenous peloids are also common in the grainier beds. Terrigenous material (quartz and illitic clays, as revealed by XRD of insoluble residues) comprises up to 30% of the rock by weight.

Figure 2.3: Characteristics of lithofacies H4.

A - *Tetradium*-rich ?bafflestone (b) and micritic mudstone-wackestone (m-w). Loc. 1. Hammer handle is 32 cm long. Light coloured mottles in ?bafflestone bed are spar-filled voids after *Tetradium* colonies.

B - Photomicrograph (crossed polars) of *Tetradium*-rich ?bafflestone. Note lack of micrite envelope around the spar-filled walls. Pale spot in lower left coralite and spar-filled patch in central coralite represent the trace fossil described by Yang (1989). Loc. 2.

C - Photomicrograph (plane light) of micritic packstone. Broken, unidentified molluscan fragments, homogenous peloids and large dasycladacean algal fragment present. Loc. 2.

D - Photomicrograph (plane light) of ooids and molluscan fragments in micritic packstone. Note apparent boring penetrating the core of the upper left ooid (arrow). Loc. 1.

E - SEM photomicrograph of ooid set in micritic packstone. Dashed line separates ooid from matrix. Loc. 1.

F - SEM photomicrograph of micrite at high magnification. Note fine crystal size and presence of subhedral clay. Loc. 1.

G - Photomicrograph (crossed polars) of apparent cryptalgal lamination in ooid-bearing (upper right), micritic packstone. This is not an oncoid - the laminae truncate against underlying spar-filled fossil void (just above scale bar, lower right). Loc. 1.

H - Photomicrograph (crossed polars) of well-preserved green algal fragment (left) and spar-filled, articulated ostracod (right) in micritic mudstone, Loc. 1.

Sedimentary features:

A range of depositional textures are present within this lithofacies. It includes massive, sparsely fossiliferous (*Tetradium*, ostracods, green algae; Fig. 2.3H) mudstone-wackestone to an oolitic-bioclastic (pelecypod, bryozoan, green algae, echinoderm, *Tetradium*) packstone (Fig. 2.3C, D, G). *Tetradium* colonies are abundant enough in places to impart a baffestone texture (Fig. 2.3 A). Bioclasts are whole to disarticulated. Bed thicknesses range from 3 to 100 cm (Fig 2.3 A). Grainier beds are usually less than 20 cm thick; only the mudstones and baffestones attain thicknesses of 50-100 cm. Some of the packstone beds are parallel laminated, and may have small ripple marks ($h=1$ cm, $\lambda=5$ cm) on their upper surfaces. Grainier beds may also exhibit normal textural gradation. Bioturbation (SVF and *Chondrites*) tends to be pervasive in muddy beds, and top-down in grainier beds. Extent of bioturbation is typically moderate to high. A peculiar, unnamed burrow is present within the coralites of many *Tetradium* colonies. It is recognizable in thin section either as a circular zone of pale, oriented micrite or a spar-filled tube with a narrow halo of pale micrite (Fig. 2.3 B). A more thorough description of this ichnofossil is provided by Yang (1989). Colour is dependent on terrigenous content: the pure limestones are creamy white, and those with more than about 10% terrigenous material take on a blue-grey colour.

Interpretation

Lithofacies H4 represents warm-water lagoon deposits located "landward" of the barrier. Wackestones and mudstones represent quiet, fair-weather deposits, while sharp-

based, graded oolitic packstone beds represent storm deposits. See Chapter Three for details.

2.2.5 (H5) Calcisiltite

Composition:

Calcisiltites in the Hull Beds are composed of medium- to coarse-silt sized (~30-60µm) peloids and other unidentifiable carbonate fragments cemented by crystalline microspar. Larger, sand- to small gravel-sized fossil fragments, comprising up to 25 % of the rock by volume, include gastropods, ostracods, trilobites and echinoderms. Many fossils are silicified (particularly echinoderm fragments), and nodular to banded chert is common.

Sedimentary features:

Bedding is typically 5 to 25 cm thick, and usually is in the form of long, narrow lenses (Fig.2.4 B). At two localities (locs. 13 and 19), 20-40 cm thick, homogenous, bioturbated beds of this lithology are present (Fig. 2.4 A). Beds have sharp bounding surfaces, and may be separated by thin, clay-rich fissile partings. A faint, approximately horizontal or slightly wavy lamination is commonly preserved in the calcisiltites. Beds usually occur in 0.4 to 2 metre-thick packages. Steep-sided, scour-based channel forms are filled with material resembling lithofacies H1 or H2 (Fig. 2.4 A, B above fieldbook). These channels may be large (up to 1 m wide and 50 cm deep) and widely spaced (as at St. Laurent Blvd. and Governor's Bay) or small (10-50 cm wide and less than 10cm deep)

Figure 2.4: Characteristics of lithofacies H5, H6 and V1.

A - Homogenous, thick bed of calcisiltite (lithofacies H5). Lenticular, grainstone-filled (lithofacies H2) channel (Ch). Loc. 19. Field book is 19 cm long.

B - Thinner, wavy-bedded calcisiltite (H5). Note large rudstone-grainstone (H1)-filled channel (outlined in white). This channel-fill is largely cemented by silica and dolomite (see Chapter Five). Loc. 23. Hammer handle is 32 cm long.

C - Photomicrograph (crossed polars) of homogenous peloidal grainstone (H6). Stylolite cuts green algal and crinoid fragments. Loc. 1.

D - Photomicrograph (plane light) of lithofacies H1 and H6 mixture. Intraclast on right is of H6, and homogenous peloids are disseminated among the coarse sand. Loc. 1.

E - Photomicrograph (crossed polars) of homogenous peloids apparently lining a burrow (outlined in white). Lithofacies H1. Note well developed micrite envelope on pelecypod fragment (centre, immediately below burrow). Loc. 3.

F - Photomicrograph (plane light) of oolitic grainstone. Note euhedral cements and poorly-defined internal fabric of ooids. Loc. 2.

G - Intraclastic rudstone, lithofacies V1. Note imbrication of intraclasts, suggesting paleoflow from right to left. Loc. 15. Hammer handle is 32 cm long.

H - Channel-fill of lithofacies V1. Note distortion of beds underlying channel by compaction. Loc. 16.

and densely packed (Hull Promontory). These channels contain abundant intraclasts of lithofacies H5. With the exception of two thick, bioturbated beds at locs. 13 and 19, burrows are sparsely but pervasively distributed. Elongate (up to 5 cm deep), solitary *Skolithos* burrows and SVF are the characteristic trace fossils.

Interpretation

Lithofacies H5 was deposited in a low-energy, shallow-water, probably warm setting. It is interpreted to represent deposition in slackwater areas on the barrier crest. The source of calcareous silt is abrasion of bioclastic material on the higher-energy environments of the barrier crest. See Chapter Three for details.

2.2.6 (H6) Homogenous Peloidal Grainstone-Packstone

Composition

Beds are composed of very fine- to fine sand-sized, homogenous peloids (Fig. 2.4 C, D). Sand-sized bioclasts, mostly ostracod carapaces and green algae with rare echinoderms and bryozoan fragments, comprise about 15 % of thin section area. Up to 30% of thin section area in this lithofacies is composed of quartz sand (silt- to fine sand-sized). Sandstone laminae, up to 1 cm in thickness, are uncommon. Where present, the matrix is composed of grey-brown micrite. As mentioned above, homogenous peloids are admixed with gravelly deposits of lithofacies H1 in some beds (Figs. 2.4 D, E).

Sedimentary features

Beds are sharp-based and tabular, ranging from 5 to 30 cm in thickness. They are massive, parallel laminated or cross-laminated (Fig. 2.2 A, 5.3 C, E). Sorting is usually excellent and these beds generally matrix-poor (zero to 10 % micrite matrix). Burrowed surfaces are common; bioturbation is light and *Chondrites* is the only trace fossil identified. Beds are partially dolomitized at two localities (see below; Fig 2.4 D, E). The fabrics and characteristics of the dolomite are discussed in section 5.3 of this thesis.

Interpretation

Lithofacies H6 is interpreted as representing a shallow-water, constantly agitated environment located along the margins of the lagoon represented by lithofacies H4. The homogenous peloids represent either faecal pellets or micritized allochems (ooids?). See Chapter Three for details.

2.2.7 Anomalous lithofacies and variations

Anomalous lithologies have been observed in the Hull Beds at particular locations. They are listed here and briefly described.

Oolitic grainstone

A single, tabular, 18 centimetre-thick bed of very fine-grained, tabular cross-laminated, oolitic grainstone is present at the top of the Highway 7 roadcut (loc. 2). Partially to heavily micritized ooids dominate the bed, and are accompanied by

pelecypods, echinoderms, bryozoans and codeacean algae. Most of the grains have a thin, *Girvanella*-like cyanobacterial coating. (Fig. 2.4 F).

Sandy grainstones

Many beds exposed at the Klock Quarry (loc. 1) resemble lithofacies H6 but have anomalously high (up to 50 %) concentration of subangular, very fine, quartz-dominated sand. Unaltered microcline and plagioclase are minor components. Quartz sand and silt rarely makes up more than 5 % of these lithologies in other locations.

Quartz Arenite

Two 10 centimetre-thick bed of quartz arenite are present at 54.1 m depth in the Lebreton Core (loc. 10). The sand is well-sorted, subrounded and coarse-grained. A weak reaction to 10% HCl suggests a calcareous cement.

Dolostone

At two horizons in the Klock Quarry (loc. 1) and at one at the Highway 7 roadcut near Stittsville (loc. 2), certain beds of lithofacies H2, H4 and H6 are partially dolomitized (see Fig. 5.3). These dolostones will be discussed in Section 5.2.

Shale

Shales are uncommon in the Hull Beds. Thin (5-20 mm) shaley partings occur between some beds of H3, H4 and H5. Shale beds of 1-3 cm thickness occur at a few localities.

The only thick shale unit observed in the Hull Beds is at the base of the section at the Klock Quarry (loc. 1). This pale grey claystone is 17 cm thick, is thinly laminated (~0.5 mm laminae) and has the lowest carbonate content of any rock measured in this study (13% carbonate by volume). This bed has been interpreted by Kolata *et al.* (1996) and by W. Ward (*pers. comm.*, 1998) as an illitized volcanic ash layer.

2.3 Lithofacies of the Verulam Formation

Lithological variation within the Verulam Formation is described as five lithofacies: four are varieties of intraclastic to bioclastic limestone (V1-V4), and one is calcareous shale (V5). The four limestone lithofacies form an effectively continuous spectrum of lithologies from V1 (intraclastic-bioclastic rudstone) through V2 and V3 (bioclastic packstones and grainstones) to V4 (very fine-grained bioclastic packstone to calcisiltite).

2.3.1 (V1) Intraclastic and bioclastic rudstone

Composition

Dominated by intraclasts and large bioclasts. Intraclasts are usually tabular, angular to subangular blocks, 1 to 30 cm long, and up to several centimetres thick (Fig.

2.4 G). Smaller, rounded intraclasts also occur. Intraclasts are typically of lithofacies V3 or V4. Clasts of shale (V5), ranging from a few millimetres to several centimetres in length, also occur (see Fig. 5.1 B). Gravel- to cobble-sized bioclasts include domal bryozoans and orthocones. Finer gravel-sized bioclasts (generally less than 1 cm) include brachiopods, gastropods, pelecypods and rugosan corals. Coarse-grained, moderately sorted bioclastic sand forms a matrix to the rudstone.

Sedimentary features

Bedding is invariably lenticular, each lens being about 10-30 cm thick and two to ten metre in length. As the beds thin at their extremities, they may grade into “wings” of medium- to coarse-grained grainstone/packstone as they pinch out (Fig. 2.4 H). The lower contact of each lens erosionally truncates the beds lying immediately below. Lenses commonly show a weak normal gradation in both average grain-size and texture (i.e., rudstone grading into floatstone). Gravel- and cobble-sized fragments are commonly imbricated, especially at the base of the beds (Fig. 2.4 G). Intraclasts may be extensively bored (*Trypanites*), even if not exposed at the top of the beds.

Interpretation

Lithofacies V1 represents deposition under the influence of an episode strong, unidirectional current action. It is interpreted as a relatively “proximal” storm deposit (tempestite) deposited in tens of metres of water on an open-marine ramp. See chapter three for details.

2.3.2 (V2) Medium- to very coarse-grained, well-sorted grainstone

Composition

Lithofacies V2 (Figs. 2.5 A, B) is dominated by crinoids, bryozoans and brachiopods with subordinate trilobites, molluscs small rugosan corals and intraclasts. Gravel-sized intraclasts and bioclasts may account for ~20 % of the bed by volume. Intraclasts are usually of obvious local origin. Broken, abraded oncoids (damaged, but otherwise identical to those described for lithofacies H1) are common, but never abundant (Fig. 2.5 B).

Sedimentary features

Beds are irregular lenses, 5 to 25 cm thick and show considerable lateral variation in thickness along their length. Lateral extent ranging from five to fifteen metres. Basal surfaces usually scour into underlying strata. Gravel fraction is concentrated in the lower few centimetres. Apart from this basal lag, very weak normal grading is typical and the beds are very well-sorted. The most striking features of this lithofacies are large, symmetrical to asymmetrical ripples commonly developed on the upper bedding surfaces (Fig. 2.5 A). Ripples are round-crested, with slightly sinuous and rarely bifurcating crest-lines. Asymmetrical ripple profiles are more common than symmetrical. Internal cross-lamination is difficult to see, but when observed in symmetrical forms it is *en echelon*, whereas asymmetrical forms may contain one or more cross-sets. This implies that the preserved rippled surfaces are commonly reworked from previously rippled sediment. Ripple amplitudes range from 5 to 12 cm, with wavelengths of 50 to 120 cm. Smaller

Figure 2.5: Characteristics of lithofacies V2 and V3.

A - Course-grained ripples at two levels in lithofacies V2 at the Victoria Island roadcut, Ottawa (loc. 8). Rippled beds outlined in white. Fieldbook is 27 cm long.

B - Photomicrograph (crossed polars) of broken oncolite in lithofacies V2. Brachiopod fragment forms core of oncolite. Loc. 8.

C - Lenticular, discontinuous beds of lithofacies V3 interbedded with thin shales (V5). Loc. 16.

D - Lenticular beds of lithofacies V3 set in a relatively thick shale (V5). Loc. 15.

E - Photomicrograph (crossed polars) of moderately-sorted, medium-grained grainstone (V3). Note dolomitized burrow-fill (see Chapter Five). Loc. 32.

F - Wavy lamination in fine-grained packstone (lithofacies V3; below pencil). Pencil is 14 cm long. Loc. 16.

G - *Helminthopsis*-like, horizontal burrow/furrow networks. Sparse network on top of bed of lithofacies V4 (left) and dense network on top of bed of lithofacies V3 (right). Hammer handle is 32 cm long. Loc. 8.

H - Flattened *Chondrites* burrows preserved on top of calcisiltite bed (lithofacies V4). Coin is 14 mm in diameter. Sample from loc. 8.

ripple forms may be present within ripple troughs. Bioturbation (SVF and *Chondrites*) is usually light with the exception of the upper bedding surface where sparse to dense, horizontal networks *Helminthopsis*-like burrows/furrows are common (Fig. 2.5 G, right side of photograph). A hash of very large pelmatozoan ossicles (up to 2 cm in diameter), brachiopod valves, ramose bryozoan twigs, gastropods and trilobite debris is common on the upper surface of beds.

Interpretation

Lithofacies V2 is interpreted as representing episodically reworked storm beds, deposited in tens of metres of water on an open-marine ramp. The agent of reworking may have been incoming swell-waves, tsunamis or minor storms. See Chapter Three for details.

2.3.3 (V3) Coarse- to fine-grained packstone-grainstone, rarely wackestone

Composition

This lithofacies is dominated by crinoid, brachiopod and bryozoan fragments with abundant ostracod and trilobite fragments (Fig. 2.5 E). Pelecypods and gastropods are locally important. Less abundant bioclasts are calcispheres, orthocones and small rugosan corals (typically unbroken). Locally derived intraclasts and shale-chips are common (but not abundant), and may be several centimetres in length. Small broken oncoids are uncommon, but present. Matrix, present as calcareous silt and/or microspar, makes up

zero to ~35 % of thin sections, imparting a range of depositional textures from grainstone through packstone (most abundant) to wackestone.

Sedimentary features.

Bedding is lenticular to discontinuous and/or wavy (Figs. 2.5 C, D). Bedding ranges in thickness from less than 1 to 40 centimetres (average ~4-12 cm), and is continuous over distances of 1 to ~100 metres. Shorter (10-50 cm) lenses (probably channels) are rarely present (Fig. 2.5 D). Lateral changes in grain-size, texture and structure are common, usually across low-angle surfaces, suggesting amalgamation of beds. Basal surfaces of beds are typically sharp and erosional, although sole marks have not been observed. Load casts are present in places where beds overlie thicker shales (lithofacies V5). Most beds are normally graded. Sorting ranges from poor to good. Sedimentary structures are abundant and well-developed. Planar and wavy parallel lamination are the most common structures observed (Fig. 2.5 F). Waviness of laminae is typically 0.5 to 3 cm in amplitude and a few decimetres in wavelength. Small- to medium-scale, low- to-moderate angle cross lamination is also common. Ripple and dune profiles are rarely preserved, but may exist as isolated swellings in beds, up to 8 cm high and 40 cm long. Lamina thickness in planar-, wavy- and cross-laminated beds tends to be consistent within a bed and ranges from 0.5 to 3 mm (cross-bedding, with individual cross-strata up to 2 cm thick, is rarely present in some of the thicker beds). Hummocky cross-stratification (HCS; Walker & Plint 1993) is occasionally well-developed (gradationally with planar- and wavy-lamination) in finer-grained strata. HCS-like

structures occur in some fine- to medium-grained beds. These structures differ from true HCS (as described by Walker & Plint 1993) in several respects: (1) they have a shorter hummock spacing (15-50 cm), (2) swales are usually wider than hummocks, (3) swales are deeper than hummocks are high and (4) lamina thickness increases into the swales. Small-scale, straight-crested to slightly sinuous ripple trains ($h \sim 1$ cm, $\lambda \sim 5$ -10 cm) are uncommon, but have been observed on the upper surface of some beds. These ripples may be asymmetrical or symmetrical in profile. Symmetrical forms may contain either bidirectional or unidirectional cross-lamination, suggesting a combined-flow origin. Biogenic structures include SVF, *Chondrites* (Fig. 2.5 H), *Helminthopsis*, *Planolites/Paleophycus* and rare *Diplocraterion*. *Trypanites* (Fig. 2.6 B, C) is present in some localities (see below). Bioturbation is very light to moderate, and is “top-down” in style.

Upper surfaces of these beds may be either smooth or irregular. When smooth, a hash of crinoid and brachiopod debris or a sparse encrustation of *in situ* bryozoans and brachiopods may be present. *Helminthopsis*-like burrows are common on the smooth-topped beds, but rarely form a dense network. When the upper surface is irregular, bioclastic debris is concentrated in topographic lows, while the topographic highs are clear of debris, dark-stained (ferromanganese oxides?) and bored (*Trypanites*). The topographic highs tend to form “plateaus”, tens of square centimetres in area and 0.5 to 1.5 cm above the lows, and are interpreted as patchy hardgrounds (Fig. 2.6 A, B).

Figure 2.6: Characteristics of lithofacies V3 and V4

A - Dark-coloured, ferromanganese oxide staining on irregular upper surface (hardground?) of medium-grained packstone (V3). Loc. 17a. Pen is 14 cm long.

B - *Trypanites* borings penetrating an apparent hardground surface developed on lithofacies V3. Loc. 11. Lens cap is 5.5 cm in diameter.

C - Photomicrograph (crossed polars) of dolomitized *Trypanites* boring (edge defined by dashed line). Note truncation of brachiopod fragment. Boring filled by dolomite. Loc. 11.

D - Photomicrograph (plane light) of mollusc-rich calcisiltite (V4). Note lack of micrite envelopes on gastropod and pelecypod fragments. Loc. 15.

E - Hummocky cross-stratification (HCS) in very fine-grained packstone (V4). Loc. 15.

F - HCS-like structure in fine-grained packstone. Note short "wavelength". Loc. 17a. Pencil is 14cm long.

G - Unnamed stellate trace-fossil, lithofacies V4. Note *Helminthopsis*-like horizontal trace (upper left). Loc. 8. Coin is 29mm across.

H - Possible "oyster bed" on bed of lithofacies V4. Loc. 8. Lens cap is 5.5 cm in diameter.

Interpretation

Lithofacies V3 shows typical features of limestone storm deposits (e.g., Sami & Desrochers 1992, Aigner 1985). These beds were deposited in tens of metres of water on an open-marine ramp. Their general depositional setting is probably more “distal” than either lithofacies V1 or V2. It contains a mixture of locally (winnowed) and distally (transported) derived sand-sized grain. See Chapter Three for details.

2.3.4 (V4) Very fine-grained grainstone-packstone and calcisiltite

Composition:

This lithofacies is composed of calcareous silt and microspar with scattered sand-sized bioclasts. Bioclasts are similar in type and relative abundance to lithofacies V3, although calcispheres and whole to disarticulated gastropod and pelecypod fragments are often abundant. Even in thin section, it is difficult to distinguish the comminuted bioclastic silt from the microspar cement that binds it (Fig 2.6 D).

Sedimentary features:

Beds are 1 to 30 cm thick, averaging about 5 cm, and are discontinuous to lenticular. Bases are sharp or stylolitic. Sorting is good to excellent and normal gradation is common, with larger bioclasts concentrated in the lower part of the beds. The beds are either massive or planar to wavy parallel laminated. Both true HCS and HCS-like forms similar to those described above are present, ranging in wavelength from 15 to 80 cm, and in amplitude from 2 to 5 cm (Fig. 2.6 E, F). Very small-scale, unidirectional ripple cross-

lamination is rare. Bioturbation is generally absent throughout the thickness of the beds, but the upper surfaces may have dense networks of *Helminthopsis*-like traces. A single, small, stellate trace (Fig. 2.6 G) has also been observed, but is of unclear affinity (R. Pickerill, pers. comm., 1998). An apparent “oyster bed” (a group of several pelecypod-shaped impressions) been observed at one location (Fig. 2.6 H). Flattened *Chondrites* occur on bedding planes, suggesting that burrow network was dominated by horizontal elements.

Interpretation

Lithofacies V4 represents the most “distal” of the Verulam storm-bed types. It contains a higher proportion of material winnowed from the interstorm deposits (lithofacies V5; see below) than the other three carbonate lithofacies, but less sand-sized, transported material. See Chapter Three for details.

2.3.5 (V5) Calcareous shale

Composition

This lithofacies is dominated by terrigenous mud. Total carbonate content ranges from 30 to 80 % by weight, up to one-half of which may be dolomite (determined by carbonate bomb; Müller & Gastner 1972). X-ray diffraction has reveals a mineralogy of quartz, illite/muscovite, chlorite, kaolinite and feldspar for the siliciclastic component (Fig. 2.7 A). Clusters of small pyrite cubes are common in thicker beds. Quartz grains are up to very fine sand-size. Bioclasts, although sparse, include trilobites, bryozoans,

Figure 2.7: Characteristics of Lithofacies V5, and the Bobcaygeon and Lindsay formations.

A - Typical powder X-ray diffractogram of shale (V5). Major components are illite-muscovite, calcite, quartz, chlorite and dolomite. Sample from Verulam Formation, Nepean Point (loc. 15).

B - Photomicrograph (crossed polars) of typical grain-types of the Bobcaygeon Formation. Brachiopods, crinoids, bryozoans dominate. Intraclast in lower right of photograph is of bryozoan-and brachiopod- rich shale. L'Orignal Quarry, Ontario (loc. 36).

C - Apparent thick (20-60 cm scale) stratification in the Bobcaygeon Formation, Cliftondale Quarry, Vankleek Hill, Ontario (loc. 35). Quarry wall is 6 m high.

D - Close-up of thin beds of the Bobcaygeon Formation jumbled by bioturbation. Note close juxtaposition of fine- and coarse-grained limestone textures. Cliftondale Quarry, Vankleek Hill, Ont. (loc. 35). Coin is 2.9mm across.

E - Contact between the Upper Bobcaygeon Formation (UBF) and the Hull Beds (HB) at Lac des Feés Parkway, Hull (loc. 3). Note thin, relatively unbioturbated, very fine- and coarse-grained beds of grainstone/packstone in the Bobcaygeon. Hammer handle is 32 cm long.

F - Transitional Verulam-Lindsay lithologies at Rideau Falls (loc. 18). Note highly bioturbated, nodular but still discernible thin beds of fine-grained packstone (lithofacies V3) and shale. Camera case is 28 cm wide.

G - Nodular packstone-wackestone of the Lindsay Formation. Note the almost complete lack of discernible stratification. Backpack is 70 cm long. Loc. 18.

echinoderms, brachiopods, skolecodonts, conchostrachans and conularids. The shale is commonly bituminous.

Sedimentary features

Strata range from thin, millimetre-scale partings up to 15 cm thick beds. Thicker beds commonly contain thin (0.5-2 cm), fine-grained limestone lenses of similar natures to lithofacies V3 and V4. Laminae range in thickness from paper-thin to ~2 mm. *Planolites* burrows are extremely common, and weather out of the beds as limestone-cemented tubes. *Chondrites* and *Phycodes* are also present.

Interpretation

Lithofacies V5 represents interstorm hemipelagic deposition of fine-grained carbonates, clay and quartz silt. Infaunal and epifaunal organisms contained in the shales were likely a major sources of bioclastic sand for the storm deposits of lithofacies V1-V4. See Chapter Three for details.

2.4 Lithological characteristics of the Bobcaygeon Formation

The Bobcaygeon Formation is similar in lithologic character to both the Hull Beds and the Verulam Formation in that it consists of bioclastic, commonly shaley limestone. Apparent bedding is deceptively thick (metre-scale) when fresh exposures are viewed from distance (Fig. 2.7 C). Closer inspection reveals that the thick “beds” are in fact composed of thinner (3-20 cm) beds separated by very thin (millimetre-scale) shaley partings (Fig 2.7

D, E). The thin limestone beds usually alternate between medium- to coarse-grained grainstone-packstone and very fine- to fine-grained packstone-wackestone (Fig. 2.7 E). The alternating coarse- and fine-grained beds may form simple parallel bands, or bioturbation (*Thalassanoides*-like boxworks with SVF, *Chondrites*, and *Helminthopsis*) may have disrupted the original stratification. At some localities (e.g., Plumadore Quarry, loc. 33), iron-stained *Thalassanoides* boxworks impart a nodular fabric to these beds. The shaley partings are most likely enhanced if not created by stylotization. Thicker shales (1-15cm), are commonly present between the metre-scale units as seen on fresh surfaces. These shales are usually fossiliferous, containing ramose and domal bryozoans, brachiopods and crinoids (see intraclast in Fig. 2.7 B). Ramose bryozoans are most common, and may form a very dense network of interwoven branches. Isolated, thick, lenticular rudstone to grainstone beds are also present. Planar to wavy parallel lamination, cross-stratification, ripples and HCS occur locally. One to five metre-scale packages of well sorted, medium-bedded, cross-laminated grainstone, strikingly similar to lithofacies H2, also occur.

In core, where bedding style and sedimentary structures are not easily discerned, the Bobcaygeon and Verulam strata may be easily confused. Both formations appear to be dominated by thin- to medium-bedded packstones with abundant shaley partings and less abundant 1-10 cm shales. The thicker shales of both formations are dark grey and contain abundant 1 to 5 millimetre, pale round spots and short streaks. Close examination of these marks in Bobcaygeon strata will immediately reveal them to be ramose bryozoan twigs. In the Verulam shales, superficially similar features represent calcite-cemented

Planolites, *Chondrites* and *Phycodes* burrows. It should be noted, however, than the Verulam shales may also contain a few ramose bryozoans.

The depositional environments of the Bobcaygeon Formation have yet to be described. The presence of such features as limestone-shale interbedding, normally graded beds and oscillatory flow structures (i.e., HCS and wavy lamination) suggest a storm-influenced offshore environment, deposited in depths ranging from fairweather to storm wave-base (10 to 100 m ?). The diverse and abundant fossils suggest a non-restricted marine environment.

2.5 Lithological characteristics of the Lindsay Formation

The Lindsay Formation is dominated by fine- to medium-grained, moderately sorted, nodular wackestone to packstone (Fig 2.7 F, G). The nodules are oblate ellipsoids, 3 to 15 cm long, and 2 to 10 cm thick. Their edges are defined by thin (less than 5 mm), anastomosing shaley partings. Like the Bobcaygeon Formation, the Lindsay Formation appears thickly bedded (metre-scale) at a distance. The thick stratification is defined by the distribution of relatively thick shales (up to 2 cm thick) and prominent, burrowed surfaces (possibly firmground hiatal surfaces). Relatively continuously bedded, non-nodular intervals, very similar in appearance to the Verulam Formation, occur at 4 to 7 metre intervals and are up to 50 cm thick. Bioclastic components are very similar to those in the Verulam Formation, perhaps with a higher proportion of brachiopods and orthocones and less crinoid and bryozoan debris. Petrographically, the Lindsay Formation bears a striking resemblance to wackestones and packstones of lithofacies V3. Simple

vertical burrows, *Thalassanoides*-like boxworks, *Chondrites* and *Helminthopsis*-like trace fossils are extremely abundant throughout.

In core, the Lindsay Formation may be distinguished from the Verulam Formation by a decrease in the abundance of shale beds. The shaley partings in the Verulam Formation tend to be horizontal, while those in the Lindsay Formation are commonly inclined at fairly steep angles to the horizontal (up to about 60°) in places where they define the edges of nodules.

The Lindsay Formation appears to represent an environment in which bioturbation outpaced sedimentation. The presence of “Verulam-like” intervals and other persistent grainstone intervals suggest that, like the Verulam, storms were major depositional agents. The higher degree of bioturbation in the Lindsay Formation may have been the result either of (1) generally lower-energy setting (more stable substrate, less frequent storms), or (2) slower rate of sea-floor cementation (allowing burrowers more time to rework the sediment while it is still unconsolidated).

CHAPTER THREE: DEPOSITIONAL ENVIRONMENTS

3.1 Lithofacies associations and depositional environments of the Hull Beds

The six lithofacies of the Hull Beds occur in three distinctive associations, which are interpreted here to represent particular depositional environments. The Hull Beds appear to represent deposition of shallow-marine, bioclastic barrier sands and associated, muddy, bioclastic and peloidal backbarrier and lagoon facies. Figure 3.1 is a generalized block diagram showing the arrangement of proposed depositional facies in their relative positions.

3.1.1 Lagoon facies association

Lithofacies interpreted to represent lagoonal conditions are H4, H1, H2 and H6. Sub-environments of the lagoon association include the quiet lagoon floor (lithofacies H4), lagoon-margin sands (lithofacies H6) and sharp-based washover packages (lithofacies H1 and subordinate H2). The lagoon facies association is characterized by a photozoan grain-type association (James 1997), suggesting that conditions were comparable to modern, tropical settings (see Section 3.3).

Lagoon floor environment

The grain-types and sedimentary features of the lagoonal lithofacies (see Chapter 2) identify a low-energy, warm ($>18^{\circ}\text{C}$) shallow (no more than 10 m deep; probably $<5\text{m}$), normal marine to slightly restricted environment. Low-energy conditions are suggested by the very fine-grained nature of the matrix (generally $<4\mu\text{m}$; Fig. 2.3 F), the presence of

Figure 3.1: General arrangement of depositional setting and resulting spatial arrangement of lithofacies in the Hull Beds. FWB=fairweather wave base (approximate).

whole to disarticulated, generally unabraded shelly and green algal fossils (including delicate dasycladaceans; Johnson & Sheehan 1985). The abundance of green algae also argues for shallow water (Tucker & Wright 1990, Jones & Desrochers 1992). A bioclast-type association which may be described either as “coralgal” (i.e., major carbonate grain-types are corals and green calcareous algae; Lees & Buller 1975) or “photozoan” (i.e., major carbonate-producing biota were probably phototrophic or had phototrophic endosymbionts; James 1997) implies a warm water temperature. Salinity cannot have been very high as most of these beds contain a ubiquitous and well-preserved accessory stenohaline fauna which includes approximately in-place, disarticulated but unbroken bryozoans, articulate brachiopods and pelmatozoans (cf. Tasch 1980, McFarlane 1992, Cain 1968). Sparsely fossiliferous beds, containing only green algae, ostracod carapaces and scattered molluscs, may represent deposition in more environmentally stressed conditions. The abundance of ostracods suggests fluctuating or high salinity (Teeter 1975, Tasch 1980). Cyanobacterial mats may have been developed on the lagoon floor, as suggested by poorly-developed clotted fabrics in the micrite (Pratt 1982, Tsien 1985) and the rarely-developed, small-scale draping algal laminations (Fig. 2.3 G). Pervasive bioturbation and lack of sedimentary structures (even in relatively unbioturbated beds) suggest slow, continuous deposition.

The packstones of lithofacies H4 are interpreted as in-lagoon storm deposits. This is suggested by (1) sharp bases, (2) normal gradation and parallel- to cross-lamination, (3) grainier texture and (4) abundant presence of exotic grains (e.g., ooids). The grains present in the packstones are a mixture of locally derived (e.g., *Tetradium* and green

algae) and distally-derived (e.g. ooids, homogenous peloids and brachiopods). They were formed as high-energy storm currents or waves winnowed the muddy sediments on the lagoon floor and carried material into the lagoon from the barrier and/or the lagoon margin environments.

Lagoon-margin sands

Lithofacies H6 is interpreted to represent a higher-energy environment located along the margins of the lagoon. The homogenous peloids of lithofacies H6 may represent either faecal pellets or intensively microbored allochems (see Perry 1998 for recent review). The extreme rounding and uniformity of size and ovoid to spheroid shape of the peloids supports a faecal origin (Flügel 1982), although they could also represent micritized ooids. At least one apparent burrow-tube is lined by homogenous peloids (Fig. 2.4 E), again supporting a faecal origin.

Sedimentary structures preserved in lithofacies H6 (planar lamination and small- to medium-scale cross-lamination) indicate a higher-energy environment than lithofacies H4. The excellent sorting of the peloids and matrix-poor texture implies a constantly agitated conditions. Bioturbation is generally sparse, top-down in style and restricted to simple vertical forms and *Chondrites* preserved at particular horizons (see Fig. 5.3 D). The burrowed horizons may represent brief periods of substrate stability in this otherwise agitated environment. These strata are among the least fossiliferous in the Hull Beds, containing only green algae, ostracods and rare molluscs. This implies some kind of environmental stress; possibly elevated salinity in very shallow water. The partial

dolomitization of this lithofacies observed at Klock Quarry will be discussed further in Chapter Five.

Lagoon margins are commonly the site of sand accumulation in siliciclastic settings (Nichols & Boon 1994), which have been more extensively studied than carbonate coastal barrier-and-lagoon systems (with the exception of the Trucial Coast of the Persian Gulf; see below). Mud is concentrated in the central portions of the lagoon, while sand accumulates on small wave-formed beach-shoreface systems around the margins. Available wind-wave energy to build lagoon-margin beaches will depend on the width of the lagoon as an available fetch distance on the protected side of the barrier (Nordstrom *et al.* 1989). Lagoon-margin sands may also accumulate in sandy tidal-flat environments but no evidence of tidally influenced sedimentation is present in the Hull Beds.

Washovers

Lagoonal facies at Klock Quarry and Highway 17 (locs. 1 and 2) contain tabular to lenticular beds of lithofacies H1 and H2. These are interpreted as representing storm-related washover fans or spits from the barrier. The grain types within these beds are usually dominated by intraclasts and fragments of echinoderms, bryozoans, pelecypods and brachiopods (the grain-types of the barrier top), but with a significant admixture of peloids, green algae, pelecypods, ostracods and *Tetradium* fragments. Intraclasts in H1 washover beds are typically a mixture of lithofacies H2, H4, H5 and H6. Grains are commonly partially micritized, perhaps reflecting the removal of pristine bioclasts to a low-energy environment conducive to microboring organisms (Perry 1998, Tudhope &

Risk 1985). Bedding is commonly lenticular, and may be as thin as 5 cm or as thick as 60 cm and continuous over a few hundred metres lateral distance. Washover packages typically overlie scours cut into beds of lithofacies H4 or H6 (Fig. 2.2 A). The predominance of plane parallel- lamination with minor tabular and trough cross-lamination is consistent with a washover fan environment (Schwartz 1982). Stacked beds of lithofacies H1 or H2 probably represent stacked washover fans, possibly representing cross-barrier transport of sediment via a long-lived conduit. No obvious evidence of tidal influence is preserved in these beds.

3.1.2 Barrier-top association

The barrier-top facies association consists of metre-scale bed-sets of lithofacies H1, H2 and H5 with less common occurrences of H6 and H4. These are interpreted as representing the very high-energy, very shallow environment of the barrier crest and the protected environment immediately shoreward. These strata generally contain a mixture of photozoan and heterozoan grain types (James 1997), suggesting transitional warm- to cool-water conditions (see Section 3.3).

Beach to upper shoreface

Features preserved in lithofacies H2 are consistent with a beach or upper shoreface environment. The sand-sized, abraded bioclasts and mud-free, very well-sorted texture implies a high-energy, constantly agitated environment. Planar, parallel lamination commonly exhibits low-angle (less than 5° with respect to one another) truncating

laminasets of a few centimetres thickness. Seaward-dipping, low-angle lamination is the typical structure of both siliciclastic (Reinson 1984, Komar 1976) and carbonate (Inden & Moore 1983) beaches. The truncation angle of the lamination in the Hull Beds is rather low; Inden & Moore (1983) and Reinson (1985) give figures of 5-15°, but see also Heward (1981), who suggests a dip of 1-10° for low-angle lamination of beach sediments. Low-angle lamination is also considered a characteristic structure of breaker-zone settings in the upper shoreface (Reinson 1984). Normal gradation of laminae, although uncommon in lithofacies H2, suggests similarity to the “beach lamination” described by Clifton (1969). Trough laminasets (5-15 cm high), possibly representing the “lunate megaripples” of Davidson-Arnott & Greenwood (1976), are also extremely common. Common and locally abundant *Skolithos* burrows, are the only common trace fossil, which is consistent with an upper shoreface or beach environment (Seilacher 1967, Pemberton *et al.* 1992). Tabular, oncolitic and *Solenopora*-bearing beds of lithofacies H1 commonly display parallel lamination and tabular cross-lamination. These may represent gravely upper shoreface or beach deposits. These deposits commonly contain abundant oncoids. Although modern marine oncoids typically occur in low-energy or periodically agitated environments, Paleozoic oncoids are commonly interpreted as being high-energy features analogous to modern rhodoids (Riding 1983, Flügel 1982, Peryt 1983b). The lack of extensive meteoric cements, keyhole vugs or evidence for extensive beachrock development suggests that these high-energy environments at the crest of the barrier were not supratidal beaches or islands. Sparse development of possible meteoric cements in some intraclasts (see Chapter Five) and the presence of grainstone intraclasts in washover

deposits is suggests limited exposure, perhaps as ephemeral sand caps on the barrier's crest.

Barrier-top silt flats

Lithofacies H5 is interpreted to represent a low- (or moderate-?) energy, shallow subtidal (to intertidal?) environment developed on the lagoonward side of the barrier crest. It is composed of silt-sized, laminated carbonate with ostracods as the only common fossils. Accessory bioclastic components are diverse but extremely sparse, and typically of similar types to lithofacies H2 (e.g., pelmatozoan ossicles, brachiopods, etc.). The source of calcareous silt may have been abrasion of bioclastic material on the barrier itself. This silt, along with some sand-sized bioclastic material, may have been washed across the (submerged?) barrier by fair-weather waves as they finally broke over it ("swashover").

These back-barrier silt flats were in an equivalent position to modern low-energy, back-barrier environments, such as the back-barrier sabkhas of the eastern Trucial Coast (Purser & Evans 1973, Kendall & Skipwith 1968, 1969) or the back-barrier marshes and tidal flats of siliciclastic barriers on the Atlantic coast of the USA (e.g., Hayes 1979, Nordstrom *et al.* 1989).

Channel and washover features

Steep-sided channels filled by lithofacies H1 or, less commonly, lithofacies H2 are found scoured into beds of lithofacies H5 in the barrier-top facies association (Fig. 2.4 B). Grain types preserved in these channels are the most diverse of any in the Hull Beds,

suggesting that the channel crossed from beach/upper shoreface environments into the backbarrier area. Intraclasts are common and are usually of local origin (i.e., they are lithologically similar to the rocks into which the channel is scoured). On the Hull Promontory (loc. 7c), numerous small (a few decimetres wide, less than 10 cm thick), coalesced channels are concentrated at one horizon, cutting into a thin, relict bed-set of lithofacies H5. In contrast to these densely packed (both vertically and laterally), small channels, larger, more widely spaced channels are incised into metre-scale packages of lithofacies H5 at St. Laurent Blvd (Fig. 2.4 B). Channels on the barrier top tend to be relatively steep-sided. In contrast, the lenses of lithofacies H1 and H2 associated with lagoon facies association tend to be preserved as much broader, sharp-based lenses (up to 300 m long at Klock Quarry), suggesting a “fan” rather than a “channel” morphology.

The smaller channels cut into lithofacies H5 may represent small subtidal (to intertidal?) channels. In the absence of tidal bundles, mud-draped ripples or other features of sandy/silty tidal flats, it seems improbable that these channels were scoured or filled by constant tidal action. Rather, they were scoured by high-energy episodes (storms) in a normally low-energy area. Whether or not the channels were filled by the storms that created them, or were active sediment conduits during subsequent storms is not readily obvious. Modern washover fans may be stacked at the mouth of a long-lived barrier breach (washover channel of Armon, 1979).

3.1.3 Barrier-front association

The barrier-front facies association consist of metre-scale intercalated bed-sets of lithofacies H2 and H3. They are interpreted to represent upper to lower shoreface environments that lay seaward of the barrier crest. These strata only contain grains of the heterozoan grain-type association (James 1997), which suggests a cool-water setting (see Section 3.3).

Significance of grain types

The grain types preserved in lithofacies H2 and H3 are, for the most part, similar to those mentioned for the barrier top. Crinoid, brachiopod and bryozoan fragments are most common, with accessory trilobite and molluscan fragments. In the barrier-front association, however, lithofacies H2 is notably poor in *Solenopora*. Oncoids and green algae are unknown in this association with the exception of very rare receptaculitid fragments in lithofacies H2. Fibrous conodonts, which are suggestive of nearshore conditions (Barnes & Fåhræus 1975) were abundant in a sample from the Aviation Parkway south outcrop analyzed by McCracken (1995).

Partial but ubiquitous micritization of grains in lithofacies H3 to produce irregular peloids is suggestive of a gently or periodically agitated environment. Constant or violent agitation tends to remove microbored rims (Young & Nelson 1985, 1988). Gentle or episodic agitation, providing exposure of grains at the sediment-water interface, is commonly associated with even or complete micritization of bioclasts (Tudhope & Risk 1985). Extensively microbored crinoid ossicles have been reported from ancient lower

shoreface settings, deposited downramp from an agitated crinoid shoal environment, from the Mississippian of southern Alberta by Brandley & Krause (1997).

Despite the disappearance of photic macrofossils, the micritization of grains in the lower shoreface suggests deposition within photic limits. Light levels may have been cut down by either depth or turbidity. The grain-type assemblage a fully marine, poorly lit but productive environment.

Shoreface environment

For the reasons discussed above, lithofacies H2 is interpreted as representing an upper shoreface and possibly beach environment. Lithofacies H3 is represents a slightly deeper, slightly lower-energy setting. This interpretation is supported by the overall finer grain size, muddier and less sorted texture. The paucity of phototrophic taxa (e.g., *Solenopora* and green algae) in both lithofacies H2 and H3 in the barrier-front facies association supports a deeper and/or more turbid environment of deposition. This “heterozoan” grain type assemblage (i.e., dominant carbonate producers were heterotrophic organisms; James 1997) suggests water temperatures of less than 18°C. The presence of rare shaley partings between decimetre-scale beds as well as horizontally-burrowed (*Helminthopsis*) and brachiopod-encrusted surface in lithofacies H3 suggests depositional hiatuses. The sparse distribution of trace fossils and encrustation attests to the short-lived nature of these breaks. Parallel lamination and medium-scale (5–15 cm) trough cross-lamination remain the most important sedimentary structures. Low-angle truncation of flat laminae is replaced by wavy laminae and structures resembling

hummocky and swaley cross-stratification (SCS; Leckie & Walker 1982). SCS is considered by Walker & Plint (1993) as diagnostic of lower shoreface settings, but see Allen & Underhill (1989) for a differing opinion. Although sparse, the ichnofauna preserved in lithofacies H3 is more diverse than that of H2, consisting of *Skolithos*, SVF, *Helminthopsis* and *Chondrites*.

Sedimentation on a shoreface is affected by both storms and fair-weather processes. In the upper shoreface, storms may be recorded by scour surfaces, gravely lag deposits and normally graded beds (Kumar & Sanders 1976). Upper shoreface tempestites are, however, subject to wave and current reworking in fair-weather and the storm sequence may be partially or completely obliterated (Major *et al.* 1996). In the lower shoreface, fair-weather wave and current energy is lower, but may be more significant. Storm deposits are more likely to be preserved here. Scour-based, graded beds with wavy, planar, swaley and cross-lamination are present, and almost certainly represent storm beds. Kumar and Sanders (1976) note that fairweather processes in the lower shoreface tend to produce wave-rippled, bioturbated sediments. The sparsity of bioturbation and paucity wave-ripples would suggest that most of the beds of lithofacies H3 represent storm deposits rather than fairweather sediments.

3.1.4 Paleocurrent data from the Hull Beds

Data

Paleocurrent directions from the Hull Beds, mostly taken from cross-set orientations, are shown for four outcrop areas in Figure 3.2. The constituent sections of

Figure 3.2: Paleocurrent rose- and stick diagrams. In all diagrams, North is towards the top of the page. In rose diagrams, n =total number of measurements and max =maximum number in any slice (i.e., represented by diameter of circle). In stick diagrams (E and F), $mean$ = vector mean of ripple-crest orientation, and is marked by the two-headed, dashed arrow.

A- D: Hull beds

- A:** Paleocurrent rose for the Klock Quarry (loc. 1, lagoon and barrier-top deposits).
- B:** Paleocurrent rose for western Hull (locs. 3, 4 and 6; barrier-top and minor barrier-front deposits).
- C:** Paleocurrent rose for downtown Ottawa-Hull (locs. 7, 13; barrier-top and barrier-front deposits).
- D:** Paleocurrent rose for eastern Ottawa (locs. 19, 20, 21, 22, 23, 25; barrier-front and minor barrier-top deposits).

E-H: Verulam Formation

- E:** Stick diagram for CGR crest-trends in downtown Ottawa (locs. 8, 15, 16 and 17).
- F:** Stick diagram for CGR crest-trends exposed on the bed of the Castor River near Embrun (loc. 29).
- G:** Paleocurrent rose for downtown Ottawa area (locs. 5, 8, 9, 10, 14, 15, 16 and 17). **G*** (inset): Paleocurrent rose for intraclast imbrication data from beds of lithofacies V1 (locs. 15, 16 and 17).
- H:** Paleocurrent rose for eastern and southern part of study area (locs. 29, 31 and 32).

A-D: Hull Beds

E-H: Verulam Formation

the particular areas were chosen in order to reflect differing stratigraphic and environmental positions. The Klock Quarry (loc. 1; Fig. 3.2 A) is dominated by lagoonal facies. Exposures in western Hull (locs. 3, 4 and 6; Fig. 3.2 B) are dominated by the barrier-top facies association, and are all stratigraphically low in the Hull Beds. Those in the downtown Ottawa-Hull area (locs. 7 and 13, Fig. 3.2 C) are dominated by barrier-top to barrier-front deposits. In the fourth area, northeastern Ottawa (locs. 19, 20, 21, 22, 23, 25; Fig. 3.1 D) exposure is dominated by the barrier-front facies association.

Interpretation

The Klock Quarry paleocurrent rose (Fig. 3.2 A) is based on few measurements, but shows a clear bimodal distribution, with the two dominant directions separated by about 90°. The dominant direction is to the southeast, and the subordinate direction is to the north. Both of the barrier-top dominated roses (western Hull and downtown Ottawa-Hull; Figs. 3.1 B and C) show a striking bimodal trend, with a strong southwest component and a slightly weaker southeast component. The paleocurrent directions from northeastern Ottawa (Fig. 3.2 D) are quite different: a north-northwest direction dominates, with a subordinate mode to the south.

The northerly arm of the Klock Quarry rose diagram (Fig. 3.2 A) is interpreted as representing “landward” flow into the lagoon across the barrier during storm overwash. The east to southeast trend likely represents longshore currents in the barrier top. The latter interpretation is supported by the strong bimodal and almost diametrically opposed directions that dominate the barrier-top to barrier-front roses from western Hull and

downtown Ottawa-Hull (Figs. 3.1 B, C). On modern, barred shorefaces, fairweather longshore currents tend to produce migrating ripple- or dune-forms within longshore troughs while rip currents tend to produce structures that migrate away from shoreline (Davidson-Arnott & Greenwood 1976, Komar 1976). The longshore directed structures have a higher preservation potential, because they are produced in negative bathymetric features (longshore troughs) and may be buried by the migration of longshore bars. Conversely, onshore-directed, rip-current produced structures are likely to be obliterated during storms or overprinted by parallel laminae (Davidson-Arnott & Greenwood 1976). General shoreward movement of grains by fairweather waves is also less easily recorded in the upper shoreface, as landward-directed ripple- and dune-forms are also likely to be overprinted by low-angle lamination (Reinson 1984). In the lower shoreface wave energy is lower and these overprinting processes are less active. In these areas, onshore- and offshore-directed storm currents are more likely to be recorded. This phenomenon is well demonstrated by the lower shoreface deposits (lithofacies H3-dominated) of northeast Ottawa (Fig. 3.2 D), where the paleocurrent directions are dominantly north/northwest and due south: approximately perpendicular to the fairweather trend recorded in the downtown Ottawa area. Fairweather rip-currents may also contribute to the offshore-directed (southerly) arm of the rose diagram shown in Fig. 3.2 D.

3.1.5 Discussion

Sediment dynamics

Barrier and lagoon complexes are common on the innermost parts of wave- and storm-dominated carbonate ramps (Tucker & Wright 1990). The general attributes of a carbonate barrier-and-lagoon system are similar to those of their siliciclastic counterparts (Inden & Moore 1983). In carbonate systems, the sediment is a mixture of authigenic and imported material. This is unlike a siliciclastic barrier system in which sediments are ultimately derived from a terrestrial sediment source. Despite this, the major pathways of sediment exchange between sub-environments are essentially the same (Table 3.1). These pathways of exchange are well-expressed in the Hull Beds by the paleocurrent patterns described above.

Complications arise in considering the provenance of grainy material in the oolitic-bioclastic wackestones and packstones of lithofacies H4. The bioclasts (pelecypods, green algae, bryozoans, *Tetradium* fragments, brachiopods, echinoderm ossicles and ostracods) appear to represent a mixture of locally-derived lagoon and imported barrier-top grain types. The ooids are usually micritized and commonly broken; suggesting they are allothenous. Furthermore, they seem unlikely to be *in situ* when encased by so much micrite. The only *in situ* ooids observed are in the ooid grainstone bed at the top of roadcut at locality 2 (section 2.1.6). This single bed of oolitic grainstone is associated with beds of lithofacies H2 (barrier-top). Its existence suggests that the ooids were swept off the barrier top into the lagoon. A second possibility is that the homogenous peloids represent (in part) micritized ooids, although not relict radial fabrics are observed in the

homogenous peloids. If these peloids are micritized ooids, then the ooids preserved in the lagoon tempestites may have been swept from lagoon-margin sandbodies, transported to and buried in a deeper environment, greatly increasing their preservation potential with respect to micritization. Lagoon-margin oolitic sands have been reported from Turks and Caicos Islands by Lloyd *et al.* (1987).

Comparison with the Trenton Group

In northwestern New York, Titus & Cameron (1976) and Titus (1982, 1986) have suggested that two intervals within the Trenton Group may be interpreted as barrier and barrier-protected inner ramp systems. The lower Trenton Group represents deposition in a system similar to that described here (Titus & Cameron 1976): a bathymetrically positive barrier sandbody with a lagoon protected behind it. For the Stueben and Hillier limestones of the Upper Trenton Group, Titus (1986) suggested a model very similar to the epeiric model as reviewed by Irwin (1965). In Titus' (1986) Stueben model, the energy barrier is not a paleobathymetric shoal with positive relief; rather, it is a zone of wave-energy dispersion by friction on a uniformly dipping surface. Shoreward of this barrier zone is a "protected shoal"; open to the ocean but with little daily agitation. Titus' (1986, 1982) reasons for proposing a paleobathymetric barrier for the lower Trenton and a homoclinal, frictional barrier for the Stueben and Hillier limestones is not clear.

Brookfield & Brett (1988) proposed a "shoal-and-basin" model for the Trenton-equivalent Upper Simcoe Group of central Ontario. They suggest a set of coeval environments that include paleobathymetric, mobile shoals scattered across a storm-dominated, muddy shelf. Their model, however, is based on the idea that the individual

facies do not fall into formally recognized or regionally correlatable lithostratigraphic units. For example, they suggest that the crinoidal grainstone shoal facies previously placed by Liberty (1969) in the upper Verulam Formation (of central Ontario) was actually a set of discrete grainstone packages located at several lithostratigraphic levels. Recent work, reviewed by Armstrong (1997) suggests that the formations of the Simcoe Group are, in fact, distinct and recognizable. Furthermore, the Hull Beds do not appear to represent mobile shoals separated by areas of sub-wavebase, storm-dominated sedimentation, and as such do not match Brookfield & Brett's (1988) model.

Pathway	To	From	Agent	Recorded Results
Onshore	Barrier front & top	Offshore areas	(1) Daily waves (2) storm approach	Piling up of sediment on barrier, onshore-directed cross laminae ^{i, iii}
Along-shore	Barrier front	Barrier front	Daily wave-induced (and storm-enhanced) longshore drift	Shore-parallel oriented cross-lamination, bared shoreface topography ^{i, ii}
Cross-barrier	Lagoon, barrier top	Barrier top & front	(1) Daily "swashover" of fine silt (2) Storm washover (3) Tidal currents	(1) Formation of barrier-top silt flats ^{vi} (2) Formation of washover channels, fans and spits in barrier top & lagoon environments ^{iv} (3) Tidal inlet and tidal deltas ^{vi}
Offshore	Barrier front offshore	Barrier top & barrier front	(1) Daily rip-currents (2) Storm-related relaxation/geostrophic flows	(1) Scouring of rip channels in barrier front, formation of offshore-directed cross-laminae ^{i, iii} (2) Transport of sediment to the lower shoreface and offshore zones ^{iii, v}

Table 3.1. General sediment transport pathways in a barrier-lagoon system. References (i) Komar 1976, (ii) Davidson-Arnott & Greenwood 1976, (iii) Niederoda *et al.* 1985, (iv) Hayes 1979, (v) Walker & Plint 1993, (vi) Reinson 1984, (vii) this study.

Pope & Read (1997) have recently provided a simplified facies model for Lexington Limestone (Trenton Group-equivalent and younger) in Kentucky. The inner-ramp portion of their model is strikingly similar to in lithofacies and the arrangement of depositional environments. They suggest a high-energy, bioclastic, bipolar cross-bedded, barrier-shoal facies (similar to the barrier-top and barrier-front environments of this study) protected a faunally restricted lagoon (similar to the lagoons represented by lithofacies H4, but heavily bioturbated). Peritidal cycles are also well-developed as a back-barrier facies belt. Pope & Read (1997) interpreted these rocks as representing a bioclastic shoal-lagoon-tidal flat facies arrangement, very similar to the Hull Beds except in the apparently strong influence of tides (peritidal cycles, bipolar cross-bedding). Pope & Read's (1997) model is further discussed in Section 3.3.

Transgressive deposits at several lithostratigraphic levels in the Cincinnati of southern Ohio (Trenton Group equivalent in part; Holland 1993) contain similar lithologies and depositional facies to the Hull Beds and Lexington Limestone. These include mollusc-, coral-, and ostracod-dominated lagoonal mudstones; cross-bedded bioclastic (bryozoan, crinoid and brachiopod) barrier-bar grainstone; and bioclastic, shoreface packstones. In some packages, these depositional facies are arranged as well-defined paleogeographic belts. Holland (1993) interpreted such strata as representing slowly transgressive systems tracts. Episodes of more rapid transgression are preserved by less well-ordered strata dominated by the bioclastic packstone shoreface deposits.

Comparison with modern environments

The best possible modern analogue for the facies arrangement inferred for Hull Beds is the central Trucial Coast of the Persian Gulf. Brookfield & Brett (1988) have suggested the same analogy for the Simcoe Group in central Ontario. The geomorphology and sedimentary environments of the Trucial Coast (Fig. 3.3) have been described by Kendall & Skipwith (1968, 1969) and Purser & Evans (1973). These works are summarized in the following description.

An onshore-offshore transect of the Trucial Coast may be simplified into five major geomorphologic and facies belts: supratidal sabkha, lagoon-margin sand flat, open lagoon, backbarrier flats, and barrier shoal. This portion of the Persian Gulf is mesotidal and has an extremely hot, arid climate. The supratidal and intertidal facies form broad belts. The famous sabkhas of the Trucial Coast are a low-energy, supratidal setting, periodically flooded during high tides and storm events. They are dominated by cyanobacterial mats, evaporites and desiccation features, and have no apparent analogue in the Hull Beds. The coastline adjacent to the sabkhas is the locally the site of bioclastic, pelletal and rarely oolitic sand accumulation on sandy tidal flats and beaches. These features form the landward margin of the Khor al Bazam lagoon. Khor al Bazam is a large, protected east-west trending embayment, open to the Gulf at its western extreme and protected on its northern side by the barrier facies belt (Great Pearl Bank). The open, western end of the lagoon is partly protected from the dominant, northwesterly winds (Shamal winds) by the Qatar Peninsula. The sediments of Khor al Bazam are dominated by lime mud and sand-sized molluscan bioclasts. Great Pearl Bank itself is a long, nearly

Figure 3.3: Comparison between the general facies arrangement of the Trucial Coast barrier-lagoon system (after Purser & Evans 1973) and the barrier-lagoon system preserved within the Hull beds. Broad similarities include (1) the presence of a very high-energy, bioclastic barrier facies belt grading seaward into offshore tempestites, (2) the presence of lower-energy facies on the barrier-top, and (3) a low-energy lagoon fringed by higher-energy facies.

continuous belt of shoals, islands and local coral bioherms. The barrier top is dominantly subtidal in the east, but rises towards the west and is dominantly supratidal in the east, eventually joining mainland Bahrain. On its lagoonward side of some islands, small lagoon-facing beaches composed of coral-algal sands are present. These are backed by locally extensive sabkhas. The subtidal to intertidal portions of the barrier front are covered by coral-algal sands, which grade seaward into muddy bioclastic sands. The general facies arrangement of the Trucial Coast, and its possible equivalence to the Hull Beds is illustrated in Figure 3.2. It is important to note that tidal (inlets, deltas, etc.) features are prominent in the Trucial Coast, and that these have not been recognized within the Hull Beds.

Another possible modern analogue is the Yucatan shelf (Ward & Brady 1979, Ward 1975). The positions of barrier islands in northeastern Yucatan are controlled by the distribution of lithified late Pleistocene aeolianites. The barrier facies belts are largely subareal and covered by modern aeolian dunes and evaporitic ponds. The system is developed in a microtidal area; tidal inlets are very widely separated and tidal deltas are not developed. Storm washover, creating washover fans, and aeolian transport are the major mechanisms of cross-barrier transport.

Brookfield (1988) and Lavioe (1995) have suggested a cool-water depositional setting for Trentonian strata in areas adjacent to the Ottawa Embayment. As such, they have drawn comparisons between the Ordovician strata and recent sediments in south Australia and New Zealand. A full discussion of these aspects may be found in section 3.3.

Sea-level change and preservation of facies

The fact that the shallow-water deposits of the Hull Beds are overlain by the deeper-water deposits of the Verulam and Lindsay formations clearly indicates that the overall setting in Trentonian time was transgressive. Transgressive intervals are commonly observed as smaller, stacked, progradational sub-intervals backstepping over one another in stratigraphic record, especially in barrier-lagoon systems (Kraft & Chrzastowksi 1985).

In a purely transgressive barrier-lagoon system, the barrier top environments (typically beach and aeolian dune facies) are not commonly preserved, since they usually lie within a zone of net erosion. With rapid relative sea-level rise, beach can be preserved due to rapid landward overstepping of deeper, lower-energy facies. In areas of slower sea-level rise, backbarrier deposits will be disconformably overlain by shoreface- to offshore sediments; the barrier is represented by a ravinement surface (Kraft & Chrzastowksi 1985, Donselaar 1989). Barrier facies in carbonate barrier-and-lagoon systems are more likely to survive erosion during transgression due to early cementation of barrier-top sediments in either meteoric water (subaerial dunes) or as beachrock (Inden & Moore 1983). The lack of evidence for extensive beachrock cementation or aeolianites in the Hull Beds suggests that either the barrier was not extensively emergent or that any emergent facies were destroyed either by fairweather wave processes or during a transgressive event. The Hull environments, however, do not appear to be transgressively stacked (see section 4.3)

In a regressive setting, such as the well-studied siliciclastic barrier of Galveston Island, Texas (e.g., Otvos 1970), the shoreface progrades as sediment is added to it by wave-driven longshore and onshore drift (Kumar 1976). A beach plain, which may develop aeolian dunes, forms on the barrier top and may reach several kilometres in width (Reinson 1993). Thus regression may result from widening of the sandy facies belt, as opposed to a simple seaward step of all facies belts in each regressive episode. The widening of the barrier-top facies belt during brief regressive intervals in overall transgressive settings allows for at least partial preservation of barrier shoreface deposits (Donselaar 1989). The Hull Beds clearly do not represent a regressive barrier system, since there is no evidence for progradation (see section 4.3) and very little evidence for a wide, emergent barrier (e.g., extensive aeolianites).

As mentioned above, Holland (1993) interprets well-ordered, lagoon-barrier-shoreface settings as representing slowly transgressive intervals. The Hull Beds are certainly “well-ordered” (see Section 4.3), in that the three major environments are characteristic of specific parts of the study area (lagoon in the west, barrier-top in downtown Ottawa-Hull and barrier-front in the east). It is possible that the Hull represents more a slightly transgressive interval, although the extreme lateral partitioning of facies suggests a relative stillstand in relative sea-level, allowing for almost in-place aggradation of lithofacies without significant progradation or backstepping (see Section 4.3).

3.2 Depositional setting of the Verulam Formation

The characteristics of storm deposits, modern and ancient, have been described by many authors from rocks of all ages and of diverse sedimentary origin (e.g. Kreisa 1981, Carozzi & Gerber 1978, Kelling & Mullin 1976, Hanford 1986, Sprecht & Brenner 1979, Aigner 1985, Sami & Desrochers 1992, and many others). The Verulam Formation is interpreted as representing a storm-dominated, shallow marine ramp setting, possibly lying in an offshore position relative to the Hull barrier (see Chapter Four).

3.2.1 Evidence of storm deposition

Bedding style

The Verulam Formation, both in the study area and in its type area of Central Ontario (see Armstrong 1997 and McFarland 1997), consists of alternating, generally thin-bedded shale and limestone. Each limestone bed appear to represent single (or multiple in the case of lithofacies V2), high-energy episodes of erosion and deposition, whereas the shales represent low-energy, relatively continuous deposition. The high-energy events responsible for limestone deposition are interpreted to have been storm waves and currents, rather than simple in-place accumulation of shelly material, turbidity currents or other slope-dependant processes. Turbidites tend to be more evenly and continuously bedded than storm deposits, and are typically associated with slump folds and other evidence of slope failure (e.g., Mehretens 1988). Furthermore, oscillatory- and wave-formed structures (see below) are not present in the deposits of a purely gravity-driven currents.

Internal sedimentary structures

A variety of wave-formed, unidirectional and probable combined-flow bedforms and laminaforms are preserved within the Verulam Formation (see Section 2.2 for details). These include: planar parallel lamination, wavy parallel lamination, hummocky cross-stratification (HCS) and related forms, tabular and trough-cross stratification, coarse-grained ripples (CGR; Leckie 1988), and small ripple- and dune-forms. Clast imbrication is common, especially in lithofacies V1. Load casts have been observed at the lower boundaries of some beds. Gutter casts and other sole marks are notably absent.

The sharp and commonly erosive lower bounding surface of the limestone beds implies sudden onset of high-energy conditions. Normal textural gradation is suggestive of waning flow-strength throughout deposition of the bed. The succession of sedimentary structures (see below) may also reflect waning flow strength and/or changes of flow style.

Sedimentary structures may be used to infer flow conditions at the time of deposition. With the exception of clast imbrication in lithofacies V1, beds are rarely dominated by unidirectional flow features. The channelized scours, extremely coarse grain-size and poor sorting associated with lithofacies V1 are interpreted as the product of extremely strong, short-lived events.

Lithofacies V3 and V4 account for the bulk of the Verulam tempestites. The most common structures preserved in these lithofacies are planar- and wavy-parallel lamination. Planar laminae may form under any flow type if of sufficiently high energy (Southard *et al.* 1990; Arnott & Southard 1990). Wavy lamination, however, implies oscillatory or combined-flow conditions. HCS is widely attributed to oscillatory-dominated combined

flow conditions (e.g., Duke *et al.* 1991, Cheel 1990, Nøttvedt & Kreisa 1987). The frequent lateral and vertical association between planar, wavy and hummocky lamination implies a genetic relationship: they were all formed under high-energy, combined-flow conditions. Low-angle cross-lamination in tempestites is interpreted by Nøttvedt & Kreisa (1987) as a product of unidirectional current-dominated combined-flow.

Coarse-grained ripples (CGR) are interpreted by Swift *et al.* (1983) and Leckie (1988) as combined- or oscillatory-flow structure expressed in sediments too coarse to develop HCS. Leckie (1988) notes that CGR in modern settings may be produced and are frequently re-activated by relatively small storms. Poorly defined, multidirectional sets of internal cross-lamination preserved below ripple profiles at Victoria Island (loc. 8) suggest multiple episodes of ripple migration. The excellent sorting exhibited by lithofacies V2 supports repeated or prolonged exposure to high-energy conditions. Lithofacies V2 is interpreted as a reworked tempestite: initially deposited as lithofacies V1 or V3, then sorted and rippled by later storm events (or incoming swell-waves?). Despite the evidence for multiple, high-energy reworking events, large (coarse sand to cm-size), well-preserved, slightly- to non-damaged crinoid ossicles and other bioclasts are found both encrusting the surface of the beds and dominating their upper portions. This suggests that the beds may have aggraded in an autocyclic manner with repeated reworking by small storm events or swells and subsequent recovery of an epibenthic crinoid-brachiopod community. Smaller ripple trains, observed in lithofacies V3 and V4, may represent either the final stage of storm waning, or reworking of the upper portions of tempestites by later storms (or swells).

Internal bedding sequences

“Ideal” tempestite internal bedding sequences, such as those described by Dott & Bourgois (1982) and Nelson (1982) are not well-developed within the Verulam. Vertical transitions of sedimentary structures do occur and, like the sequences described by these authors, probably reflect waning storm conditions. Apart from normal gradation, beds of lithofacies V1, V2 and V4 are effectively homogenous in terms of structure. V1 exhibits only imbricated clast fabrics, V2 contains only CGR and associated cross-laminations, while V4 will usually contain only one type of lamination (planar, wavy, hummocky or trough-cross). Lithofacies V3 may have a V1-like intraclastic lag, or grade upwards into very fine grainstone (V4-like). It may also exhibit vertical variation in structure similar to portions of the “ideal” storm sequence described by Dott & Bourgois (1982). For example, planar- or trough cross-laminae passing upwards into wavy laminae or HCS; or massive beds passing upwards into HCS and/or small ripples. The upwards transition from planar- or low-angle cross-lamination to wavy laminae or HCS may also reflect a drop in the strength of the unidirectional component and increase in oscillatory influence on the combined flow affecting the bed. No single bed contains a complete, ideal tempestite sequence (as defined by Dott & Bourgois 1982 or Nelson 1982).

Grain types, provenance and taphonomy

The grain types (sand or coarser in size) found in the Verulam tempestites fall into four categories: locally-derived bioclasts, abraded bioclasts, exotic particles and intraclasts. Intraclasts are commonly present at the base of storm beds, providing further

evidence of high-energy conditions at the onset of deposition. Usually, the intraclasts are of obvious local origin (i.e., shale chips or limestone of immediately underlying lithologies; see Figs. 2.4 G and 5.1 B). The presence of shale clasts, usually as centimetre-size chips, but occasionally up to 10 cm long, demonstrates that basal scours eroded into consolidated, buried mud. Limestone intraclasts attest to early lithification, either in the very shallow subsurface or on the sea-floor. Cemented burrow-tubes were not observed as intraclasts.

Bioclastic material makes up the bulk of the Verulam limestones. Bioclasts of probable local origin are recognized on the basis of being extremely well-preserved and clearly of similar form or taxonomy to those whole fossils found encrusting limestone beds and within the interbedded shales. Abraded bioclastic material, including the very fine sand- to silt-sized carbonate that dominate lithofacies V4 and forms a matrix for lithofacies V3 packstones, is of indeterminate provenance. It may represent locally derived but extensively reworked shelly material, or bioclasts transported from other environments (i.e., the Hull Beds).

Three types of exotic particles (i.e., particles clearly not formed in the local environment) are present in the Verulam Formation. Most widespread is siliciclastic material (clay and quartz silt to fine sand). Apart from the shales, terrigenous material is disseminated in the limestones (clay content tends to increase upwards within graded beds). The second exotic particle type are calcispheres. These are most common in lithofacies H4, but are occasionally found in other beds. Calcispheres are thought to represent reproductive spores of dasycladacean algae (Wray 1977). Due to their small

size, and possibly hollow initial state, calcispheres were easily transported, and may have originated in the barrier-top and lagoon environments similar to those represented by the Hull Beds. The third type of exotic particle are the broken oncoids found in lithofacies V1, V2 and V3 (Fig. 2.5 B). These are interpreted as exotic as they are uncommon and almost always broken. Like calcispheres, the oncoids may have been hydrodynamically light (Verrecchia *et al.* 1997) and thus easily transported from an environment similar to the Hull's barrier top.

3.2.2 Paleocurrent indicators

Current patterns on storm-dominated shelves are variable and complex (Walker & Plint 1993). During storm events, onshore-directed winds pile water onto the shoreline, creating a storm surge. The ensuing onshore to offshore pressure gradient results in an offshore-directed relaxation flow along the sea-floor, which is then deflected by the Coriolis force to become a geostrophic current (Niedoroda *et al.* 1985). The Coriolis deflection of these initially offshore-directed flows may be up to 90° (Walker & Plint 1993). The geostrophic flows themselves are commonly too weak to move sand, but combined flows (oscillatory storm-waves plus geostrophic currents) will entrain and move sand with great efficiency (Arnott & Southard 1990; Walker & Plint 1993). Low-angle cross lamination in tempestites is interpreted by Nottvedt & Kreisa (1987) as the product of unidirectional-dominated combined flow. Laminae in such structures should generally dip in the direction of the unidirectional component of the combined flow.

Some of the most widely-used paleocurrent indicators in ancient storm deposits are sole-marks (e.g., gutter casts, tool marks, etc.), which are oriented parallel to current directions during early, intensive erosional phase of a storm event (e.g., Sami & Desrochers 1992, Leckie & Krystinik 1989). Unfortunately, no sole marks were observed in the course of this study, and the only paleocurrent data available is from cross-set orientations, imbrication directions (of intraclasts and bioclasts) and ripple-marks.

Ripple-crest trends

CGR crest trends are usually oriented parallel to gross shoreline trends (Leckie 1988). In the Verulam, two areas yielded excellent ripple-field orientations. On the Castor River near Embrun (loc. 29; Fig. 3.1 F), ripple crests show a strong northeast-southwest trend. In downtown Ottawa (locs. 8, 15 and 16; Fig. 3.2 E), a slightly wider spread between due north and due east is observed. These trends argue for an approximate shoreline trend of northeast to southwest.

Cross-set orientations

Composite paleocurrent roses were drawn for two areas: downtown Ottawa (Fig. 3.1 G; data from locs. 5, 8, 9, 11, 14, 15, 16 and 17 as well as Chaudière Falls) and the Embrun-Finch area (Fig. 3.1 H; data from locs. 29, 31 and 32). Both areas show a fairly broad spread of data, as may be expected from storm-dominated, shelf-like areas (Walker & Plint 1993). The rose diagrams show a strong southerly flow component, and a broadly spread but discernible, strong northeast-southwest component. A subordinate northerly

trend is also present in both data sets. If there is a regional northeast-southwest paleoshoreline trend, as suggested by the CGR orientations, then these diametrically opposed, broadly defined, approximately shore-parallel flow directions may represent geostrophically deflected storm currents. The southerly, apparently offshore flow direction may represent stronger currents less affected by geostrophic forces, or currents generated by a subordinate but persistent storm-track oriented parallel to the paleoshoreline.

Channel orientations and imbrication of intraclasts

It is difficult to determine the orientation of broad, shallow channels in a two-dimensional outcrop. Most of the clearly channelized beds of lithofacies V1 in were observed in downtown Ottawa (locs. 15, 16 and 17). They tend to have approximate north-south orientations. More precise paleoflow data can be acquired from imbrication of clasts within these channels (Fig. 3.1 G* - inset). Although there is little data from imbricated clasts in lithofacies V1, a marked north-south trend is indeed present. It would appear that these highest-energy events produced currents flowing normal to ramp's strike.

3.2.3 Tempestite proximity

General

The actual proximity of a single storm bed to the paleoshoreline, the actual depth of water in which it was deposited and the actual intensity or duration of the storm that is

responsible for its deposition are not easily determined. Tempestites may, however, be described in terms of relative *proximity* (Aigner 1985, Sami & Desrochers 1992). Qualitative, general proximity may be inferred from such lithological characteristics as texture, presence of intraclasts, presence of scours, bed thickness and thickness/frequency of tempestites relative to fairweather beds. Quantitative data, based largely on bedding thickness and frequency, may also prove useful in determining vertical changes in overall proximity (Sami & Desrochers 1992).

Relatively proximal tempestites (i.e., thicker, coarser-grained, amalgamated and more frequent storm beds) are the result of more intense, longer lived storm events, and are more likely to occur in shallower offshore environments. Conversely, distal tempestites (thinner, finer-grained and widely spaced storm beds) are the product of less intense, shorter lived and less frequent storm events, and are more likely to occur in deeper water offshore environments (Dott & Bourgois 1982, Aigner 1985, Sami & Desrochers 1992). Fluctuations in proximity can therefore be ascribed to either changes in relative sea-level or climatic changes (in actual storm frequency and intensity).

Proximity of the Verulam tempestites

In the Verulam Formation, the various lithofacies represent a range of relatively proximal to distal tempestites. The thick, coarse-grained and possibly reworked beds of lithofacies V1 and V2 are commonly associated with scour surfaces (e.g., Figs. 2.4 G, H), and appear to represent relatively proximal tempestites. Beds of lithofacies V4, which are the products of winnowing and fine calcareous sand-silt transport (see above) are

generally thinner-bedded and associated with more frequent and thicker interstorm shales; they are interpreted as relatively distal tempestites. The broadly-defined lithofacies V3 makes up a continuum of proximal (thicker, coarser-grained and better sorted) to distal (thinner, finer-grained packstones-wackestones) tempestites.

Proximal trends

Quantitative data from storm beds may be compiled and plotted against stratigraphic position in order to determine vertical shifts in tempestite proximity (Sami & Desrochers 1992). The section at Nepean Point (loc. 15) is the thickest exposure of the Verulam Formation examined in this study. The upper 17 m of the formation (about half of its total thickness) and its transition into the Lindsay Formation are exposed. The section was divided into 25 cm intervals and the following characteristics were recorded or calculated per interval: (1) total percentage of thickness occupied by limestone (Fig. 3.4 A); (2) maximum tempestite thickness (Fig. 3.4 B); (3) mean tempestite thickness (Fig. 3.4 C) and (4) tempestite frequency (i.e., number of tempestites per interval; Fig. 3.4 D). These characteristics were chosen based on the study of Sami & Desrochers (1992). The gaps in the proximity graphs (Fig. 3.4) are covered intervals or intervals dominated by nodular, Lindsay-like lithology.

Although fluctuations occur in the proximity trend graphs, there is only a faintly discernible upwards decrease in proximity. This implies that there was only subtle change in depositional environment as Lindsay-type deposition began to supplant Verulam-type deposition.

Figure 3.4: Tempestite proximity trends for the upper Verulam Formation at Nepean Point (loc. 15). Apparent proximity increases to the right side of each graph, with an increase in the value of each of the indices. Note that there is no clear trend as the base of the Lindsay Formation is approached. Cross-hatched box in lower part of graphs represents covered section. Grey boxes in upper part represent intervals of nodular, Lindsay-like lithofacies. The base of the Lindsay Formation is marked by bold, dashed line.

A: Percent thickness of limestone per 25 cm interval

B: Maximum tempestite thickness per 25 cm interval

C: Mean tempestite thickness per 25 cm interval

D: Tempestite frequency (number of tempestites per 25 cm interval).

3.2.3 Discussion

Style of tempestite deposition

The majority of the Verulam limestone beds are typical of bioclastic tempestites (compare to Kreisa 1981, Aigner 1985, Sami & Desrochers 1992). Several mechanisms by which storms can produce sharp-based, normally graded, wave- and current influenced beds have been proposed. In order to produce offshore, sandy tempestites in a siliciclastic setting, an offshore-directed storm current is required to move sediment from the shoreface. In carbonate systems, the same general physical processes must operate. The system is complicated, however, by the presence of local authigenic sediment production from the indigenous biota. Winnowing processes may outweigh the offshore transport. Indeed, Gagan *et al.* (1987) have shown that in at least some modern carbonate settings, storms may simply suspend and drop sediment, leaving a sorted, normally graded tempestite layer composed of essentially untransported material. Sprechtt & Brenner (1979) have suggested a similar model for shell accumulations in siliciclastic shale beds in the Jurassic of Wyoming. The presence of well-preserved bioclasts of identical type to the apparent fair-weather conditions (i.e., those fossils found within shales and encrusting limestone beds) are found as well-preserved, broken and unabraded grains in the Verulam tempestites implies that a great deal of the material within each bed is of essentially local origin. The presence of calcispheres, broken oncoids and fine terrigenous sand suggests that at least some of the sediment was transported from another source. Highly abraded bioclastic material may have also been transported from another environment, or could be grains of local origin which have survived multiple storm events.

The Verulam deposits were clearly influenced by oscillatory currents, unidirectional currents and combined flows, which could have moved sediment in from the shoreface and/or winnowed in-place fossiliferous muds. Whether these currents indicate transport of sediment only within the Verulam environment, or transport from another environment is difficult to tell. The paleocurrent data suggest a northeast-southwest trending strandline, with storm-current flows directed both parallel to and away from it. The paleocurrent data in from the Hull Beds (see above) suggests a similar strandline trend, perhaps slightly rotated (from northeast-southwest to approximately east-west), which provides some weak support for the Hull environments as a source for the exotic grains in the Verulam tempestites.

Inter-storm shales

Two basic conceptual “end-member” mechanisms may explain the formation of shale interbeds between storm-deposited sands: (1) the shales represent “background”, fair-weather sediments or (2) the clay- and silt-sized material was suspended/transported with the sand and deposited out of a cloud of suspended fines which may have persisted for a geologically short period (on the order of days) after the storm, and thus may be considered a part of the same event. The latter idea fits best in beds where sandy beds grade smoothly into the background muds. The first model, which is suggested as more likely for the Verulam Formation, is supported by the presence of sharp, encrusted or bored surfaces between the tempestites and the shales. It should be noted that many of the

Verulam beds exhibit an upwards increase in argillaceous content. This, however, is merely a function of waning flow, as are the other features of normal textural gradation.

In modern environments, hardgrounds may form in high- (Dravis 1979) or low-energy (Shinn 1969) environments, but in all examples their formation appears to be restricted to settings extremely low siliciclastic input. Within the Verulam, many apparent hardgrounds are overlain by directly shales (e.g., Fig. 2.6 A). This suggests that shale accumulation was either very slow or siliciclastic supply was ephemeral. Many hardgrounds have up to 2 cm of topographic relief the upper bounding surface of the bed on which they have formed. Episodic current or wave (swell?) activity of insufficient strength to significantly rework the tempestites may have kept their upper surfaces free of mud, allowing for sea-floor lithification. The presence of vertically scattered, *in-situ* benthic fossils in the shales (brachiopods and bryozoans) suggests relatively continuous deposition, or depositional “events” causing relatively imperceptible aggradation of the shale bed. The episodes of non-deposition recorded by the hardgrounds must have been of sufficient length to produce significant lithification and allow for the often dense *Trypanites* borings to have been produced. It seems probable that several pauses in deposition (or gentle winnowing events) may have occurred during the deposition of a given centimetre-scale shale bed.

Calcareous silt

Calcareous silt is abundant in the Verulam Formation, forming discrete beds (lithofacies V4), providing a matrix for wackestones and packstones (lithofacies V3) and

comprising a significant proportion of the shale beds (lithofacies V5). A major source of suspended, silt-sized particulate carbonate on modern shelf waters is the abrasion and breakdown of bioclastic material (e.g., Fitzgerald *et al.* 1979). Mechanical abrasion is accelerated by the inorganic (Alexanderson 1974) and/or microbial (e.g., Young & Nelson 1985, Tudhope & Risk 1985) degradation of grains. Grain shapes of bioclastic silt may reflect the boring activity of particular organisms (sponge chips of Young & Nelson 1988). Alternately, the shape of bioclastic silt may reflect the microstructure of the organism that produced the original shell (e.g., *Mytellus* fibres of Fitzgerald *et al.* 1979, see also Young & Nelson 1985, 1988). Such characteristic shapes have not been recognized in the Verulam calcareous silts, which are often difficult to distinguish from the cement that binds them. It is also difficult to determine whether or not the silt is of local origin. The abundant presence of calcareous silt in the fair-weather shales certainly suggests that it was present as “background” suspended load.

The calcisiltite/very fine grainstone tempestites (lithofacies V4) are characterized by sharp bases, normal gradation and hummocky cross-stratification. They are often spatially associated with thick and/or abundant shale beds. Only a few of these calcisiltites are observed to smoothly grade into shale. This implies that lithofacies V4 may be the product of winnowing of thick calcareous shale beds.

3.2.4 Summary: depositional conditions of the Verulam Formation

Each of the Verulam limestone lithologies represents storm-induced deposition on an open-marine, northeast-southwest striking ramp. The interbedded shales (lithofacies

V5) represents intermittent, slow, hemipelagic deposition. The intermittence of the shale deposits may reflect either episodic supply or episodic, weak current or wave activity. Apparently re-activated coarse-grained ripple beds (lithofacies V2) provide further evidence for relatively weak current and/or wave activity between recorded storm events.

The various limestone lithologies represent differing storm intensities, water depths and sediment sources. The carbonate sediment was a mixture of locally-derived bioclasts (and their abrasion products?) and imported carbonate and siliciclastic material; the proportions of imported to locally-derived material is difficult to ascertain, but it is probable that the latter outweighs the former. The characteristics of the four limestone lithofacies may be used to imply a general trend of “proximal” to “distal” tempestites; in order of decreasing proximity: V1, V2, V3, V4.

3.3 Paleoclimatic setting of the Upper Ottawa Group: tropical or temperate?

3.3.1 Potential evidence of cool-water deposition

General

Chave (1967) and Lees & Buller (1972) noted that modern carbonate sediments were not restricted to tropical settings, and that temperate carbonate deposition should be represented in the ancient sedimentary record. For a recent review of current concepts in cool-water carbonate sedimentology, see James (1997). Several authors, including Brookfield (1988), Patzkowsky & Holland (1993), Lavoie (1995) and Pope & Read (1997), have suggested that the Trenton Group and equivalent units in eastern North America represent temperate- rather than tropical-style carbonate deposition. The Upper

Ottawa Group is equivalent to the Trenton Group of other areas (see Chapter One), and is subject to similar interpretation. The temperate carbonate interpretation is largely based on the fact that the shallow-water facies of the Trenton-equivalent successions are, in most areas, characterized by a profusion of echinoderm, bryozoan and brachiopod debris and lack micrite, ooids and aggregate grains. This *bryonoderm* grain type association (i.e. *bryozoans* and *echinoderms*; Beauchamp 1994) is considered by some workers (e.g., Pope & Read 1997, Beauchamp 1994, Lavoie 1995, Brookfield 1988) to be a Paleozoic equivalent of the modern *foramol* (*foraminifers* and *molluscs*; Lees & Buller 1972) and *bryomol* (*bryozoans* and *molluscs*; James 1997) grain type associations which are characteristic of modern cool-water carbonate depositional settings. In contrast, other Upper Ordovician carbonates in eastern North America (including the Black River Group and its equivalents; Patzkowsky & Holland 1993, Lavoie *et al.* 1998, Salad Hersi 1998) are more similar to modern warm-water carbonate settings. They contain abundant green algae and colonial corals, directly analogous to the modern *chlorozoan* assemblage (*chlorophytes* and *anthozoans*; Lees & Buller 1972) as well as ooids, micritic sediments and small, frame-built bioherms (e.g., Harland & Pickerill 1988).

Lees & Buller (1972) and Lees (1975) noted that, in the cases they studied, chlorozoan carbonates are typical of modern tropical zones and foramol carbonates are typical of modern temperate zones. Lees noted that the foramol association also occurred in tropical settings in areas where minimum annual salinity was low. Few workers have recognized ancient potential cool-water carbonates as potential low-salinity carbonates (Brandley & Krause 1997 are a notable exception).

James (1997) provides six potential criteria for the recognition of cool-water carbonate depositional environments in the sedimentary record. In order of *decreasing* reliability, these are: (1) interbedding with glacigene deposits; (2) high paleolatitude; (3) presence of abiotic, cool-water carbonate phases (e.g., glendonite or ikaite) or pseudomorphs thereof; (4) deposits exclusively of heterozoan grain-type associations (including bryonoderm, bryomol and foramol); (5) Interbedding of heterozoan and chlorozoan grain-type associations; and (6) geochemical evidence from bioclasts and cements. Geochemical criteria are considered unreliable, as they are subject to extensive alteration during diagenesis. The main line of evidence for cool-water carbonate deposition in the Ordovician, then, ranks only fourth on James' (1997) list. Furthermore, Tasch (1980) and other workers (B. Pratt and P. Copper, pers. comm. 1998) suggest caution in drawing such paleoecological conclusions from such high-level taxonomic groups. Lees & Buller (1972), who first initiated the use of grain type associations, did so in order to provide a tool for sedimentologists working in situations where lower-level taxonomic identifications are difficult or impossible. Furthermore, Lees & Buller (1972) notes that the phylum-level changes in biotic associations observed on modern shelves (i.e. the transition from "chlorozoan" to "foramol" sediments) occur rapidly and with only minor transition zones. The change in depositional environment would be "heralded by other changes" (Lees & Buller 1972, p. M69) if plotted out at a lower level of taxonomy. Thus, although extensive research on the distribution of low-level taxa (genera, species) might provide for more detailed paleoecological interpretations, the high-level divisions appear to be sufficient for the warm- and cool-water differentiation in modern

environments and those Holocene settings directly comparable (Lees 1975, Lees & Buller 1972). Lees (1975) does, however, caution that the general changes in the ecological roles of phyla and their distribution in all carbonate-producing environments have occurred through the Phanerozoic (e.g., the diminishing role of crinoids as sediment producers since the end of the Paleozoic).

Upper Ottawa Group

Like the other Trenton-equivalent units in eastern North America, most of the Upper Ottawa Group is characterized by a bryonoderm grain type association, and lacks ooids or aggregates (Figs. 2.1, 3.5). Only the lagoon and barrier-top lithofacies associations of the Hull Beds contain significant calcareous chlorophytes, colonial corals, ooids and abundant micrite (Figs. 2.1, 3.5). The barrier-top association contains a transitional grain type association, including elements of both the bryonoderm and chlorozoan associations. Thus it is possible that the Hull Beds represent mixed cool- and warm-water deposition (Kiernan *et al.* 1998, Fig. 3.5), with cool-water deposits in the open ocean and shallow, solar-heated, marginal lagoons.

No other evidence of cool-water carbonate deposition has been observed in this study. Brookfield (1988) suggests that the initial calcite mineralogy of most bioclasts and cements of the Upper Simcoe Group was suggestive of early diagenesis in a cool-water setting. This does not appear to be a reliable indicator, however, since the early cements present in the warm-water, chlorozoan carbonates the lagoon lithosome of the Hull Beds also appear to be calcitic (see Chapter Five). The paleolatitude (~15° to 30° south of the paleoequator; Van der Voo 1988) certainly does not support cool-water deposition, rather

Figure 3.5: Facies model and grain-type distribution of the Hull Beds. Note the Warm-water lagoon environments contain abundant “photozoan” (James 1997) or “coralgall” (Lees & Buller 1972) bioclast types as well as ooids and homogenous peloids. Oncoids are restricted to the high-energy barrier crest, which contains a transitional grain-type association. The barrier-front environments are characterized by brachiopods, pelmatozoans, and bryozoans: a “heterozoan” (James 1997) or “bryonoderm” (Beuachamp 1994) grain-type association.

suggesting that bryonoderm carbonates were not restricted to temperate zones in the Ordovician. Lees (1975, p.185) points out that grain-type associations should be used only to interpret paleotemperature and paleosalinity, not paleolatitude. If the Upper Ordovician bryonoderm sediments are cool-water deposits, then why are the equatorial oceans not warm? Lavoie (1995) suggests that abundant phosphatic material preserved on hardgrounds in the Trenton Group of southern Quebec is evidence for upwelling of cool, nutrient-rich waters from the Taconic foredeep. Similar phosphates occur in the post-Trentonian Collingwood Formation of central Ontario (C. Tsujita, pers. comm., 1997). In the central Appalachians, the appearance of abundant, possibly upwelling-related phosphates roughly coincides with the switch from tropical (chlorozoan) to temperate (bryonoderm) carbonate deposition at the end of Blackriveran time (Patzkowsky & Holland 1993). No such phosphate, however, has been observed in the Ottawa Group.

As already mentioned, Pope & Read (1997) have suggested a tide-influenced, but otherwise generally Hull-like, barrier-and-lagoon arrangement as the inner-ramp facies of interpreted cool-water, Trenton-equivalent carbonates in Kentucky. They also note that their innermost ramp facies (lagoon) is characterized by a restricted, chlorozoan grain type assemblage, while the open ramp facies contain grains of the bryonoderm assemblage. Accordingly, they have proposed that the open-ramp facies were deposited in cool-water, and the coëval lagoons were warmed by solar radiation.

3.3.2 Discussion

Comparisons with Cenozoic and Recent temperate environments

Extensive descriptions of Tertiary to Recent temperate carbonate-producing are found in the volumes edited by James & Clarke (1997) and Nelson (1988). Lavoie (1995) and Brookfield (1988) have suggested that the Trentonian successions in southern Quebec and central Ontario may resemble modern cool-water carbonate environments from the southern hemisphere. These high-energy shelves, described by Nelson *et al.* (1992), Collins (1988), Boreen & James (1993), Bone & James (1993) and James & Bone (1994), are the sites of extensive carbonate deposition off the coasts of New Zealand and southern Australia. These are wave- and swell-dominated settings with an effective fairweather wave-base of 80-100 m or deeper (Bone & James 1993, Collins 1988). The inner portions of these shelves, which may be tens to hundreds of kilometres wide, are generally swept clear of sediment and are the site of regionally extensive hardground formation (Nicolaidis & Wallace 1997, James *et al.* 1994). Near and below fairweather wave-base, bioclastic sands and gravels accumulate. Grain-types are dominated by bryozoans, molluscs, calcareous rhodophytes, foraminifers and echinoids. Bedforms include large sand-wave complexes and large ripples (Boreen & James 1993, Boreen *et al.* 1993). At the coast of south Australia, beach and dune complexes are composed of relict and wave-reworked carbonate and siliciclastic material, a certain portion of which is derived from the encrusting skeletal fauna of the inner, non-aggrading shelf (Boreen *et al.* 1993, James *et al.* 1994, Spriggs 1979, Von der Borsch 1976). Some of these nearshore systems act as barriers to protect lagoons and ephemeral saline- to fresh-water lakes

(including the famous Coorong; Von der Borsch 1976.; Spriggs 1979) or estuaries. The Upper Ottawa Group, however, lacks regional unconformities marked by extensive hardground formation as reported by James *et al.* (1994) and Nicolaides & Wallace (1996). The southern Australian shelf is characterized by a “distally-steepening ramp” morphology (Read 1985, Jones & Desrochers 1993). There is no evidence of a shelf-break preserved in the Upper Ottawa Group or the stratigraphically adjacent strata.

Modern nearshore temperate carbonates have also been recently described from a warm-temperate carbonate ramp off the Balearic Islands by Fornos & Ahr (1997). Although the descriptions of the inner-ramp facies are not detailed enough to permit close comparison, they reveal some striking similarities. A barrier island-lagoon system is locally developed on the coasts of Mallorca and Menorca. The lagoons are ~1m deep and characterized by seasonal fluctuations in temperature (~10-25°C) and variable salinity (depending on local hydrographic factors, 1.5 to 45 ppm). Lagoon sediments are dominated by laminated, bioturbated, shelly siliciclastic mud. The bioclastic components are mostly molluscs, ostracods and foraminifers with rare *Halimeda* - a grain assemblage comparable to some beds of lithofacies H4 and H5. The barrier islands are composed of ~10 m thick, stacked Pleistocene and Holocene packages of beach and dune facies. Beach sediments are composed of planar, low-angle laminated gravely sand. Sediments are characterized by intraclasts, molluscs, benthic foraminifers, rhodolites, bryozoans and echinoids: a heterozoan assemblage (James 1997) that may be compared to the grain-types not only of the barrier-front facies association of the Hull Beds, but the other major units of the Upper Ottawa Group as well (Bobcaygeon, Verulam and Lindsay formations).

Comparison with Late Paleozoic cool-water environments

Cool-water carbonates have been interpreted from the Permian (e.g., Draper 1988, Beauchamp 1994, Beauchamp & Desrochers 1997) and Mississippian (see review by Martindale & Boreen 1997). Both Permian and Mississippian shallow-marine (less than ~50 m) facies are characterized by bryonoderm grain type associations. These studies present further evidence for cool-water paleoenvironments including with ice-rafted dropstones either in bryonoderm carbonates (Draper 1988) or spatially and temporally equivalent sediments (Beauchamp 1994) and ikaite pseudomorphs (Brandley & Krause 1997). Facies models are not currently available for the Permian examples. Beauchamp (1994) and Beauchamp & Desrochers (1997), however, demonstrate that bryonoderm carbonates migrate from cool, sub-thermocline environments to supplant to warmer-water carbonates in shallow environments in northwest Pangea as global climates cooled through the Permian.

Martindale & Boreen (1997) have described a general model for mixed cool- and warm-water carbonate sedimentation on Mississippian ramps in Western Canada. A sketch of their model is shown in Figure 3.6. The Hull Beds lacks the extensive ooid shoals incorporated as part of Martindale & Boreen's (1997) barrier system. Although bryozoan bioherms, found on the middle- to outer-ramp facies in the Mississippian model, have not been observed in eastern Ontario, they have been reported from the equivalent Deschambault Formation in southern Quebec by Lavoie (1992, 1995). The shallow thermocline, which is figured prominently by Martindale and Boreen (1997), is considered by some workers to be an oceanographic improbability, as it is unlikely to be a stable

arrangement of water masses (B. Pratt, pers. comm., 1998). A shallow thermocline is not required for a mixed warm- and cool-water interpretation of the Hull, however, as all of the warm-water environments are concentrated behind or directly on top of a barrier, where solar heating could easily warm water to greater than 18° C.

As already mentioned, Brandley & Krause (1997) have noted the presence of ikaite pseudomorphs in Mississippian bryonoderm carbonates of the southern Rocky Mountains. Their overall depositional model is similar to the ideal model presented by Martindale & Boreen (1997; Fig. 3.6). They suggest, however, that the without the ikaite pseudomorphs to prove cool-water conditions in their middle- to outer-ramp facies that they would be unable to distinguish between a temperature or salinity control on the distribution of apparent warm- and cool-water grain type associations. Lees (1975) has demonstrated that modern foramol sediments occur in tropical areas where annual minimum salinity is low. This idea presents an intriguing possibility for the Upper Ottawa Group: did the Ottawa Embayment, or indeed the entire marginal Taconic foreland basin, contain a relatively low-salinity sea? Railsback *et al.* (1990) present isotopic and morphometric data from fossil brachiopods in deeper-water Trenton Group facies (New York State) that suggest deep, relatively warm water was ponded in the deeper parts of the basin.. Could this partitioning in salinity have resulted in a layer of abnormally fresh water above a halocline, thus bathing the shallow areas of the foreland basin in brackish water? A thorough geochemical, paleontological and sedimentological investigation of the shallow-water facies would be required to make such a determination. Railsback *et al.* (1990) further suggest a complex set of paleoceanographic conditions could not only

Figure 3.6: General facies model for Mississippian ramps in Western Canada (after Martindale & Boreen 1997). Shallow-water, inner-ramp facies show "tropical" characteristics (ooids, algae, micrite, etc.). Deeper-water, middle- to outer-ramp facies display "temperate" characteristics (abundant bryozoans and crinoids, very little micrite, etc) and may contain other features suggestive of cool water temperatures (e.g., ikaite pseudomorphs, Brandley & Krause 1997).

lead to this saline water mass in the foredeep, but also allow cold polar currents to enter the Taconic basin from the paleo-south polar ocean.

3.3.3 Summary: is the Upper Ottawa Group a cool-water carbonate deposit?

Based on the available evidence (i.e., a bryonoderm grain type association), it is difficult to justify a cool-water interpretation for the Upper Ottawa Group. The evidence present in the Hull Beds, however, suggests that there is some fundamental environmental factor that differs between the open-ocean and lagoonal settings. This control could possibly be temperature, but without supporting evidence of cool-water deposition, salinity differences provide an equally likely alternative. A third possibility is evolutionary ecology: perhaps crinoids, bryozoans, brachiopods and pelecypods were the most abundant organisms adapted to survive in abundance in high-energy, shallow marine environments in the late Ordovician. The only distinctively “warm-water” high-energy deposits in the Ordovician tend to be dominated by calcite ooids (e.g., Cantrell & Walker 1989). Abraded coral fragments are never reported in abundance from carbonate sands of Ordovician age in spite of the fact they are a major constituent of modern, warm-water biocalstic sands in both reef-dominated (e.g., Bahamas; Ball 1967) and non-reef-dominated (e.g., Persian Gulf; Kendal & Skipwith 1968) tropical settings.

The predominance of calcite over aragonite bioclasts in modern temperate carbonate sediments is also widely expressed in the interpreted temperate environments of the Paleozoic (e.g., Beauchamp 1994, Pope & Read 1997). The general geochemical state of the oceans was one that preferred calcite, rather than aragonite precipitation

(Sandberg 1983): a fact which may have many unpredictable effects on faunal distribution.

Could the Hull lagoons have been small, local “aragonite seas” in a “calcite ocean”?

Chapter Four: STRATIGRAPHY OF THE UPPER OTTAWA GROUP

4.1 Introduction

4.1.1 General

Lithostratigraphic reconstruction of the Upper Ottawa Group is limited by the availability of data from outcrop and the subsurface. From the Russell and Lebreton cores (locs. 28 and 10), it is clear that the four major stratigraphic units overlie each other in the order Bobcaygeon Formation, Hull Beds, Verulam and Lindsay formations as stated in previous work (see Fig. 1.8). However, the Hull Beds cease to be a mappable lithostratigraphic unit at some point southeast of Ottawa. Salad Hersi (1998) and Salad Hersi & Dix (1997b) have suggested an interfingering relationship between the Hull and Verulam strata. Dix *et al.* (1997a) further suggest that the Verulam strata may onlap shoal-intershallow paleotopography on the upper contact with the Hull Beds. The present study has involved re-evaluation of three of Salad Hersi's (1998) key sections: Clifftondale and L'Orignal quarries (locs. 35 and 36) and the McCarthy Road outcrop (loc. 26), and places these exposures within the Bobcaygeon Formation. Salad Hersi's (1998) suggestion that the Hull Beds and Verulam Formation are lateral equivalents was largely based on his observation that, in at least one area (northeastern Ottawa; sections 20b and 25), the Hull Beds are overlain by several metres of distinctive Lindsay Formation lithologies: the Verulam Formation appears to be absent. A variation of Salad Hersi's (1998) model and alternatives to it are explored in this section. New biostratigraphic, lithostratigraphic and environmental-stratigraphic interpretations present here support an interfingering relationship between the Hull Beds and the Bobcaygeon Formation, and

suggest that the Lindsay-like beds at localities 20b and 25 are an anomaly in the lower Verulam Formation.

4.1.2 Biostratigraphy

The biostratigraphy of the Upper Ottawa Group (Fig. 4.1) is poorly constrained. Conodont studies on the Ordovician strata of eastern Ontario place the age of the Hull Beds and Bobcaygeon Formation between the Rocklandian and lower Shermanian stages (McCracken 1995, Uyeno 1974). McCracken's (1995) study provides a slightly younger upper age limit for the Hull Beds than Uyeno (1974). Conodonts from the Lindsay-like beds and the Hull strata that underlie them at Aviation Parkway (loc. 20b) give the same age range (Rocklandian to early Shermanian) as samples from the Bobcaygeon Formation at McCarthy Road (loc. 27) (McCracken 1995). The graptolite-zone equivalent upper age limit of early Shermanian is upper *Climacograptus americanus* or lower *Orthograptus ruedemanni* (Bergström & Mitchell 1986). All of these ages are older by at least one graptolite zone than the upper half of the Verulam Formation based on graptolites collected from its upper ~20 m in downtown Ottawa (locs. 14, 16 and 17), which belong to the *Climacograptus spiniferus* zone (J. Riva, written comm.). The *C. Spiniferus* zone is equivalent to the Edenian stage (Bergström & Mitchell 1986, Melchin *et al.* 1994).

4.1.3 Chronostratigraphy

Two possible K-bentonites have been reported from the Hull Beds in the study area: one at the Klock Quarry (loc. 1; Kolata *et al.* 1996), and one near the intersection of

CHAMPANIAN	Richmondian
	Maysvillian
	Edenian = <i>Climacograptus spiniferus</i> zone
	Shermanian
	Kirkfieldian
CHAZYAN	Rocklandian
	Blackriveran

- (1) Conodont age-range for the Hull beds determined by Uyeno (1974) from outcrops throughout Ottawa and Hull, including locs. 19, 23 and 24 of this study.
- (2) Conodont age-range for the Bobcaygeon Formation at loc. 27, the Hull beds at loc. 20 and the Lindsay-like strata at loc. 20 determined by McCracken (1995). Identical age-range found for all strata.
- (3) Graptolite age of Verulam strata within 15-20 m of the Verulam-Lindsay transition. Provided by J. Riva (written comm.) based on specimens collected from locs. 14, 16 and 17a.

Figure 4.1: Conodont- and graptolite-based biostratigraphic control for the Upper Ottawa Group. After Uyeno (1974), McCracken (1995), J. Riva (pers. comm.), Melchin et al. (1994) and Bergstrom & Mitchell (1986). Note that the the upper half of the Verulam Formation (range-line 3; J. Riva, written comm.) is significantly younger than the Lindsay-like beds exposed at Aviation Parkway (range-line 2; McCracken, 1995).

St. Joseph Blvd. and Tenth Line Rd. in Orleans, Ontario (Salad Hersi 1998). The ash-bed exposed in the Klock Quarry (loc. 1) has been interpreted by Kolata *et al.* (1996) as an equivalent the Deike Bed: a very widespread K-bentonite age-dated at 457 million years (Samson *et al* 1989). W. Huff (pers. comm., 1998), however, suggests that this bed may actually correlate to an unnamed, biotite-bearing bentonite reported from central Ontario by Liberty (1969). The bulk mineralogy of the bed (illite-quartz-biotite-calcite as determined by X-ray diffraction; ~13% total carbonate from carbonate bomb analysis) supports Huff's interpretation. The stratigraphic position of Liberty's bentonite in central Ontario (almost coincident with the Bobcaygeon-Verulam contact) is also preferable over the Deike correlation, since the Deike ashfall is widely considered to be a Blackriveran event (Kolata *et al.* 1996). The K-bentonite reported by Salad Hersi (from the intersection of Tenth Line Rd. and St. Joseph. Blvd. in Orleans, Ontario) lies in Hull strata, about 1 m below the base of the Verulam Formation. It is unknown at present whether or not these two ash-beds represent the same volcanic event.

4.2 Lithostratigraphy of the Upper Ottawa Group

4.2.1 Bobcaygeon Formation

Characteristics

The Bobcaygeon Formation of eastern Ontario is characterized by pale grey weathering, alternating fine- and coarse-grained, occasionally cherty, thin- to medium-bedded bioclastic packstone, grainstone and calcisiltite-wackestone and very thin (millimetres) to ~15 cm thick, fossiliferous shales (Williams 1991, Salad Hersi 1998,

Section 2.4). The major distinguishing characteristics are: (1) apparent thick stratification on fresh surfaces; (2) actual bedding thickness of 3-20 cm, often marked by regular alternation between coarse- and fine-grained limestone textures; and (3) bryozoan-rich shales. When heavily bioturbated, these alternating fine- and coarse-grained beds may have a nodular appearance on weathered surfaces. One or more intervals of thicker-bedded, cross-stratified, crinoid-dominated medium- to coarse-grained grainstone are encased by the typical Bobcaygeon lithologies in the upper portion of the formation. Intraclastic and bioclastic rudstones fill 20-50 cm deep channellized scours at some horizons. See Section 2.4 for details.

Boundaries

The Chaumont-Bobcaygeon boundary has been described by Salad Hersi (1998). The upper boundary of the Bobcaygeon is present at five of the studied localities. In four of these localities (locs. 3, 6, 10 and 26), the Bobcaygeon is overlain by Hull strata. In the Lebreton core (loc. 10), the base of the Hull Beds is marked by the first appearance of micritic wackestone (lithofacies H4). At Lac des Fees Parkway (loc. 6), the Bobcaygeon is overlain by thick, *Solenopora*-bearing beds of lithofacies H1 and H2. At Boul. de Maisonneuve in Hull, it is overlain by thick beds of lithofacies H2. In the Russell core (loc. 28), the contact is more subtle: medium-bedded bioclastic limestones with thin shaley partings of the Bobcaygeon are overlain by somewhat thinner-bedded, conspicuously graded beds of bioclastic packstone interbedded with slightly thicker shales of the Verulam Formation. The Hull Beds do not appear to be present in the Russell core.

A significant scour surface is developed at top of the Bobcaygeon Formation in the city of Hull. At Boul. de Maisonneuve (loc. 6), the scour is essentially planar and dips to the southwest, progressively truncating Bobcaygeon strata. At Lac des Fees, the scour is highly irregular and undercut with up to 30 cm of sharp relief. Minor evidence of subaerial exposure is preserved in the uppermost Bobcaygeon strata at this locality (e.g., vadose cement fabrics; see Section 5.1).

Regional correlations

The Bobcaygeon Formation of eastern Ontario is correlative with strata in its type area, central Ontario (Armstrong 1997, Liberty 1969). The bryozoan-rich shales, which are defined in this study as a critical tool in distinguishing the Bobcaygeon strata from Verulam strata, do not exist in the type area (M. Brookfield, pers. comm.). Their presence in the section in eastern Ontario does, however, identify a similarity between the eastern Ontario's Bobcaygeon Formation and the Deschambault Formation of southern Quebec, where densely bryozoan-rich shales and rare bryozoan bioherms have been reported in association with similar lithologies (Lavoie 1992, 1995; Lavoie *et al.* 1998).

Remarks

The interval(s) of Hull-like crinoidal grainstone mentioned above are a major cause of confusion in previous stratigraphic studies in eastern Ontario. These 2 to 7 metre thick grainstone bodies essentially consist of lithofacies H2. Any apparent Bobcaygeon-Hull contact observed where the Hull Beds contain only a few metres of strata resembling

lithofacies H2 is therefore suspect. This problem is well-illustrated by the upper 5 m of the L'Original Quarry (loc. 36). Although this interval shares many lithological characteristics with the Hull Beds, but cannot be assigned to them since it cannot be demonstrated to immediately underlie the Verulam Formation. Other examples include the Embrun Quarry (Salad Hersi 1998), the McCarthey Rd. section (loc. 27), the lower grainstone body in the Lebreton core (91 to 84 m depth, loc. 10) and the isolated small sections consisting entirely of cross-bedded crinoidal grainstone at localities 24 and 30. The Bobcaygeon-encased grainstone bodies are generally poor in *Solenopora* and oncoids, and have medium-scale trough cross-lamination as the dominant structure rather than the planar lamination that is characteristically dominant in the Hull strata.

4.2.2 Hull Beds

Characteristics

The lithological characteristics of the Hull Beds are described in Section 2.2. The Hull strata show considerable lithological heterogeneity, ranging from micrites and calcisiltites to rudstones and grainstones. The unit generally shale-free.

Boundaries and thickness

The lower boundary of the Hull is defined as the top of the Bobcaygeon Formation (see above). The upper surface of the Hull is known from only four localities (locs. 11, 20b, 25 and Salad Hersi's [1998] Tenth Line Road outcrop in Orleans, Ontario). In the Lebreton core (loc. 10), the uppermost strata of the Hull Beds are bioturbated calcisiltite

(lithofacies H5) which are sharply overlain by Verulam strata. At Aviation Parkway, the southern portion of the outcrop (loc. 20b) contains a knife-sharp contact between medium- to thick-bedded, fine grained bioclastic and peloidal grainstones (lithofacies H2 and H3), and heavily bioturbated, nodular, argillaceous packstone to wackestone apparently representing the Lindsay Formation. At Beechwood Cemetery (loc. 25), an abandoned quarry exposes 8 m of the Hull Beds (lithofacies H2 and H3). A short distance (about 25 m) to the North and less than 2 m uphill from the top of the quarry, several small outcrops of the Lindsay Formations are present. As Salad Hersi (1998) noted, the Verulam Formation does not appear to overlie the Hull Beds at localities 20 or 25 in northeast Ottawa (see remarks on Verulam Formation). Salad Hersi (1998) also reports an outcrop of the Hull-Verulam contact on Tenth Line Road in Orleans, Ontario. He reports that thin-bedded, bioclastic limestones of the Verulam Formation sharply overlie 8 m of shale-free, thick-bedded crinoidal grainstone of the Hull (lithofacies H2 and/or H3 of this study). Salad Hersi (1998) also mentions a potential K-bentonite from this locality located about 1 metre below the Hull-Verulam contact.

The Lebreton core (loc. 10) provides a thickness of 29.3 m for the Hull Beds. This is greater than any of the major outcrops, including the Klock Quarry (loc. 1; 27.1 m), Francon Quarry (loc. 26, 22 m) and downtown Ottawa-Hull (locs. 6, 7a, 7b, 7c and 13 combining for a total of 26.9 m assuming no stratigraphic overlap).

Regional correlations

The Hull Beds have no lithostratigraphic equivalent outside of eastern Ontario. The upper member of the Verulam Formation of central Ontario (Liberty 1969, Armstrong 1997, McFarland 1997) resembles lithofacies H2, but does not likely represent a formerly continuous unit with the Hull strata. Salad Hersi (1998) and Salad Hersi & Dix (1997b) compared the Hull Beds with the King's Falls limestone of upstate New York, a unit which also bears lithological similarities to the Bobcaygeon Formation (Cameron 1973). Certain outcrops ascribed to the Deschambault Formation of southern Quebec (Lavoie 1992, 1995) are also lithologically similar to the Hull, while others resemble the Bobcaygeon of eastern Ontario.

Remarks

The Hull Beds do not represent a *regionally extensive mappable unit*, as required for a unit of formation rank under the North American Stratigraphic Code (NACSN 1983, article 24) The Hull strata should, as such, be assigned to either the Bobcaygeon or the Verulam formations in the capacity of member or as informally named *beds*. The precise position of the Hull in the formal nomenclature is discussed below.

4.2.3 Verulam Formation

Characteristics

The lithological characteristics of the Verulam Formation are described in section 2.3. Like the Bobcaygeon, the Verulam Formation consists of pale- to blue-grey

weathering, thin- to medium bedded bioclastic packstone/grainstone and shale.

Distinguishing features of the Verulam Formation include: (1) generally thinner limestone beds than the Bobcaygeon; (2) conspicuous normal textural gradation of limestones; (3) comparatively unfossiliferous shale beds; and (4) presence of cemented burrow-tubes (*Planolites*, *Chondrites* and *Phycodes*) in shale beds. The lower parts of the Verulam Formation may locally contain lenses of nodular, bioturbated wackestone-packstone very similar in appearance to the Lindsay Formation (see Sections 4.1 and 4.3).

Boundaries and thickness

The base of the Verulam Formation was not observed in outcrop in the course of this study. Its base was, however, observed in both the Russell and Lebreton cores (locs. 28 and 10). The known exposures are described above as the tops of the Hull Beds and Bobcaygeon Formation. The Verulam Formation is gradationally overlain by the Lindsay Formation at six of the studied outcrops (locs. 9, 10, 15, 18 and 33) and in the Russell core. The transition is expressed as a twofold gradation: both vertical lithological gradation and stratigraphic interfingering. At all exposures of the transition, a three to six metre thick stratigraphic interval of interfingering between Verulam and Lindsay lithologies is observed. Intervals of nodular Lindsay lithologies are typically between 25 and 80 cm thick, and are separated by 0.5 to 2 metre thick intervals of Verulam beds. In addition to the interfingering of facies, the Verulam becomes more heavily bioturbated in its upper portions, although the bedding is still well-enough defined to be lithologically

distinct from the very heavily bioturbated and stylonodular Lindsay strata (see Figs 2.7 F). This pattern is best seen at Nepean Point (loc. 15) and the Ste. Isadore Quarry (loc. 33).

In this study, the top of the Verulam Formation is defined as the *base of the first package of heavily bioturbated, stylonodular, argillaceous packstone-wackestone of greater than one metre thickness*. Williams (1991) arbitrarily defined the upper contact of the Verulam Formation as the top of highest shale bed of greater than five centimetres thickness. Shales of five or more centimetres thickness are not common in the Verulam Formation; only six such beds occur in 17.3 m of exposed Verulam strata at Nepean Point (loc. 15). Thus Williams' (1991) definition is likely to place the boundary within about two or three metres of the actual contact (assuming the thick shales are evenly distributed through the formation, as the available data would indicate). At Nepean Point, Williams' (1991) definition is fairly accurate: the major lithologic break (i.e., the top of the uppermost prominent Verulam "finger") occurs about 35 cm above the last thick shale bed of >5 cm thickness. In the Russell core (loc. 28), Williams' (1991) contact is located at a three centimetre-thick shale, which lies several metres above the last shale of greater than five centimetres thickness. Williams' (1991) pick for the top of the Verulam Formation in the Russell core does appear to be accurate, however, because it is located at the apparent final switch from relatively well-bedded, shaley grainstone-packstone to nodular, bioturbated shaley packstone-wackestone.

The Russell core (loc. 28) contains the only complete section through the Verulam Formation. Here, the formation is 40.1 m thick. The Lebreton core (loc. 10) terminates within the Verulam Formation, but was drilled ~20 m away from an outcrop that exposes

the Verulam-Lindsay transition (Lebretton St., loc. 11). The base of the Verulam occurs at 29.4 m depth in the Lebretton core, and its top occurs at 6 m in the Lebretton Street outcrop. Allowing for a 2.5 m uncored interval at the top of the borehole and about 1 m difference in elevation between well-head and the base of the outcrop, a thickness of about 39m is obtained for the Verulam Formation. A cursory examination of unmapped strata in the Lebretton Flats-Chaudière area of Ottawa suggests a similar thickness. This suggests a remarkably consistent thickness of about 40 m for the Verulam Formation between downtown Ottawa and Russell, with the possible exception of northeast Ottawa (locs. 20b and 25). The anomaly of the Aviation Parkway south outcrop (loc. 20b), where strata apparently belonging to the Lindsay Formation rest directly on the Hull Beds, is suggestive of extreme variations in thickness of both the Hull Beds and/or Verulam Formation (and/or Lindsay Formation!), but can be accounted for if the Verulam contains pods of Lindsay-like lithologies (see below). Biostratigraphic data (see above) also suggests that the Lindsay-like lithologies exposed at locality 20b are older than the upper half of the Verulam Formation in downtown Ottawa.

Regional correlations

The Verulam Formation of eastern Ontario is lithologically similar to the Lower Member of the Verulam Formation in its type area in central Ontario (Armstrong 1997, Liberty 1969), although it appears to be rather less shaley (personal observation). The term “Sherman Fall” is still used by petroleum industry workers in the southwestern Ontario subsurface in reference to the equivalent strata (T. Carter, pers. comm. 1996).

The Verulam Formation of eastern Ontario would also appear to be equivalent in part to the Neuville Formation of southern Quebec (Lavoie *et al.* 1998). The Sugar River Formation of New York State (Cameron 1973) is also a probable equivalent, since it is lithologically very similar and occupies the middle portion of the Trenton Group.

Remarks

The Verulam Formation is easily distinguished from most of other formations in the Upper Ottawa Group by its relatively thin-bedded nature, shaley interbeds and conspicuous storm-generated features. It is, however, similar to and could easily be mistaken for parts of the upper Bobcaygeon Formation. The two units may be distinguished by (1) the presence of abundant ramose bryozoans in the Bobcaygeon shale beds and cemented burrow tubes in the Verulam shales; (2) the generally thinner-bedded nature of the Verulam; (3) almost ubiquitous normal grain-size gradation in Verulam limestone beds; and (4) rapid alternation between fine- and coarse-grained texture among Bobcaygeon limestone beds.

4.2.4 Lindsay Formation

Characteristics

The characteristics of the Lindsay Formation are described in Section 2.5. The Lindsay strata are characterized by a highly bioturbated, nodular wackestone-packstone lithology in which 1 to 10 cm long, 1 to 7 cm thick, oblate ellipsoidal nodules are separated by 2 to 10 mm thick stylolite-enhanced shaley partings. The nodular lithology is

arranged in metre-scale sets, interrupted by occasional 1-3 cm thick shales and/or 5-15 cm thick graded packstone-grainstone beds. Petrographically, the Lindsay is similar to lithofacies V3 and V4 of this thesis, although it is generally more argillaceous.

Boundaries

The transitional lower boundary of the Verulam Formation is described above. The upper boundary is somewhat problematic. In the upper portions of the Lindsay Formation, the nodules tend to become large (up to 25 cm) and the wackestones become more matrix-rich (personal observation). An upper member (the Eastview beds) has been defined by Wilson (1946a) to include 20-100 cm scale interbedded nodular limestones and black, petroliferous shales. Exposures are extremely rare: one exists on Aviation Parkway, Ottawa (about 300 m south of the Aviation Parkway outcrop, locality 20 of this study). The Eastview beds also occur in the Russell core (Williams 1991).

Regional correlations

The lower parts of the Lindsay Formation in eastern Ontario are identical to the Lindsay Formation in its type area of central Ontario (Sanford 1969, Armstrong 1997). It is equivalent in part to the Neuville and Montreal formations of southern Quebec (Lavoie *et al.* 1998).

Remarks

The Lindsay Formation is usually easy to distinguish from the Verulam in the field, but some confusion may arise between the Lindsay and the Verulam in core. Both formations consist of rather thin limestone beds separated by shaley partings of a few millimetres to a few centimetres thickness. Centimetre-scale shales are much less common in the Lindsay Formation than in the Verulam Formation. The thinner (millimetre-scale) shaley partings are generally horizontal in the Verulam strata, whereas they wrap around the sides of nodules in the Lindsay Formation.

4.2.5 Discussion

On a scale of formations, the available data set allows several lithostratigraphic interpretations. A simple, “layer-cake” lithostratigraphic approach is clearly not possible because the Hull Beds cease to exist as a mappable unit east of Ottawa and the apparent absence of the Verulam in northeastern Ottawa.

The Hull and Verulam as laterally equivalent units - Fig. 4.2

This is a refinement of Salad Hersi’s (1998) interpretation of the Hull and Verulam Formations. Based on the fact that the Verulam Formation is apparently missing in northeastern Ottawa (see above), and an interpretation of interbedded Hull and Verulam lithofacies at two locations in eastern Ontario (the Clifftondale and L’Original quarries; locs. 35 and 36), Salad Hersi (1998) and Salad Hersi & Dix (1997a) proposed an interfingering relationship between the two formations. In this study, the beds exposed in

these two quarries (locs. 35 and 36) are re-correlated within the Bobcaygeon Formation based on the characteristics listed above and in Chapter Two of this thesis. Salad Hersi's (1998; see also Salad Hersi & Dix 1997b) assertion of extreme thickness variation in the Hull Beds (2-40m within the city of Ottawa) is largely based on the presence of a 2m thick grainstone body in the southern portion of the McCarthy Road outcrop (loc. 27). The McCarthy Rd. outcrop is here re-interpreted an exposure of Bobcaygeon strata (see above). Despite this, Salad Hersi's (1998) model is not ruled out.

If the Hull and Verulam strata are laterally equivalent, representing contemporary nearshore and offshore environments, then an interfingering between the two formations accompanied by a vertical and lateral intergradation of lithological characteristics should be expected. In terms of petrography and composition, lithofacies H2 and H3 bear striking similarities to lithofacies V2 and V3. The presence of exotic grain types in the Verulam strata that may have originated in Hull environments (i.e., broken oncoids and calcispheres) is also potential evidence for there lateral equivalence. It is possible that the thinning of beds and increase in abundance of shale interbeds required to transform lithofacies H3 into lithofacies V3 may have taken place over a short paleogeographic distance, allowing for a lateral equivalence without obvious lithological intermediates. Rather than the metre-scale interfingering proposed by Salad Hersi (1998), stratigraphic interfingering may be represented, for example, by the 30 to 50 cm-scale, shale-free intervals observed at locality 15 (at 7.85 m and 9.03 m in the Nepean Point section).

**Figure 4.2: Formation-scale lithostratigraphic model for the Upper Ottawa Group
I: Verulam and Hull formations both overlie the Bobcaygeon have a narrow, unobserved zone of lithological interfingering.**

**Figure 4.3: Formation-scale lithostratigraphic model for the Upper Ottawa Group
II: Hull beds interfinger with Bobcaygeon Formation, and both are overlain by the Verulam across a flooding surface. Assumes Hull-like lithologies locally developed at the top of the Verulam Formation.**

**Figure 4.4: Formation-scale lithostratigraphic model for the Upper Ottawa Group
III: Hull Beds and Bobcaygeon Formation are assumed to interfinger. Verulam Formation overlies both the Hull and Bobcaygeon across a flooding surface. Assumes the presence of Lindsay-like lithologies encased in the Verulam**

NW

SE

NW

SE

NW

SE

Bobcaygeon Fm

Hull Beds

Verulam Fm

Lindsay Fm

The Hull Beds and Upper Bobcaygeon Formation as lateral equivalents - Fig. 4.3, 4.4

In this model (which essentially supports the lithostratigraphic interpretations of Liberty 1969 and Williams 1991), the Hull Beds are laterally equivalent to the upper Bobcaygeon Formation (Figs. 4.3, 4.4). According to this model, the Hull Beds form a thick accumulation in the Ottawa area, and interfinger with the Upper Bobcaygeon Formation to the southeast. The model is supported by the presence of metre-scale packages of crinoidal grainstone that are similar to lithofacies H2 and/or H3 occurring in the Upper Bobcaygeon Formation at locations 19, 27, 28 and 35 as well as quarries near Stittsville (Clarke Quarry; Salad Hersi 1998) and Embrun (Embrun Quarry, Salad Hersi 1998). The upper contact of the Hull Beds represents an important marine flooding surface with barrier and lagoon facies overlain by (non-laterally equivalent) offshore deposits of the Verulam and Lindsay formations. One or more, two- to seven-metre-thick grainstone bodies are observed to be encased within upper Bobcaygeon strata located well below the Hull Beds at the Clarke Quarry near Stittsville (Salad Hersi 1998; close to loc. 2 of this study), the McCarthy Road outcrop (loc. 27) and the Lebreton Core (loc. 10). These “sub-Hull” grainstone bodies likely represent a number of lensoidal bodies. They probably also include the small exposure of cross-bedded grainstone at the Chrysler dam (loc. 30), which is located southeast of Russell. A similar, small exposure of cross-bedded grainstone at location 24 in northeastern Ottawa lies only a few metres above apparent Bobcaygeon Strata located nearby. This outcrop is difficult to interpret; does it represent the lower Hull Beds, or is correlative to one of the “sub-Hull” grainstone lenses?

In order to accommodate the succession exposed at Aviation Parkway (loc. 20), however, the uppermost Verulam Formation must either contain pods of Hull-like grainstone (Fig. 4.3) , or the lowermost Verulam Formation must locally resemble the Lindsay Formation (Fig. 4.4). Although the Verulam Formation of central Ontario include an upper member that strongly resembles lithofacies H2 (Liberty 1955 and 1969, Armstrong 1997, McFarland 1997), there is not other evidence for such lithologies existing in the upper Verulam Formation of eastern Ontario (see Section 4.2.4). Thus the model presented in Figure 4.4 (i.e., Lindsay-like strata in the lowermost Verulam Formation) is preferred.

The available biostratigraphic data (Figure 4.1) supports the model presented in Figure 4.4. The conodont study of McCracken (1995) provides an age-range of Rocklandian to lower Shermanian for the Bobcaygeon Formation (at loc. 27), the Hull Beds *and* the Lindsay-like strata exposed on Aviation Parkway (loc. 20). Graptolites collected from the upper 15 m of the Verulam Formation in downtown Ottawa (locs. 14, 15 and 16), however, are of the lower *Climacograptus spiniferus* zone (J. Riva, written comm. 1997), which is equivalent to the lower Edenian (Bergström & Mitchell 1986). Thus the Lindsay-like strata exposed at loc. 20 are older by at least “half” of the Shermanian stage than the lower Lindsay Formation proper, as exposed in downtown Ottawa.

Recommendations for formal stratigraphic nomenclature

No formal revision has been made to the stratigraphic nomenclature of the Trenton-equivalent succession in eastern Ontario since the publication of Kay's (1942) paper. The problems of Kay's stratigraphic scheme are reviewed in Chapter One. The publications of Uyeno (1974) and Williams (1991) are unrefereed government reports and, as such, do not constitute "acceptable" forums for the publication of stratigraphic nomenclature under the North American Stratigraphic Code (NACSN 1983). Similarly, this thesis is not an appropriate type of document to define new stratigraphic terms; although it is hoped that the work described herein will lead to formally published revision of Upper Ottawa Group stratigraphy.

Since the Hull strata are a distinctive lithostratigraphic package in the Ottawa region, the name "Hull" warrants retention in the stratigraphic nomenclature of eastern Ontario. The apparent local extent of the Hull lithofacies as a discrete package, however, suggests that it does not warrant the rank of formation (NACSN 1983). The Hull strata could be usefully defined as a member of either the Bobcaygeon or Verulam formations. In order to define a Hull Member, there must be a confident determination of which formation the Hull lithologies interfinger because a defined member must belong to a defined formation (NACSN 1983). Until such a determination is made, I recommend that the term **Hull Beds** be applied to the interval between the Bobcaygeon and Verulam formations in the Ottawa-Hull-Stittsville area.

4.3 Internal stratigraphy of the Hull Beds and Verulam Formation

This section discusses the internal stratigraphic arrangement of the Hull Beds and Verulam Formation. More attention is given here to the Hull succession, which is divided into lithosomes to facilitate internal correlation. The Verulam Formation is discussed in terms of tempestite proximality indicators. The results are used to facilitate discussion with regard to the various lithostratigraphic models proposed above.

4.3.1 Lithosomes of the Hull Beds

The lithofacies associations described and interpreted in Chapter 3 may be translated into lithosomes for purpose of stratigraphic description. A *lithosome* is “a rock mass of essentially uniform or uniformly heterogeneous lithologic character having intertonguing relationship in all directions with adjacent masses of different lithologic character” (Bates & Jackson 1980, p. 364). This term avoids the semantic difficulties of the term “magnafacies”, which must be demonstrated to cross-cut defined chronostratigraphic units or time-lines (Bates & Jackson 1980, p. 375).

Lagoon lithosome

The lagoon lithosome exists at locations 1, 2, and 10 (Klock Quarry, Highway 7 roadcut, and the Lebreton core). The lithosome is distinguished by the presence of lithofacies H4 and/or H6, even if it is subordinate to washover deposits of lithofacies H1 and H2. Problems may arise in distinguishing thicker washover packages from thinner expressions of the barrier-top lithosome. The presence/absence of lithofacies H5 is one

useful criterion (see below), as is the broadly lenticular nature of H1 and H2 washover beds in the lagoon lithosome.

Barrier-top lithosome

Barrier-top lithosomes are composed mostly of lithofacies H1 and oncoid- or *Solenopora*-rich H2, but decimetre- to metre-scale sets of lithofacies H5 are diagnostic. Lithofacies H6 and H4 may also be present in minor amounts. Packages tend to be greater than two metres in thickness. Examples include the lower portions of the St. Laurent Blvd. (loc. 23) and Governor's Bay (loc. 19) outcrops as well as the upper parts of the Hull Promontory (loc. 7a, b and c) and the Lac des Feés Parkway outcrop (loc. 3). Beds of lithofacies H2 in the barrier-top lithosome are notably enriched in oncoids, calcareous green algae and *Solenopora* relative to those in the barrier-front lithosome.

Barrier-front lithosome

Barrier-front lithosome consist of relatively monotonous sets of lithofacies H2 and/or H3. Packages are generally two or more metres thick. Examples include the lower part of the Hull Promontory (loc. 7c), Aviation Parkway (loc. 20) and the Beechwood Quarry (loc. 25). Oncoids are absent in lithofacies H2, and *Solenopora* is very rare. Planar laminasets lack the low-angle truncations observed in the barrier-top.

Lithosome distribution and correlation

Several possible interpretations of environmental stratigraphy could be produced based on the available data. Two of the more probable interpretations are shown in Figures 4.5 and 4.6. It is important to note that, although it follows a rough west-east trend, the line of these cross-sections is not straight. Figure 4.5 is based on the preferred lithostratigraphic interpretation shown in Fig. 4.4, while Figure 4.6 assumes the model of Salad Hersi (1998; see Fig. 4.3). Important features of the Hull Beds appear to be (1) dominance of the lagoon lithosome in the northwest passing into the barrier-top and barrier-front lithosomes to the southeast; (2) the apparent interfingering of the lagoon and barrier-top lithosomes between the Lebreton core and downtown Ottawa; (3) the complex interfingering between the barrier-front and barrier-top lithosomes in the eastern portion of the study area; and (4) the disappearance of the Hull Beds as a discrete set unit between Francon Quarry and the Russell well (locs. 25 and 28).

Discussion

Each of the three proposed lithosome correlations present a particular difficulty. If the Hull Beds represent nearshore facies equivalent of the Verulam Formation, two problems arise: (1) there is no perceptible interfingering between the two formations and (2) extreme thickness variations must be invoked in one or more of the stratigraphic units in the Upper Ottawa Group within the Ottawa area (Figs. 4.2, 4.6). If the Hull Beds define nearshore facies equivalent of the Bobcaygeon facies, then "pods" of a Lindsay Formation-like lithology of at least 5 m thickness must exist within the lower Verulam

Figure 4.5: Lithosome correlation for the Hull Beds I. Assumes Bobcaygeon-Hull interfingering and the presence of Lindsay-like lithologies within the Verulam. The position of individual columns within the composite sections is highly subjective, but interpretations would not be changed greatly if the positions were changed.

- SV = Stittsville area. Lower column represents Clarke Quarry (see Salad Hersi 1998), upper column represents Highway 7 roadcut (loc. 2).**
- KQ = Klock Quarry (loc. 1)**
- MW = Intersection of McCarthy Rd. & Walkely Rd., Ottawa (loc. 27).**
- LB = Lebreton Core and Lebreton St. outcrop (locs. 10 and 11).**
- LF = Lac des Feés Parkway (loc. 3).**
- DT = Downtown Ottawa-Hull composite section. In ascending order, constituent sections are: Boul. de Maisonneuve (loc. 6), Hull Promontory (7c), Hull Promontory (7b), and Nepean Point (15).**
- GB = Governor's Bay (loc. 19).**
- NE = Northeastern Ottawa composite section. In ascending order, constituent sections are: Montreal Rd. (loc. 24), Quarry Rd./St. Laurent Boulevard (locs. 21 and 23), and Aviation Parkway (loc. 20a and b, fault assumed to have no significant offset).**
- FQ = Francon Quarry south (loc. 26). See also Salad Hersi (1998).**
- CD = Chrysler Dam (loc. 30).**
- RC = Russell Core (loc. 28).**

Figure 4.6: Lithosome correlation for the Hull Beds II. Assumes lateral equivalence of the Hull and Verulam Formations as suggested by Salad Hersi (1998).

- SV = Stittsville area. Lower column represents Clarke Quarry (see Salad Hersi 1998), upper column represents Highway 7 roadcut (loc. 2).
KQ = Klock Quarry (loc. 1)
MW = Intersection of McCarthy Rd. & Walkely Rd., Ottawa (loc. 27).
LB = Lebreton Core and Lebreton St. outcrop (locs. 10 and 11).
LF = Lac des Feés Parkway (loc. 3).
DT = Downtown Ottawa-Hull composite section. In ascending order, constituent sections are: Boul. de Maisonneuve (loc. 6), Hull Promontory (7c), Hull Promontory (7b), and Nepean Point (15).
GB = Governor's Bay (loc. 19).
NE = Northeastern Ottawa composite section. In ascending order, constituent sections are: Montreal Rd. (loc. 24), Quarry Rd./St. Laurent Boulevard (locs. 21 and 23), and Aviation Parkway (loc. 20a and b, fault assumed to have significant offset).
FQ = Francon Quarry south (loc. 26). See also Salad Hersi (1998).
CD = Chrysler Dam (loc. 30).
RC = Russell Core (loc. 28).

(Figs. 4.4, 4.5). The crinoidal shoals at the top of the Verulam Formation (Fig. 4.3) are equally awkward in application: sudden, local change of depositional environment at what is everywhere else (in eastern Ontario) a conformable, gradational transition at the Verulam-Lindsay contact. The lateral equivalence of the Hull Beds and Bobcaygeon Formation is the preferred model, because: (1) the barrier-front and top lithosomes of the Hull strata have greater lithological similarity to the Bobcaygeon Formation than the Verulam Formation; (2) the Verulam Formation strata are lithologically similar to those of the Lindsay Formation, with the main difference being in bedding style, degree of bioturbation and resulting overall rock fabric; (3) the 1-7 metre thick, Bobcaygeon-encased grainstone bodies in the eastern portion of the study area are better candidates as “fingers” (or lenses?) of the Hull Beds than the rare, half-metre thick shale-free intervals present in the Verulam; and (4) the distribution of the Hull-like beds in the Upper Bobcaygeon Formation in the Russell core spans a stratigraphic interval of ~28 metres (Fig. 4.5), a similar thickness to the Hull Beds in the Lebreton area (locs. 10 and 11; see Section 4.2.2).

It is possible that the upper 5m of the L’Original Quarry (loc. 36) represents an expression of the barrier-front lithosome, and that the Hull Beds may locally exist in the L’Original-Hawkesbury area. These beds would represent the “toe” of the barrier-front environment of a northeast-southwest trending barrier system (Fig. 4.7). The remainder of the barrier system would have existed in the area that is now occupied by the Precambrian exposure of the Gatineau Hills.

Figure 4.7: Possible paleogeographic arrangement of depositional environments during "Hull time". The area of deposition of the three lithosomes is marked. Note that deposition of the Hull Beds likely also occurred north of the Ottawa River's present position, in the area now occupied by the Gatineau Hills.

4.3.2 Verulam Formation trends

The extremely poor lateral continuity of beds in the Verulam Formation precludes internal correlation of individual strata. Even among the closely-spaced exposures in downtown Ottawa (e.g., locs. 14, 15, 16, 17 and 18), no marker bed can be positively identified, despite the high probability of stratigraphic overlap. Attempts to correlate apparent cycles (shaler-up, thinning-up, etc.) were unsuccessful, even with these closely-spaced outcrops. The general trend of upwards increasing bioturbation in the Verulam Formation has already been noted.

As already discussed in Chapter 3, vertical variations in proximity trends in the upper 17 m of the Verulam Formation at locality 15 (Nepean Point) show only a slight upwards increase in apparent proximity (Fig. 3.4). This suggests that the depositional environments represented by the Lindsay Formation differ only subtly from that represented by the Verulam Formation. The probable similarity environment lends further support to the stratigraphic models proposed for the Upper Ottawa Group shown in Figs. 4.4 and 4.5.

Chapter Five: DIAGENESIS AND GEOCHEMISTRY

5.1 Diagenesis

Most of the diagenetic features discussed here occur in all lithofacies of the Hull Beds and Verulam Formation. Exceptions will be noted where appropriate, and a section on silica-bearing concretions, unique to the Hull, is included here. Two of the more important dolomite habits are not included here, and are described in the Section 5.2. Emphasis is placed on those diagenetic effects with the greatest importance to depositional environment and lithological character. The general paragenetic sequence is shown schematically on Figure 5.1.

5.1.1 Sea-floor and early burial (marine) diagenesis

Grain degradation

Both the homogenous and irregular types of peloid are interpreted in part as microbored and/or recrystallized grains (see Section 2.1.2). In modern settings, microboring produces micrite envelopes around skeletal fragments (Bathurst 1966, 1975), completely or partially micritized particles (e.g., Perry 1998, Tudhope & Risk 1985, Zeff & Perkins 1979). This is best expressed in the Hull Beds (Figs. 5.2 C, D; 2.2 H), which is expected, because the Hull Beds represent shallower-water facies than the Verulam Formation, and grain destruction by microboring organisms is most intensive in such shallow-water settings (Kobluk & Risk 1976, Tudhope & Risk 1985). Reid & Macintyre (1998) have recently suggested that inorganic recrystallization of grains on the sea-floor

Figure 5.1: General sequence of diagenetic events in the Hull Beds and Verulam Formation. Burial depths approximatley based on James & Choquette (1990a, b, c), Hesse (1990), Wanless (1979) and Tucker & Wright (1990). * Early dolomite associated with lithofacies H4 and H6 only.

Figure 5.2 Early diagenetic effects.

A - Mechanical compaction expressed by grain fracture. Photomicrograph (crossed polars) of crushed trilobite fragment. Verulam Formation, loc. 15.

B - Large shale clast (V5; arrow and dotted line) in bed of lithofacies V3. Shale clast is bent over large intraclast below (marked by bold, dashed line). Note "sheltering" of shale below the intraclast and curved parallel lamination of underlying bed. Pencil is 14 cm long. Loc. 15.

C - Photomicrograph (crossed polars) of micrite envelope, early and late cements in lithofacies H4 packstone. Note that fringing cements are developed on both sides of the micrite envelope (arrows). Later clear spar is denoted by "cs". Loc. 1.

D - Photomicrograph (crossed polars) of fringing cements in lithofacies H4 packstone. Note well-formed terminations and isopachous fringing of pore-spaces. Loc. 1.

E - Photomicrograph (crossed polars) of geopetally-filled shelter void below brachiopod fragment. Small, equant fringing calcite (arrow) lines the edges of the void and is best developed on the brachiopod fragment itself. Clear spar (cs) fills the remaining pore space. The "geopetal" nature of the filling may be a compaction effect: the brachiopod valve could have been pressed into unconsolidated packstone rather than internal sediments filling a shelter void. Loc. 15.

F - Photomicrograph (crossed polars) of radiaxial-fibrous calcite (fringe outlined by bold line). Cement lines lower surface of brachiopod fragment, the upper surface of which is encrusted by an unidentified green alga (or cyanobacteria?). Lithofacies H1-H6 mixture. Loc. 2.

G - Photomicrograph (crossed polars) of borings in domal bryozoan. Note cements filling bryozoan chambers and geopetal infill of borings. Finely crystalline (~8-15µm) brown calcite lines even the upper surfaces of the geopetally filled *Trypanites* boring, suggesting a cement rather than sedimentary origin. Bryozoan frond on upper surface calcisiltite bed (V4) at Nepean Point, Ottawa. Loc. 15.

H - Photomicrograph (crossed polars) of ragged syntaxial overgrowth on partly micritized echinoderm ossicle. Hull Beds (lithofacies H2), Loc. 25.

may also be an important process in the reduction of recognizable particles to structureless peloids.

Micrite envelopes are best developed around molluscan fragments in the low-energy deposits of lithofacies H4 (Fig. 5.2 C, D). They are 20 to 80 μm -thick rinds of brown micrite. The envelopes are often lined with well-developed fringing cements (see below). Microprobe analyses (Appendix III, Table 1) of micrite envelopes revealed relatively high concentrations of Si (1500-1800 ppm), suggesting that the micrite envelopes contain some siliceous material (possibly authigenic clays or silica).

Early lithification

Early lithification is expressed in non-reefal carbonate rocks as beachrock and hardgrounds. These two styles may be difficult to distinguish in the rock record (James & Choquette 1990a). Field and petrographic evidence does exist in both formations for early marine lithification. Intraclasts in high-energy beds of both units studied (e.g., lithofacies H1 and V1; see Figs. 2.2 A, D; 2.4 D, G; 5.1 B) typically overlie scours and are usually of obvious local origin (i.e., derived from the immediately underlying beds). This implies that the underlying beds were lithified at the time of scouring; either on the sea-floor or at less than a few tens of centimetres burial. The sparsity of evidence for extensive mechanical compaction of limestones in either the Verulam Formation or Hull Beds also suggests at least partial lithification prior to significant burial (James & Choquette 1990a). The abundant bioturbation preserved in the Verulam Formation and (less commonly) in the Hull Beds prove that the substrate was soft for a significant period of time after

deposition, but the presence of apparent borings (*Trypanites* isp.; Figs. 2.6 B, C; 5.3 G) and the ferromanganese precipitates on certain surfaces within the Verulam implies exposure at the sea-floor as a hard, cemented substrate (James & Choquette 1990a).

Early cements occur in direct contact with grains boundaries or pore-space walls, often as isopachous fringes (James & Choquette 1990a). Five different types of fringing cement were noted in thin sections of the various Hull and Verulam lithofacies. No petrographic or geochemical evidence of aragonite cements, as outlined by Sandberg (1985) or Tucker & Wright (1990), was observed. All of these cements appear to have been low- or high-Mg calcite at the time of formation. The early, fringing cements are (1) small (40-100 μ m) equant calcite; (2) small (<10 μ m long) bladed calcite, (3) larger (30-50 μ m long) bladed calcite, (4) microspar and (5) fibrous calcite. The first three types are the most common and most easily recognized. Any one of these three types may occur lining pore spaces or bioclasts. They are very well developed in micrite envelopes in lithofacies H4 (micritic packstones) and H6 (Fig. 5.2 C, D), and moderately to poorly developed lining shelter voids and other interparticulate spaces in other lithofacies (Fig. 5.2 E) except V5. In most lithofacies, open intraskeletal cavities (particularly within bryozoans and articulated brachiopods) are lined if not filled by these cements (Fig. 5.2 G). The fourth type (microspar) is indistinguishable from the calcareous silt matrices present in several of the Hull and Verulam lithofacies (a similar problem to that reviewed by Reid *et al.* 1990). In some places, this finely crystalline calcite (6-20 μ m subequant crystals) appears to line even the upper sides of otherwise spar-filled pores (e.g., *Trypanites* borings; Fig. 5.2 G). Fibrous calcite is extremely rare. Both radiaxial-fibrous and fascicular-optic fibrous

calcites have been observed, usually in shelter cavities below ostracod or brachiopod valves (Fig. 5.2 F). A few geochemical analyses were taken of fringing cements by microprobe and are listed in Appendix III, Table 1. Assuming the cement fabrics to be primary (supported for fibrous calcites by Kendall, 1985), the low Sr levels (0 to 1100 ppm) support an initial calcite mineralogy.

Syntaxial overgrowths on echinoderm fragments (Figs. 2.2 G, 2.4 E, 2.5 E, 5.1 H, 5.2 A, B) are very abundant in all lithofacies. These are well-developed locally and completely encase ossicles, or they may be partial and ragged (Fig. 5.2 H). Wilson *et al.* (1992) have demonstrated that syntaxial overgrowths of echinoderm fragments may be a very early, sea-floor to shallow-burial feature. Staining has revealed that they are often concentrically or patchily zoned between non-ferroan and ferroan calcite (Fig. 5.3 A, B).

Vadose cements

Paleokarst surfaces were not observed in the course of this study. The barrier-lagoon model for the Hull, however, predicts that (1) the Upper Bobcaygeon strata, which immediately underlie the Hull Beds, may have been exposed to meteoric diagenesis to the north of the study area; and (2) that small, emergent beach islands may have developed on the barrier crest during deposition of the Hull Beds. At the Lac des Fées outcrop in Hull (loc. 3), some beds of the Upper Bobcaygeon Formation display possible vadose-zone cementation. The cements form large (several mm across), downward-directed pendular masses of columnar, ferroan- and non-ferroan calcite below bryozoan skeletal fragments. They also form meniscus fabrics between particles (Figs. 5.3 C). The same cements,

Figure 5.3 Later diagenetic features.

A and B - Photomicrographs (A - plane light, B - crossed polars) of irregular chemical zonation in syntaxial overgrowth on echinoderm fragment. Note very inclusion-rich echinoderm fragment in centre, overgrown by pink-stained non-ferroan calcite passing into ferroan calcite (purple stain) only at the bottom of the photograph. Hull beds, Loc. 3.

C and D - Photomicrographs (A - plane light, B - close-up under crossed polars) of possible vadose cement fabric in bryozoan fragment from the uppermost Bobcaygeon Formation at Lac des Feés Parkway, Hull (loc. 3). Note drip- (arrow D) and meniscus-like (arrow M) cement fabrics with dashed outline and columnar cement fabric.

E - Photomicrograph (crossed polars) of large, ragged, poikilotopic calcite cement in lithofacies H3, Loc. 20a.

F - Photomicrograph (crossed polars) of partially chertified brachiopod fragment. Lithofacies H2, loc. 20a. Note small sutured stylolite below brachiopod.

G - Photomicrograph (crossed polars) of "chert envelope" developed in silica-dolomite concretion. Fibrous chert (Ch, arrows) lines the cavity, which is filled by crystalline quartz (Qz). Opaque material is limonite-rich silica and carbonate. Lithofacies H2, Hull Beds, loc. 6.

however, exist within bryozoan skeletons, and appear to “overprint” them (Fig. 5.3 D). Similar cements within detrital, rounded bryozoan fragments are observed in lithofacies H1, and possibly identify brief periods of exposure to meteoric-vadose diagenesis followed by erosion of the beds.

Mechanical compaction

The main effects of mechanical compaction are the movement of grains into a close-packed arrangement and the breakage of grains (Coogan & Manus 1975). Compaction tends to affect sandy and muddy lithologies differently. In the high-energy, highly-agitated and mud-free Hull lithologies (H1, H2, H3 and H6 grainstones), grains were likely close-packed at the time of deposition. Within muddy sand and sandy mud lithologies (e.g., the H3 packstones and V3 packstone-wackestones), grains show little evidence of movement to a close-packed arrangement, although the amount of matrix compaction is difficult to estimate. Broken grains are rare but some ostracod, brachiopod and trilobite fragments are crushed or broken when located below large bioclasts or intraclasts (Fig. 5.2 A).

In muddy rocks (e.g., lithofacies H4, H5, V4 and V5), effects of mechanical compaction are much more pronounced. Shales compact very rapidly in the first few metres of burial. Even within the first decimetre or so of burial, clay-rich fine-grained sediments may be well compacted and competent (Baldwin 1971, Meade 1966). The presence of bent shale chips as intraclasts within Verulam tempestites (Fig. 5.2 B) implies that storms commonly scoured into semi-consolidated shales.

5.1.2 Progressive Burial

Aragonite dissolution and calcite neomorphism

None of the initially aragonitic fossils (molluscs and *Tetradium* corals) contain any preserved skeletal microstructure (Figs. 2.3 B, 2.6 D). As such they are interpreted to have been dissolved and the resulting voids filled by cements, as opposed to being replaced by calcite. In the Hull Beds, where micrite envelopes are commonly well developed, dissolution appears to take place early in the burial history. Both sides of the micrite envelope are commonly fringed by cement as described above for the shallow burial or sea-floor diagenetic environments (Fig. 5.2 C, D). In the other lithofacies, the dissolution appears to have occurred later. Even in lithofacies H4, *Tetradium* corals have not developed micrite envelopes but show no evidence of having collapsed (Fig. 2.3 B), thus dissolution of the skeleton must have taken place after the surrounding matrix was at least partially lithified. The same is true of molluscan voids in the Verulam Formation (see Fig. 2.6 D). In modern environments, aragonite dissolution is usually attributed to meteoric water (James & Choquette 1990b). The Ordovician, however, was a time of “calcite seas” (Sandberg 1983), such that aragonite may have dissolved in the presence of even slightly modified marine water. Palmer *et al.* (1988) have demonstrated this phenomenon in both Ordovician and Jurassic strata. Early subsurface aragonite dissolution is a likely source of material for calcite cementation in sea-floor and shallow burial diagenesis (Wilson *et al.* 1992, Tucker & Wright 1990).

Most of the bioclasts present in the Hull Beds and Verulam Formation were originally composed of low-Mg calcite (LMC), with the exception of the molluscs,

Tetradium corals and echinoderms. Modern echinoderms build their individual skeletal components (spines, plates, ossicles, etc.) out of single crystals of high-Mg calcite (HMC). HMC is metastable in most natural waters (with the exception of seawater). Within the both the studied succession, echinoderms and their syntaxial overgrowths are composed of LMC, but retain their overall original structure (i.e., they are still single calcite crystals). Thus, the HMC to LMC transition occurred without significant crystallographic rearrangement (i.e., neomorphism; Tucker & Wright 1990, Bathurst 1975). Many of the echinoderm fragments examined in this study, and their syntaxial overgrowths, contain abundant, small (1-10 μm) inclusions of dolomite (revealed by staining). These inclusions are considered diagnostic of an original HMC mineralogy (Lohmann & Meyers 1977). In contrast, the fringing cements are clear, inclusion-free and often euhedral, suggesting a lack of neomorphic alteration and an initial mineralogy of LMC. Most fringing calcites in the modern shallow, tropical seas are usual composed of HMC (James & Choquette 1990a, Tucker & Wright 1990).

Fine-grained carbonate (e.g., micrite and calcareous silt) is particularly prone to neomorphism and recrystallization (Tucker & Wright 1990). Lasemi and Sanberg (1984) outlined the characteristics of micrites in rock with aragonite or calcite precursors. A crystal size of less than four microns (Fig. 2.3 E, F), along with low strontium content (see Appendix III, table 1), and lack of elongate pits or aragonite inclusions strongly suggest a calcite-dominated precursor for micrite present in the Hull Beds.

Fabric-controlled replacement

Replacement of carbonate bioclasts and cements by calcite, dolomite and chert is common in both formations. Complete silicification of some bioclasts (usually brachiopod valves or crinoid ossicles) is rare, but are seen in outcrop (locs. 7, 23; also at the Scott St. Transitway, Ottawa; O. Salad Hersi *pers. comm.*). More typical is fabric-selective replacement of brachiopod, bryozoan and echinoderm skeletal fragments by chert, ferroan and non-ferroan calcite and, rarely, dolomite (Fig. 5.3 F, 5.3 B). The homogenous peloids of lithofacies H6 are, in places, extensively replaced by ferroan calcite and dolomite (Fig. 5.4 A, B). Partial replacement of quartz (which may itself be authigenic; see below) by calcite or dolomite is also extremely common.

Cements

Clear, blocky, non-ferroan or ferroan calcite spar is typical of burial cements in most limestones (Tucker & Wright 1990), although it may also form in shallower meteoric settings (James & Choquette 1990). Clear, blocky cements occlude most of the intergranular, intragranular and shelter pore spaces within the Hull Beds and Verulam Formation that were not filled by matrix. These cements are composed of non-ferroan or ferroan calcite. Concentric and non-concentric zonation with respect to iron content is not uncommon (similar to that seen in the syntaxial overgrowths, Fig. 5.3 A, B). Clear sparry calcite fills most of the inter- and intraparticulate and is present in veins at all scales veins (from mm-thick fractures observed in thin section to fault gouges and veins up to a

Figure 5.4 Dolomite occurrence in the Hull Beds and Verulam Formation

A - Photomicrograph (plane light) of dolomitized homogenous peloids (H6). Klock Quarry, Aylmer (loc. 1). Note that this replacement is not responsible for the dolostones as seen in Fig. 53c to f.

B - Photomicrograph (plane light) of dolomitized green algal fragment in lithofacies H6. Loc. 1.

C - Dolostone bands (yellow-brown colour) in lithofacies H6. Fieldbook is 19cm long. Loc. 1.

D - Limestone-filled burrows in dolostone band. Bioturbation is "top-down" in style. Note minor stylotization along the boundary. Loc. 1.

E - Partially dolomitized beds of lithofacies H6 at the Highway 7 roadcut near Stittsville (Loc. 2). Note that dolomitization follows lamination. Hammer head is 12 cm long.

F - Photomicrograph (plane light) cloudy-cored dolomite rhombs from dolomite-replaced burrow in lithofacies H4 (loc. 1).

G - Photomicrograph (crossed polars) dolomitized burrow in lithofacies H4 mudstone (loc. 1)

H - Photomicrograph (crossed polars) of small, blue-stained, ferroan dolomite rhombs (white arrows) in *Trypanites* boring, lithofacies V3. Verulam Formation, loc. 11.

few decimetres in width). In general, crystal size of sparry calcites appears to depend on the size of the pore that they are filling.

Continued growth of syntaxial cements occurred in deeper burial diagenetic environments. Clear, inclusion-free, typically more Fe-rich rims are commonly developed on the more euhedral overgrowths. This increase in iron content seen in both syntaxial cements and clear spar is typically a result of iron enrichment in pore fluids with increasing burial depth (James & Choquette 1990c), which is in turn due to the increased solubility of iron in reducing pore waters.

Authigenic quartz is also a common feature of the burial environment (Hesse 1990). Silt-sized, apparently euhedral quartz is common in the Verulam Formation. It is not always easy to distinguish between angular detrital silt and euhedral authigenic quartz. It is possible that some or all of the euhedral crystals contain syntaxial overgrowths on detrital cores.

Potassic clays lithofacies H4 may also be authigenic in origin. SEM images reveal that clays within micrite are identical to those found within the poorly- to moderately-preserved ooids of the same lithofacies (Fig. 2.3 E). High silicon counts in micrite envelopes revealed by microprobe analysis relative to the matrix (Appendix III, Table 1) also suggest that they may have been preferred sites for clay precipitation.

Chemical compaction

Chemical compaction processes have had significant effects on both the Hull and Verulam formations. On the smallest scale, sutured contacts along crystal edges and grain

boundaries are commonly observed in thin section. Ragged boundaries of bioclasts or cements isolated in a calcareous silt matrix are also common. Sutured and non-sutured dissolution seams (Ricken & Eder 1991) are present at several scales, ranging from microscopic (e.g. Fig. 2.4 C) to the prominently macroscopic. Sutured dissolution seams (or simple stylolites) range in amplitude from a few tens of microns to a few centimetres. Non-sutured dissolution seams are expressed in thin section as 10-30 μm thick seams of dark material argillaceous (or organic?) that are observed to truncate bioclasts and cements. They are usually arranged in "swarms", creating millimetre-scale "shaley partings". These partings are not always visible in outcrop. In the Verulam Formation, the upward increase in argillaceous material associated with normal textural gradation is diagenetically enhanced by an increase in the frequency and thickness of dissolution seams. This effect allows for the diagenetic enhancement (or possibly even the creation) of thin shale interbeds. A similar process is at least partially responsible for the stylonodular fabric of the Lindsay Formation.

5.1.3 Silica-bearing concretions in the Hull Beds

Nodular chert

Two of the Hull lithofacies, H1 and H5, contain nodular to banded chert. In lithofacies H1, chert occurs on bedding planes as vertically flattened nodules with a rounded, blobby appearance in plan view. Nodules are 0.5 to 2 cm thick and up to about 10 cm long. In lithofacies H5, chert occurs both at bedding contacts and within beds. It is present as either isolated, oblate nodules 1 to 10 cm thick and 3 to 30 cm long. The larger

nodules may coalesce to form banded chert. In both lithofacies, the concretions are non-displacive (i.e., sedimentary fabrics are neither compacted around nor pushed aside by the concretion), suggesting that their formation occurred after compaction and/or cementation.

Silica-dolomite concretions

Ellipsoid to irregularly-shaped, 3-20 cm long nodules composed of chert, chalcedony, crystalline quartz, dolomite and pyrite are common but rarely abundant in lithofacies H1, H2 and H5. In grainstones (H2), concretions tend to be spherical while in calcisiltites (H5) they tend to be more oblate. The concretions are non-displacive. Relative proportions of quartz, fibrous silica and dolomite are variable. In some locations, the carbonate and pyrite have been dissolved out, leaving a rusty, porous set of “chert envelopes” of bioclasts, some of which are filled by quartz (Fig. 5.3 G). One particularly large concretion, first reported by Salad Hersi (1998), replaces an entire channel of lithofacies H1 cut into lithofacies H5 at the St. Laurent Blvd. outcrop (loc. 23). It is over 80 cm wide 35 cm thick (see Fig. 2.4 B). The nodules are usually concentrated at a discrete stratigraphic level in a given outcrop (e.g., Boul. de Maisonneuve section; loc. 6).

5.1.4 Discussion

In most of the Verulam and Hull lithofacies, the effects of deeper burial diagenesis are more pronounced than those of early burial and sea-floor diagenesis. Lithofacies H4 and H6 are the major exceptions to this rule, with excellent preservation of early cements

and extensive sea-floor grain degradation. Grain degradation is prominent in other lithologies, notably lithofacies H3. As discussed in Chapter Three, the presence of extensively microbored grains suggests deposition under well-lit conditions in still to gently or periodically agitated water in either a warm (e.g. Tudhope & Risk 1985) or temperate (Young & Nelson 1988) setting. In the Verulam Formation, the presence of micritized grains (e.g., irregular peloids) suggests that microboring (or possibly the recrystallization described by Reid *et al.* 1998) was a potentially important process in deeper water. Zeff & Perkins (1979) have reported heavily microbored and completely micritized grains at hundreds of metres of water depth on the Bahamian slope. Alternately, the presence of irregular peloids in the Verulam Formation may demonstrate transport from other depositional facies (as the “exotic particles” discussed in section 3.2.1). The homogenous peloids are still problematic in that they may represent fecal pellets or microbored grains (see Chapter 2).

Despite the field evidence for early marine lithification in the Verulam Formation (i.e., macrobored hardgrounds), there is relatively little reliable petrographic evidence. Fringing cements are not notably well-developed within such beds and the calcareous silt matrix in lithofacies V3 and V4 may contain large quantities of cement that are not easily distinguished from the small detrital carbonate particles. Further complexity arises, however, if some unknown portion of the calcareous silt is cement or internal sediment (Reid *et al.* 1992). Borings on the ferromanganese oxide-stained hardgrounds truncate bioclasts (Fig. 2.6 C), but cannot be proven to truncate obvious cement fabrics. This is

partly due to a lack of distinguishable cement (i.e., the calcareous silt vs. microspar), and partly an effect of pressure solution and dolomitization of the boring (5.3 G).

The common association between normal textural gradation and upwards increased frequency of pressure-dissolution seams (esp. in lithofacies V3 or V4) is most likely a function of an upward increase in clay content. Wanless (1979) has noted that argillaceous carbonates are more susceptible to pressure-dissolution than pure carbonates. Furthermore, he notes that sutured stylolites occur in pure limestones, while smooth, undulatory dissolution seams and microstylolite swarms occur in argillaceous carbonate. All stylolites observed in this study concentrate insoluble residues to some degree. Sutured stylolites tend to be marked by very thin (<10 to ~50µm) clay- or organic-rich seams with scattered quartz grains. Non-sutured seams are usually thicker (up to 1 mm). Within the Verulam Formation, patches or seams of argillaceous material containing abundant, corroded fossils or millimetre-scale limestone “blebs” occur within beds of lithofacies V3. These are interpreted as examples of extreme pressure dissolution and accumulation of insoluble residue. Similar textures have been described by Cantrell & Walker (1985) and Logan & Semeniuk (1976) as “stylobreccias”.

Wanless (1979) also discussed the association of pressure dissolution and dolomitization. In the Verulam Formation, dolomite associated with stylolites appears to be identical to that associated with argillaceous burrow fills (see below).

5.2 Dolomite

Dolomite occurs in several distinct habits in the studied interval. These are: (1) partially dolomitized beds of lithofacies H4 and H6, (2) dolomitized burrow-fills, throughout the Verulam Formation and in lithofacies H3 of the Hull Beds; (3) dolomite crystals concentrated along stylolites; (4) dolomite-silica concretions (see above), and (5) replacive dolomite, restricted to individual particles (see above). The first two of these types were selected for detailed study, because they are volumetrically most important. Burrow- and stylolite-associated dolomites appear to be petrographically similar. Dolomites were examined using standard petrographic techniques, as well as cathodoluminescence (CL) and backscattered electron microscopy (BSE).

BSE images and geochemical data were obtained from four thin sections (see data listed in Appendix 3). One of these, sample AB-30 was of a large dolomitized burrow in the Verulam Formation from the Nepean Point section (loc. 15). The other three thin sections came from the strata exposed at Klock Quarry (loc. 1). KQ-00, a dolomite-free an oolitic packstone, was analyzed to provide data on early calcite cements and micrite. KQ-20 is from lithofacies H6 in the lower dolomitized horizon of the Klock Quarry (see below), while KQ-50 is from lithofacies H4 in the upper dolomitized horizon.

5.2.1 Dolomite in lithofacies H6 and H4

Occurrence and Petrographic Fabrics

In the Hull Beds, dolomite occurs as partial replacement of beds at two horizons in the Klock Quarry (loc. 1) and another at the Highway 17 roadcut (loc. 2) (Fig. 5.4 C-F).

In the lower of the two dolomitized horizons at the Klock Quarry, dolomite has replaced peloidal grainstone of lithofacies H6 (Fig. 5.4 B, C). Replacement is discontinuous and stratiform, and appears to be partially controlled by sedimentary structure (parallel lamination). Dolomite “bodies” may be as thin as one millimetre or up to 5 cm thick, and are a few decimetres to several metres in long (Fig. 5.4 C, E). Burrows penetrating the dolomitized units from an overlying undolomitized bed are commonly filled by undolomitized sediment (Fig. 5.4 D). This suggests that the dolomite or its precursor formed very early in the diagenetic history. The upper dolomite at the Klock Quarry occurs in lithofacies H4 as well as lithofacies H6. In lithofacies H6, the dolomite is identical in habit to the lower horizon, although no limestone-filled burrows were observed. In lithofacies H4, the dolomite is restricted to burrow-tubes. The burrow-confined dolomite observed here is, however, much different than that associated with the Verulam limestones discussed in the next section. The dolomite at the Highway 17 roadcut (loc. 2) occurs in lithofacies H6 and is similar in habit to dolomite in the lower horizon at the Klock Quarry (loc. 1).

Petrographically, the Klock Quarry dolomites consist of an interlocking mosaic of subhedral to euhedral rhombic crystals. Most of the larger crystals have cloudy cores (Fig. 5.4 F). Staining reveals that many of the dolomite rhombs are partly ferroan and the interstitial material in the mosaic is non-ferroan calcite. The true nature of the dolomite-calcite mosaic is best seen with CL and BSE microscopy. A patchy mosaic of euhedral rhombs is revealed by CL microscopy, most of which have only very dull red to almost no luminescence. Many crystals, however, exhibit a vague, complex mottling of very dull- to

dull/medium red CL. In places, concentric zonation in the luminescence appears.

Interstitial calcite between the rhombs is non-luminescent.

BSE images provide the best views of dolomite zonation (Fig. 5.5). Each rhomb typically contains an inclusion-rich phase with a medium- to dark-grey backscatter shade and a relatively inclusion-poor phase with a darker-grey backscatter shade (Fig. 5.5 A-D). An inclusion-free, narrow, discontinuous rim with a pale grey backscatter shade is commonly developed on the outermost edge of many rhombs (Fig. 5.5 B, C, D). The dark- and medium grey backscattering phases are typically observed as a complex mottled and interfingering pattern. The medium-grey dolomite is usually dominant in the middle of the rhomb, while the darker grey is best preserved along the straight edges. Areas just inboard of the rhomb corners are often the sites of the most intricate interfingering between these two phases.

Interstitial to the rhombic dolomite of the Hull Beds is subhedral to euhedral, cloudy calcite. These calcites appear to be partially replacing the dolomite rhombs (Fig. 5.5 C). Many of the dolomite rhombs contain rounded, equant to subequant inclusions of calcite ranging in width from about 5 to 30 μm (Fig. 5.5 A, D).

Geochemistry

Results of microprobe analysis of the dolomites are listed in Appendix III, table 1. Trace elements (Sr, Mn, Na and Ba) were usually close to or below detection limits. Variations in Ca, Mg and Fe only are interpreted here. A plot of Fe vs. stoichiometry of Klock Quarry dolomite (Fig. 5.6 A) reveals that the three BSE-defined dolomite types

Figure 5.5: Backscattered electron images of dolomite rhombs

A - D: Hull Formation, Klock Quarry (Loc. 1).

A - Irregular zonation between dark- (D) and medium-grey (M) backscattering dolomites. Note 5-15 μ m calcite inclusions (white) within dolomites.

B - Pale-grey backscattering (P) rims on dolomite rhombs. Note essentially concentric zonation in these dolomite crystals (dashed outlines in larger crystal, also visible in smaller crystals below).

C - Rimmed dolomite rhombs with apparently replacive calcite (arrow).

D - Subtle mottling of dark- and medium-grey backscattering dolomite with pale backscattering rims. Note stylolitic contacts between rhombs (centre).

E - F: Verulam Formation, Nepean Point.

E - Dolomite rhombs replaced by calcite. Note intricate interfingering pattern between calcite (pale backscattering shade) and dolomite (darker shade) within each rhomb.

F - Almost completely calcitized dolomite rhombs.

Figure 5.6: Iron content vs. dolomite stoichiometry. A - data from this study. B - comparisons with other Ordovician dolomites. See text for explanation of significance.

correspond to three distinct geochemical groups: the dark-grey backscattering dolomite plots in an area between ~51 and ~53 %CaCO₃ and <5000 ppm iron; the medium-grey backscattering dolomite plots in an ill-defined band, ranging from ~52-59.5 % CaCO₃ and ~1000 to 20000 ppm iron; and the light-shade backscattering dolomite rims plot in a very distinctive, highly calcian (~55-59 %CaCO₃) and ferroan (~23000–40000 ppm iron) field.

Discussion

The dolomite in lithofacies H6 and H4 is the most distinctive of all types in the Hull Beds. Field characteristics of dolostone bands, notably the limestone-filled burrows, in lithofacies H6 (Fig. 5.4 D) suggest very early dolomitization. Although the limestone-filled burrows penetrate dolostone, the crystal mosaic of the dolostone is undisturbed. This implies that dolomite was present in the sediment before bioturbation but that the final, interlocking growth of the dolomite post-dated the bioturbation. Dolomite in lithofacies H4 occurs only in burrows penetrating strata which underlie partly dolomitized beds of H6. The burrows may have acted as a permeable conduit (relative to the micritic matrix) for the dolomitizing fluid. Crystals predate pressure dissolution: fully-formed rhombs are truncated by stylolites at the scale of beds (e.g., along the burrowed dolostone-limestone contact shown in Fig. 5.4 D) and at the scale of grains (Fig. 5.5 D).

The tight grouping of the dark grey backscattering dolomite on the stoichiometry vs. Fe content plot may suggest that they are the result a single, consistent process. The wider range of geochemistry and richness in inclusions in the medium grey dolomite suggest a more chaotic or inconsistent processes, or that they are replacement products of

a chemically variable precursor. The medium grey dolomite appears to have “invaded” fully-formed rhombs of the darker grey dolomite from the corners, and have almost always replaced the cloudy (as seen in thin section) core of the rhomb. This implies that the cores were unstable relative to either or both of the medium- and dark-grey dolomite phases.

In the absence of isotope data, geochemical interpretations are limited, as are comparisons with other data sets. Bein & Sass (1988) noted that dolomites which precipitated from near-normal sea-water are commonly calcian (51-56 % CaCO_3), and have very low sodium contents when compared to dolomite associated with gypsum, anhydrite or relics thereof. The stoichiometry vs. Fe plot of Lower Ordovician supratidal (with very rare silicified evaporite nodules) dolomites of Kupecz & Land (1994) overlaps the dark- and medium-grey phases of this study. Montañez & Read (1992) have reported similar values for supra- and subtidal dolomites from the Lower Ordovician Knox Group of the southern Appalachians. Lumsden & Chimahusky (1980) noted that early dolomite associated with non-evaporated sea-water tend to have stoichiometries between 51 and 52% CaCO_3 , while those not associated with evaporated sea-water are more calcian (54-56% CaCO_3). The lack of evaporite minerals or evidence of their former presence does not preclude early dolomitization by hypersaline brines (Muir *et al.* 1980).

The highly calcian, ferroan dolomite rims (pale grey backscattering) clearly post-date both the medium- and dark-grey phases. Higher iron content may indicate precipitation from more reducing pore fluids, or a simply a greater availability of iron. An apparent negative covariance between stoichiometry and iron content of the pale

backscattering dolomite (Fig. 5.6 A) is disregarded due to the small number of data points (n=5).

Dolomitization model for lithofacies H6 and H4

A model is suggested here to explain the observed field and geochemical attributes of dolomitization of lithofacies H6 and H4 at Klock Quarry (loc. 1) and Highway 17 (loc. 2). The model is schematically shown in Figure 5.7. The peloidal sediment (lithofacies H6) was deposited in a shallow, lagoon-margin environment. Slightly evaporative conditions may have locally prevailed in such an environment, allowing for the precipitation of small (<5 μm), metastable dolomite crystals either in the water column or in the very shallow subsurface (e.g., Carbello *et al.* 1987, Mitchell 1987, Berhens & Land 1982). The result was peloidal grainy sediment with small “seeds” of metastable dolomite (Fig. 5.7 A), which would also be present in underlying burrows. These periods of evaporative, dolomitic deposition were followed by more normal marine conditions, during which the dolomitic sediments were bioturbated and overlying, non-dolomite seeded beds/laminae of lithofacies H6 were deposited (Fig. 5.7 B). This accounts both for the presence of limestone-filled burrows within lithofacies H6 (Fig. 5.4 D) and the alternation of dolomitized and undolomitized bands observed in both the Klock Quarry and Stittsville (Figs. 5.4 C, E). Early-formed dolomite in modern hypersaline environments, however, is often unstable with respect to less saline fluids (Folk & Land 1975). Evaporation-driven circulation of hypersaline pore-waters then allowed for continued growth of dolomite on these early-formed nuclei, now as a more stable phase represented by the dark

1. Deposition of homogenous peloidal grainstone (H6) with metastable, early dolomite "seeds". Very early burial compaction forces grainstone and "seeds" into burrows in underlying micritic bed (H4).

2. Bioturbation of "seeded" bed and deposition of overlying bed of H6. "Unseeded" homogenous peloidal sands forced into new burrows.

3. At some undetermined burial depth, hypersaline brines percolate through bed B. Protodolomite seeds provide nucleation sites for growth of dark-grey backscattering dolomite. NOTE: partial or complete replacement of early, metastable "seeds" may have occurred at this stage.

4. As hypersaline pore fluids change (become more reducing?), the more ferroan, variably stoichiometric medium-grey backscattering dolomite replaces the corners and cores of dolomite rhombs.

5. Overgrowth of partially replaced rhombs by thin, incomplete rims of ferroan, calcian dolomite.

Figure 5.7: Model for the partial dolomitization of lithofacies H4 and H6 as observed at the Klock Quarry (loc. 1) and the Highway 17 roadcut near Stittsville (loc. 2).

backscattering dolomite (Fig. 5.7 C). With continuing burial and accompanying pore-water evolution (probably to a more reducing chemical state as suggested by increased Fe), a more ferroan dolomite phase (medium-grey backscattering) began to replace the previously formed dolomite (Fig. 5.7 D). Either or both of these shallow-burial stage dolomites replaced the early-formed, metastable dolomite core. Replacement or dissolution of early-formed, metastable dolomite from within a more stable, overgrown envelope has been reported by Vahrenkamp & Swart (1994). At some later stage of burial, after the dark- and medium-grey dolomites had both stabilized, they were partially overgrown by the pale-grey phase (Fig. 5.7 E).

5.3.2 Burrow-related dolomite in the Verulam Formation

Occurrence and petrographic fabric

In the Verulam Formation, dolomite is restricted to the inside of burrows and borings and along stylolites seams. Small dolomite rhombs have also been observed in shales. Petrographically, the burrow-related dolomite forms a loosely crystal- or matrix-supported framework with the interstices filled by clay-rich, fine-grained material, most of which appears to be clayey calcareous silt, that commonly appears green in stained thin sections (Fig. 2.5 E). The rhombs are subhedral to euhedral, range in size from 20 to 150 μm and commonly have cloudy cores. The rhombs do not stain well, usually taking on a patchy blue stain (Fig. 5.4 G). CL reveals a complex mottling of very dull red to medium red luminescence in the rhombs, which denotes concentric zonation in some samples, but is typically patchy.

BSE images of the Verulam Formation dolomite reveal a complex fabric of intergrown light- and dark- backscattering material. The darker backscattering material is dolomite, and the lighter material calcite. The rhombs usually have a dolomite core and a calcite rim, with a wide, complex zone of intracrystalline interfingering (Fig. 5.5 E, F). Many of the rhombs contain much more calcite than dolomite (Fig. 5.5 F).

Geochemistry

Geochemical data are listed in Appendix III, Table 1. The Verulam Formation burrow-related dolomite is typically ferroan (~25000 ppm Fe) and moderately to highly calcian (53 to 59% CaCO₃; Fig. 5.6 A). Other trace elements (Sr, Ba, Na) are depleted. Manganese is slightly enriched compared to the interpreted early dolomites from the Klock Quarry. The calcites replacing the dolomite contain little iron (<4000 ppm).

Discussion

Dolomitized burrows have been reported from many Paleozoic carbonate successions. Morrow (1978) suggested that burrows act as conduits for dolomitizing fluids in early- and well-cemented limestones during burial diagenesis.

The geochemistry of the Verulam Formation burrow dolomites closely resembles that of the late-stage overgrowths in the Klock Quarry (Fig. 5.6 , Appendix III, Table 1). It is possible that they are contemporary phenomena, forming as the Hull and Verulam reached similar depths of burial and were affected by similar fluids.

5.3 Shale geochemistry

5.3.1 Data set

Material

Ten shale samples were analyzed by X-ray fluorescence (XRF) for SiO₂, Al₂O₃, CaO, MgO, Na₂O, K₂O, Fe₂O₃, MnO, TiO₂, P₂O₅, Cr₂O₃ and L.O.I. (Appendix III, Table 2). Additional data was acquired by XRF spectroscopy for trace elements Cr, Ni and Nb (Appendix III, Table 3). Samples were analyzed from the Bobcaygeon Formation (n=3), the Hull Beds (n=1) and the Verulam Formation (n=6). The Hull Beds sample is the bed interpreted by Kolata *et al.* (1996) as a K-bentonite. As with the microprobe analysis discussed above, interpretations based on so few data may only be used to make broad comparisons.

Results

Ti, Cr, Ni and Nb are useful in provenance studies of calcareous shales since they are immobile during diagenesis (see Andersen 1995 and references therein) and essentially incompatible with carbonate minerals. In provenance studies, the abundances of and ratio between Cr and Ni may be used to estimate the importance of ultramafics in the source area (e.g., Garver *et al.* 1996). Ti is also generally associated with mafic and ultramafic source rocks, while Nb is much more abundant in felsic rocks (Krauskopf 1979, Faure 1986). Andersen (1995) uses the quantity:

$$\frac{\sqrt[3]{(Cr \cdot Ni \cdot Ti)}}{Nb}$$

to represent a mafic to felsic ratio (MFR). Andersen noted that this quantity ranged from ~3 to ~12 in the Blountian foreland basin, and from ~6 to ~37 in the Taconic basin, implying that ophiolitic material was present in the source area for the Taconic basin, but not the Blountian flyshe. The MFRs derived from the data of this study range from zero to ~13.8, suggesting a dominantly felsic source. A cross-plot of MFR and Si/Al was employed by Andersen (1995) to demonstrate the presence of mixed felsic and mafic/ultramafic sources in the Taconic foreland flyshe. All of the points used in this study fit within the lower left portion of Andersen's (1995) plot, again suggesting a dominantly felsic source (Fig. 5.8). The provenance of the siliciclastic material in the Upper Ottawa Group, which was deposited on the margins of the Taconic foreland basin, was most likely the granitic and gneissic rocks of the Grenville Province of the Canadian Shield. These rocks form the basement to the Cambrian-Ordovician basins in eastern Canada, and are currently exposed in the area surrounding the Ottawa Embayment. As discussed in Chapter One, the Adirondack Dome is the only feature known to have been emergent during the late Ordovician (Kay 1942, Titus 1986). The presence of significant quantities of felsic-derived clay and quartz on the far side of the Ottawa Embayment from the Adirondacks may imply contemporary basement exposure elsewhere, perhaps on the northern margin of the basin.

Few distinct trends were noted in various cross-plots made of geochemical data. The most convincing trends observed are between Cr/Nb and Ni/Nb when plotted against Ti/Nb (Fig. 5.9). Nb was chosen as a normalizing denominator, since it is "felsic" relative to the "mafic" Cr, Ni and Ti. In both instances, a well-fitted trendline plots through Verulam data, which approaches the K-bentonite from the Hull (even though this data

Figure 5.8: Cross-plots of mafic:felsic ratio vs. silicon to aluminum ratio for shales from the Bobcaygeon, Hull and Verulam Formations. A - Data from this study. B - Data from the Taconic and Blountian foreland basins from Andersen 1995.

Figure 5.9: Cross-plots of Ni/Nb and Cr/Nb vs. Ti/Nb in shales from the Upper Ottawa Group. Note that data points from the Bobcaygeon Formation shales typically lie well off the regression line, while the K-bentonite from the Hull beds falls close to it. **NOTE: Only the Verulam Formation data were used in the regression calculation for the trend-lines.**

point was not included in the regression calculation). The three Bobcaygeon data do not match the trend of the Verulam shales, and were left out of the regression analysis and plotted separately on these graphs. This may reflect their subtly different mineralogy (i.e., more abundant chlorite). Moreover, these results suggest that Cr, Ni and Ti likely have a common provenance. It is presumed that they are adsorbed onto clay particles.

Chapter Six: SUMMARY, IMPLICATIONS AND CONCLUSIONS

6.1 Summary of observations and interpretations

6.1.1 Lithofacies and depositional environments

Hull Beds

The Hull Beds contains six lithofacies, which represent sub-environments in three environmental lithofacies associations (Table 6.1) within a bioclastic barrier and lagoon system. Lagoon sub-environments include marginal, peloidal (pellet?) sands (lithofacies H6), muddy lagoon floor (lithofacies H4) and sandy or gravely washover fans (lithofacies H1 & H2). The barrier-top environments include a protected, back-barrier silt flat (lithofacies H5); gravely- to sandy beach and upper shoreface (lithofacies H1 & H2); and, sand- or gravel-filled channels (lithofacies H1 & H2) of either tidal or storm-overwash origin. The barrier-front environments are divided into a fairweather-wave dominated upper shoreface (lithofacies H2) and a storm-dominated lower shoreface (lithofacies H2 & H3).

Verulam Formation

The Verulam Formation contains five lithofacies, V1-V5, which are interpreted as a single lithofacies association representing storm-dominated deposition on a carbonate ramp. Lithofacies V1 through V4 represent various types of storm deposits (Table 6.2), and V5 represents interstorm fairweather deposition of mixed calcareous and argillaceous silt- and clay-sized sediment. Sedimentation was episodic and net accumulation was

probably low, as suggested by common ferromanganese oxide-stained hardgrounds and pervasive bioturbation of interstorm shale.

Lithofacies	Association	Sub-environment
H6	Lagoon	Lagoon-margin sand accumulations
H4	Lagoon	Muddy lagoon floor
H1 & H2 (large lenses)	Lagoon	Washover fans
H5	Barrier-top	Back-barrier silt flats
H1 & H2	Barrier-top	Gravelly to sandy beach/upper shoreface
H1 (Channels)	Barrier-top	Washover (or possibly tidal?) channels
H2	Barrier-front	Upper shoreface
H3	Barrier-front	Lower shoreface

Table 6.1 Summary of environments and sub-environments of the Hull Beds lithofacies.

Facies	Particles	Grain size, texture	Sed. structures	Interpretation
V1	Intraclasts, bioclasts	•Cobble to coarse sand •Poorly-sorted rudstone	Basal scour, channelized beds, imbrication of clasts	Proximal tempestite
V2	Bioclasts, intraclasts	•Gravel to medium sand •Well-sorted grainstone	Basal scour, normal gradation, large ripples	Reworked tempestite
V3	Bioclasts, calcareous silt, intraclasts	•Course to fine sand •Mod. to poorly sorted grainstone to packstone	Sharp base, normal gradation, discontinuous bedding, planar & wavy parallel lamination, cross lamination, HCS-like lamination, small ripples	Proximal to distal tempestite, depending on texture/grain size
V4	Calcareous silt, bioclasts	•Silt to very fine sand •Well-sorted, grainstone-packstone-calcisiltite	Sharp base, weak normal gradation, HCS, wavy- and planar- parallel lamination, rare cross lamination and small ripples	Distal tempestite
V5	Calcareous silt, clays and quartz silt	•Clay to silt, sparse sand- to gravel-sized bioclasts •Calcareous shale	Millimetre-scale laminations; carbonate-cemented, mostly horizontal burrow-tubes	Interstorm hemipelagic deposits

Table 6.2: Lithological characteristics and depositional interpretation of the Verulam Formation lithofacies.

6.1.2 Lateral and vertical trends

Hull Beds

The three lithosomes defined in Chapter Four interfinger with one another in the Stittsville-Aylmer-Ottawa area (Fig. 4.4). The lagoon lithosome is restricted to the western parts of the study area, and interfingers with the barrier-top lithosome between Stittsville and downtown Ottawa. The barrier-top lithosome, in turn, interfingers with the barrier-front lithosome between downtown Ottawa and the Orleans-Blackburn Hamlet area to the southeast. Finally, the barrier-front lithosome interfingers with lithologies of the Upper Bobcaygeon Formation between Orleans and Russell. This lateral change in depositional facies appears to occur within an approximately equal stratigraphic thickness (~30-35 m) between Aylmer and Russell. The vertical interfingering shown in Figure 4.4 is highly interpretive due to the limited availability of outcrop and core.

Verulam Formation

The Verulam Formation lacks obvious of marker beds or other laterally correlatable features. Proximality trends defined for the thickest available exposure revealed no convincing stratigraphic trend. Two qualitative observations should be mentioned: first, there is an overall increase in bioturbation upsection; and, second, the Verulam Formation grades into the Lindsay Formation by interfingering of lithofacies. This suggests that depositional environments represented by the Verulam and Lindsay Formations are similar. The Verulam Formation represents a storm-dominated depositional setting in which sedimentation outpaced bioturbation, whereas the Lindsay

Formation represents an environment in which biological reworking was the more rapid and, thus, the dominant process. A second possible interpretation is that early lithification of calcareous beds in the Verulam deposits precluded burrowing, and that bioturbation prevailed in the Lindsay Formation as the rate of early lithification decreased.

The Hull-Verulam relationship

The Hull Beds are conformably overlain by the Verulam Formation in the Ottawa area. This contact is interpreted to be a significant marine flooding surface. The Hull Beds interfinger with the upper Bobcaygeon Formation to the east and southeast of Ottawa.

6.1.3 Depositional model

Paleogeography

The paleogeography of the Ottawa Embayment during Bobcaygeon-Hull time is broadly reconstructed in part from the distribution of Hull lithosomes and paleocurrent data (see Fig. 4.7). Paleocurrents in both the Verulam Formation and Hull Beds suggest a northeast-southwest trending belt of barrier facies. The ramp sloped to the southeast, away from the shield and deepening towards the Appalachian foreland basin. This is supported by the restriction of the lagoonal facies to the northwestern part of the study area and the interfingering of the barrier-front facies with the apparent offshore facies of the Bobcaygeon Formation. It is possible that the five-metre-thick grainstone body at the top of the L'Original Quarry represents a finger of the barrier-front lithosome that

extended southeast from a portion of the barrier that lay on what is now the Gatineau Hills.

Depositional history

The history of sea-level fluctuation and resulting stratigraphy of the Upper Ottawa Group is reconstructed based on the interpretations of depositional environment and stratigraphy presented in Chapters Three and Four. For the following discussion, the correlations shown in Figure 4.4 are taken as the correct stratigraphic model. The depositional history of the Upper Ottawa Group in the study area is summarized as follows:

- (1) Deposition of the Bobcaygeon Formation occurred on a southeast-sloping, open-marine, storm-dominated carbonate ramp (Salad Hersi, 1998; Kiernan *et al.* 1998).
- (2) A relative sea-level fall in the study area resulted in erosion (and local subaerial exposure?) of the ramp forming the basal scour of the Hull Beds in the western part of the study area. This regressive surface may also be represented by the prominent scours observed within Bobcaygeon strata in the L'Orignal and Plumadore Quarries (locs. 35 and 36).
- (3) Northeast-southwest trending, parallel belts of barrier and lagoon facies developed in the western part of the study area. Whether this represents a seaward shift in pre-existing facies, or a change in general depositional style is not known.
- (4) Small-scale progradation and backstepping of the various sub-environments of the barrier facies belts. This resulted in interfingering lithosomes. Throughout the

depositional history, the barrier and lagoon facies belts appear to have remained relatively stationary. Lagoonal deposits aggreed in the Stittsville-Aymler-eastern Ottawa area, while barrier-top sediments accumulated in central Ottawa-Hull and barrier-front sediments accumulated in eastern Ottawa, probably grading downramp into offshore facies of the Bobcaygeon Formation.

(5) A major flooding event occurred, represented by deposition of Verulam Formation lithologies across the study area. Whether the depositional facies of the Hull Beds and Bobcaygeon Formation were re-established farther inboard on the craton is not known.

(6) Accumulation of storm and interstorm deposits (Verulam Formation) continued on a southeast-sloping, open marine carbonate ramp.

(7) Slow rise in sea-level or change in some other environmental condition allowed bioturbation to outpace sedimentation, and Lindsay Formation lithologies replaced those of the Verulam Formation.

6.2 Implications

6.2.1 Regional geologic history of the St. Lawrence Platform

Sea-level history

The presence of a preserved (coastal?) barrier-and-lagoon depositional system in the Trentonian succession of the Ottawa Embayment has certain implications for interpretation of the region's sea-level history. As noted above, preliminary studies of the Bobcaygeon Formation in eastern Ontario (and equivalent units in adjacent areas) suggest deposition on an open-marine, storm-dominated, and possibly temperate, ramp setting

(Salad Hersi 1998, Kiernan *et al.* 1998, Lavoie 1995, Brookfield & Brett 1988). The onset of Hull deposition must, therefore, represent a relative sea-level drop within the Ottawa Embayment. The overall aggradational, as opposed to progradational or retrogradational, nature of the Hull Beds suggests that lowstand conditions existed long enough for ~30 m of barrier and lagoon sediments to accumulate. Similar deposits have been described by Lavoie (1992, 1995) from the equivalent Deschambault Formation of southern Quebec. If these represent stratigraphically and paleogeographically localized lowstand systems of demonstrably similar age as the Hull Beds, then the drop in RSL was regional across the St. Lawrence Platform. Otherwise, change in RSL may be due to differential tectonism within the embayment itself. The Embayment was tectonically active as early as Canadian (early to middle Ordovician) time (Dix *et al.* 1998; Dix & Molgat 1998).

Tectonostratigraphy

The bounding structural features of the Ottawa Embayment (the Laurentian, Frontenac and Beauharnois arches and the Adirondack dome; Fig. 1.4) are expressed today as Precambrian exposures or, in the case of the Beauharnois Arch, by stratigraphic thinning of units (Salad Hersi *et al.* 1998). The Blackriveran Pamela Formation, in particular, thins over the Beauharnois Arch. This suggests that it was in a state of uplift or was undergoing relatively slow subsidence during the early Blackriveran. The Bobcaygeon-equivalent Deschambault Formation of southern Quebec (Lavoie 1992, 1995) also thins over the arch: the Deschambault is less than 10 m thick in the Montreal

area, and thickens to over 60 m in the Quebec City area (Lavioe 1992). More detailed correlations between eastern Ontario and southern Quebec are required to confirm whether or not this implies an episode of uplift or reduced subsidence over the Beauharnois Arch during late Trentonian times.

According to Kay (1942), both the Frontenac Arch and the Gatineau Highlands were submerged during the late Ordovician. Kay's interpretation is certainly supported by the very narrow Precambrian exposure along the axis of the Arch in the Kingston region. If the upper 5 m of the L'Orignal Quarry represents a seaward extension of the barrier-front environment from the general northeast-trending barrier system, then the barrier-top and lagoon environments likely existed within a few tens of kilometres to the north or northwest of L'Orignal. This supports Kay's (1942) suggestion that the Gatineau Hills are the product of a post-Ordovician uplift.

The Frontenac Arch represents a prominent divide in the regional geology of the St. Lawrence Platform, whether it represents a paleogeographic isthmus or not. With the exception of a thin succession of Cambrian siliciclastics, no strata older than the Shadow Lake Formation (earliest Blackriveran) exist on the St. Lawrence Platform west of the arch; both the Canadian (Lower Ordovician) and Chazy (Middle Ordovician) successions are absent (Sanford 1993). East of the Arch, in the Ottawa Embayment, the combined thickness of the Canadian and Chazy strata (Beekmantown and Chazy groups) is over 200 m. (Williams 1991, Bernstein 1992). In the Upper Ordovician succession, difficulty has arisen in applying stratigraphic nomenclature developed in central Ontario (Liberty 1955 and 1969, Armstrong 1997) to the equivalent strata in

eastern Ontario (see Chapter One; Dix *et al.* 1997a, Salad Hersi 1998). This is especially true of *strata below the Bobcaygeon-Verulam boundary* (Fig. 6.1). The Verulam and Lindsay formations are almost lithologically identical in eastern and central Ontario, but the Blackriveran strata and, to a degree, the Bobcaygeon Formation are significantly different (Salad Hersi 1998). Interestingly, the upper Trenton Group of southern Quebec is of rather different character than the Verulam and Lindsay Formations of Ontario (Lavioe *et al.* 1998, personal observation); for example, it is muddier, less fossiliferous and the individual formations are thicker. This suggests that prior to the flooding event represented by the base of the Verulam Formation, the Ottawa Embayment was effectively an extension of the Quebec basin. After the flooding event, the Ottawa Embayment had greater affinity to central Ontario. The Bobcaygeon Formation in eastern Ontario shares lithological characteristics with both its namesake in central Ontario and the equivalent Deschambault strata in southern Quebec (e.g., the presence of bryozoan-rich shales), and may represent an intermediate in this transition from a “Quebec-style” to “central Ontario-style” basin (Fig. 6.1).

The change in depositional style occurring at the base of the Verulam Formation may be the result of either relatively local tectonism, or larger-scale foreland basinal processes. The observed change may be the result of a reactivation of the Beauharnois Arch in southern Quebec (as suggested by the thinning of the Deschambault Formation around Montreal) at a time when the Frontenac Arch was relatively inactive. Lavioe (1994) has described the east- to west diachronaity of collapse of the St. Lawrence Platform as the Taconic foredeep migrated inboard in the late Ordovician. The early

Figure 6.1: Schematic tectonostratigraphy of the central St. Lawrence Platform.

NOTE: these diagram is not meant to imply present stratigraphic continuity of units across major structural features (Frontenac and Beauharnois arches). The general succession of lithologies in the Ottawa area (see Dix *et al.* 1997a,b, Williams 1991, Bernstein 1991) is similar to that in southern Quebec (see Lavoie *et al.* 1998, Bernstien 1991), but markedly different from the succession in central Ontario (see Armstrong 1997, Melchin *et al.* 1994). The Bobcaygeon Formation (marked in grey) of the Ottawa Embayment (1) shares lithological characteristics with its namesake in the Lake Simcoe area (2) , and with the equivalent Deschambault Formation (3; Lavoie 1995) of southern Quebec. Above the Bobcaygeon Formation, the remainder of the Upper Ordovician succession in the Ottawa Embayment more closely resembles the equivalent Upper Simcoe Group in central Ontario rather than the Trenton Group of southern Quebec. Thus the Bobcaygeon Formation appears to represent the transition from a “Quebec” style basin (“b”) to an “Ontario” style basin (“a”).

effects of tectonic collapse may have been manifested by this change in depositional style in the late Trentonian.

6.2.2 Ordovician paleoenvironments

Brookfield (1988) and Lavoie (1995) suggested a cool-water depositional setting for Trenton Group-equivalent rocks in areas adjacent to the Ottawa Embayment. Other workers (e.g., Pope & Read 1997, Patzkowsky & Holland 1992) have noted a switch from tropical to temperate styles of carbonate sedimentation in slightly younger rocks in the central Appalachians. While the ideas presented by Brookfield (1988) and Lavoie (1995) are, in general, applicable to the Upper Ottawa Group, they are not readily applied to the Hull stratigraphy. Based on the grain type associations as outlined by various workers (e.g., Pope & Read 1997, Martindale & Boreen 1997, Lavoie 1995, Brookfield 1988), the Upper Ottawa Group appears to contain coëval warm- (lagoon and barrier-top) and cool-water (barrier-front and open ramp) environments of deposition (Kiernan *et al.* 1998; see Fig. 3.6). Their paleogeographic and paleobathymetric arrangement may be comparable to those described from the Mississippian of Western Canada (Martindale & Boreen 1997). The inner portions of the Balearic Ramp (Fornos & Ahr 1996) may provide a good modern analogue, but this region awaits more detailed description. In absence of supporting data for cool-water, the grain type distributions in the Upper Ottawa Group may be also interpreted as the result of differential salinity between inner- and middle- to outer-ramp environments (see section 3.3).

6.3 Conclusions

- 1. The Upper Ottawa Group contains, in ascending order, the Bobcaygeon, Verulam and Lindsay formations. The Hull Beds form the uppermost part of the Bobcaygeon Formation in the Ottawa-Aylmer-Stittsville area. Below the Hull Beds, the Bobcaygeon Formation contains metre-scale bodies of well-sorted, cross-stratified grainstone that may be easily confused with the Hull Beds. The Hull Beds are ~30 m thick and interfinger with the Upper Bobcaygeon to the east and southeast of Ottawa over a similar stratigraphic thickness. The Verulam Formation is ~35 to 40 m thick in the Ottawa area.**
- 2. The Hull Beds were deposited as a set of approximately parallel, northeast-southwest trending lagoon, barrier-top and barrier-front facies belts. The lagoonal deposits are expressed by micritic mudstone to packstone and peloidal grainstone lithologies. The barrier-top environment is expressed as bioclastic, intraclastic and locally oncolitic grainstone to rudstone and backbarrier, low-energy calcareous silt flats. Storm-related washover processes carried coarse-grained sediments across the barrier via channelized barrier breaches and into the lagoon as washover fans. The barrier-front (shoreface) environment is expressed as bioclastic grainstone-packstone. These three environments interfinger with one another with lagoonal facies dominant in the west and disappearing to the east. Barrier-top deposits are most abundant in downtown Ottawa, whereas barrier-front deposits characterize eastern Ottawa.**

3. The Verulam Formation was deposited on a southerly dipping, storm-dominated carbonate ramp. Storm deposits are represented by a range of lithofacies, including intraclastic rudstones, bioclastic grainstone to wackestone and calcisiltite. A variety of storm-generated sedimentary structures are preserved in these beds. Between storms, hardground formation, hemipelagic calcareous shale deposition and bioturbation were the dominant processes.

4. Grain types preserved in most of the Upper Ottawa Group (echinoderms, bryozoans, brachiopods, *Solenopora*, intraclasts, etc.) are suggestive of a temperate-like carbonate depositional style. The lagoon and barrier-top environments of the Hull Beds provide an exception, with grain-types suggestive of tropical style deposition (e.g., ooids, oncoids, colonial corals, sedimentary micrite, etc.). While this suggests that the Hull Beds represent coeval warm- and cool-water environments, it is equally likely that the grain-type distribution reflects slightly brackish conditions on the open ramp.

5. With the exception of grain degradation (via microboring?), and fringing cements occurring in lithofacies H4 and H6, burial diagenetic features (clear blocky spar cements and pressure-dissolution) are more prominent than early diagenetic features. There is, however, abundant field evidence for early lithification (hardgrounds and intraclasts) in both the Hull Beds and Verulam Formation.

6. Dolostone bands in lithofacies H6 (and associated beds of H4) at locs. 1 and 2 may be the result of synsedimentary dolomite “seeding” and subsequent replacement and overgrowth of the early, metastable dolomite.

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Appendix I: Study locations

Appendix I, Table 1: Studied locations. The various G.S.C. Bulletins of A. E. Wilson (see Table 1.2) are referred to collectively in the references column.

Number/Name	Thickness, Units	Easting	Northing	Notes	References
1. Klock Quarry (p. 209)	27 m, Hull Beds	441 500	502 9700	Large Quarry owned by Deschenes Construction. Located at southeast corner of Pink & Klock Roads, north of Aylmer, Quebec	Koaltia et al. 1996
2. Highway 17 Roadcut near Stittsville (p. 212)	10.7 m, Hull Beds	429 100	501 5000	Roadcut on south side of Highway 7, x km west of its junction with Hwy 417	Salad Hersi 1998, Yang 1989
3. Lac des Fees Parkway (p. 1213)	3.8 m, Bobcay.-Hull contact	441 500	502 9700	Roadcut on east side of Lac des Fees Parkway, just north of St. Jean de Bosco, Hull, Quebec	Salad Hersi 1998
4. Pharand & St. Louis (p. 214)	1.5 m, Hull Beds			In small park on southeast corner of Pharand & St. Louis Roads, Hull, Quebec	
5. Baker Park (p. 214)	2.4 m, Verulam Fm	441 500	502 9700	Cut on old railway lines, now a bicycle path. ~300m along the old tracks to the large rail bridge over the Ottawa River	Uyeno 1974
6. Boul. de Maisonneuve (p. 215)	3.9 m, Bobcay.-Hull	442 350	5030020	Roadcut exposed on either side of Boul. de Maisonneuve at the Victoria St. overpass, Hull, Quebec	
7a, b & c. Hull Promontory (7a, 7b - p. 216 7c - p. 217)	Three sections, (a) 3.75 m, (b) 4.9 m (c) 8.95m, all expose Hull Beds.	442 600	502 9250	7a: On south side of bicycle path, immediately east of service road overpass, 300 m from north side of Portage Bridge. 7b: 10 m farther east from 7a, on north side of path 7c: Main promontory - take small dirt path through trees on the south side of the bike path, just across from 7b.	
8. Victoria Island (p. 218)	2.2 m, Verulam Fm	442 100	502 9000	Small road-cut just below middle part of Portage bridge, Ottawa.	Williams 1991, Dix et al. 1997a, Williams & Telford 1986

9. Primrose & Lorne (p. 219)	11 m +, Verulam-Lindsay transition	441 600	502 8150	Cliff section exposed at corner of Primrose & Lorne Aves, Ottawa. Near public staircase.	
10. Lebreton Core (p. 220)	60m +, Bobcay., Hull & Verulam	441 700	502 6750	Core drilled at Lebreton St, just south of Carling Ave, Ottawa. Core stored at GSC facility, Tunney's Pasture, Ottawa	Williams 1991
11. Lebreton Street (p. 225)	7.7 m, Verulam-Lindsay transition	441 750	502 6750	Back of GSC parking lot, Lebreton St. just south of Carling. Located about 30 m west of the Lebreton corehole's wellhead.	Williams 1991
12. Kippewa & Bronson (p. 226)	2.1 m, Verulam Fm	442 000	502 6350	Apartment building entrance, Kippewa Dr., 10m south of Bronson Ave, Ottawa	
13. Behind Supreme Court (p. 227)	5.25 m, Hull Beds	442 500	502 8800	Near drainage pipe adjacent to small bridge on bicycle path along the south bank of the Ottawa River, below the Supreme Court, Ottawa	
14. Behind Parliament (p. 228)	4.8 m, Verulam Fm	443 200	502 8800	~200m east of Loc. 13 on same path. Thickest point in a long, nearly continuous set of cliffs along the path.	
15. Nepean Point (p. 229)	20 m +, Verulam-Lindsay transition	443 500	502 9450	Base of section at River level, below Alexander Bridge, Ottawa.	
16. Lady Jane Grey Dr., behind Royal Mint (p. 232)	4.5 m, Verulam Fm	443 950	502 9850	Lady Jane Grey Dr., Ottawa. Two sections measured - one in eastern parking lot, other ~50 m to the west.	Dix et al. 1997a, A. E. Wilson
17 a & b. Ottawa Rowing Club (p. 233)	Tow sections, both expose the Verulam Formation. 17a - 4.8 m 17b - 1.7 m	444 150	502 9900	Sections on South Bank of Ottawa River, access available via small service road off Lady Jane Grey Dr. 7a: Main section measured at far east portion, 7b: small section ("2nd dock") measured ~200 m further west on the service road itself.	A. E. Wilson
18. Rideau Falls (p. 234)	9m + m, Verulam-Lindsay transition	444 600	503 0350	Measured on west side of Rideau Falls, on small service road behind NRC heating-cooling plant	Salad Hersi 1998
19. Governor's Bay (p. 235)	7.1 m, Hull beds	445 400	503 0850	On east side of Governor's by, across from 24 Sussex Dr. In Rockcliffe Park, Ottawa	A. E. Wilson 1946a, Uyeno 1974

20a, b. Aviation Parkway (p. 236)	Two sections: 20a - 6.3m, Hull beds 20b - 5 m, Hull beds and Lindsay or Verulam?	449 625	50. 2750	On west side of Aviation Parkway ~ 500 m north of Montreal Road, Ottawa. Outcrop is cut by two obvious faults. 20a is the far north portion, 20b is the far south portion. The portion of the outcrop between the two faults was not measured	Salad Hersi 1998, Dix et al. 1997a
21. Quarry Rd. (p. 237)	2 m, Hull beds	449 125	503 3650	Small exposure in townhouse parking lot, north side of Quarry Rd., just west of Brittany Rd.	Salad Hersi 1998
22. Brittany Rd. (p. 238)	3.4 m, Hull beds	448 875	503 3650	Exposed near small staircase on path towards townhouses, south side of Brittany Rd, across from Talbot Rd.	Salad Hersi 1998
23. St. Laurent Blvd (p. 239)	6.4 m, Hull beds	448 850	503 3500	Old quarry face in parking lot of "Brittany Towers" apartment block. East side of St. Laurent Blvd, just south of Brittany Rd.	Salad Hersi 1998, Williams 1991, Derry et al. 1988
24. Montreal Rd. (p. 240)	1.9 m, Bobcaygeon Fm. or Hull beds?	449 100	502 7750	On small service road, just south of Montreal Rd. (small overpass), NRC grounds.	
25. Beechwood Cemetery Quarry (p. 241)	7.1m, Hull beds	448 300	503 2500	Abandoned quarry in centre of Beechwood Cemetery, northeast Ottawa.	Salad Hersi 1998
26. Francon Quarry south (p. 242)	56 m, Bobcaygeon Fm. & Hull beds	456 250	5503 6500	Large quarry owned by Lafarge, Inc. General observations recorded to supplant Salad Hersi's (1998) data.	Salad Hersi 1998, Derry et al. 1988
27. McCarthy Road (p. 243)	15.4 m, Bobcaygeon Fm	446 625	502 4200	Roadcut on west side of McCarthy Rd. just north of intersection with Walkley Rd., Ottawa. Section measured from southmost fault.	Salad Hersi 1998
28. Russel Core (p. 245)	102m + , Bobcay, Hull, Verulan & Lindsay	469 400	501 7600	Core drilled near town of Russel, Ontario. Core stored in GSC facility, Tunney's Pasture, Ottawa	Williams & Telford 1986, Salad Hersi 1998
29. Castor River (p. 251)	4 m + , Verulam Fm	480 500	501 4000	River bank & bed exposure on both sides of the Castor River, ~ 1 km east of Embrun, Ontario. Section measured on north bank.	A. E. Wilson

30. Crysler dam (p. 252)	1.6 m, Bobcaygeon Fm. ?	487 800	500 7150	Riverbank exposure on north shore of Payne River. Near dam on west side of Crysler, Ont.	A. E. Wilson
31. Laflyshe Farm Quarry (no section)	1 m+, Verulam Fm	489 600	500 4700	Flooded Quarry in pasture owned by Sylvaine Laflyshe, on County Rd. 12, between villages of Berwick and Crysler. NO SECTION MEASURED - paleocurrents only.	A. E. Wilson's "Quarry north of Finch"?
32. McLean Quarry (p. 253)	6.5 m, Verulam Fm	491 000	499 5000	Small quarry owned by Blair Construction, Ltd., ~1.5 km southwest of Finch.	A. E. Wilson (Quarry west of Finch); Derry et al. 1988
33. Plumadore Quarry (p. 254)	7.7 m, Bobcaygeon Fm	508 6400	404 5500	Small quarry owned by Blair Construction, Ltd. northwest of Osnabrock Centre, Ontario	Derry et al. 1988
34. St. Isadore Quarry (p. 255)	10 m+, Verulam-Lindsay transition	508 000	502 2000	Small but deep quarry owned by Bertrand Construction, Ltd. Lowest ten metres measured to cover Verulam-Lindsay transition.	Derry et al. 1988
35. Cliftondale Quarry (p. 256)	11.2 m, Bobcaygeon Fm	523 300	504 2350	Small, disused quarry near Vankloek Hill, Ont., owned by Dale & Lorrie Clare.	Derry et al. 1988, Salad Hersi 1998
36. L'Original Quarry (p. 257)	19.4 m, Bobcaygeon Fm.	518 200	504 9450	Large Quarry owned by Bertrand Construction. On north side of Highway 17, ~12 km west of Hawkesbury, Ont.	A. E. Wilson, Derry et al. 1988, Salad Hersi 1998

Appendix II: Stratigraphic Sections

Notes

The legend and sample column shown in Figures II-1 and II-2 respectively apply to most of the sections shown in this appendix. Three of the larger sections (locs. 10, 26 and 28) are shown as simplified columns, and the two cores (locs. 10 and 28) are accompanied by tables. Sections exposing only the Bobcaygeon Formation (locs. 27, 33, 35 and 36) are also shown in a simpler style, but use the symbols shown in Fig. II-1.

Figure II-1 (overleaf): Legend for stratigraphic sections.

Appendix II, Fig. 2: Sample stratigraphic column.

(1) Interbedded fine-grained packstone and shale. Packstone beds average ~3 cm thick. Shale makes up 11-25% of the unit's thickness. Structures present are normal gradation, planar lamination and HCS. Chondrites burrows, brachiopods and echinoderm debris are present. Apparent hardground with *Trypanites* borings at top of unit.

(2) Set of four grainstone beds, decreasing in thickness towards top. Lowest bed is cross laminated with apparent paleoflow direction of 332° . Single, thin shale bed @ 0.35 m. Brachiopods, echinoderms, bryozoans, gastroopods and SVF.

(3) Scour at base cutting into underlying strata. Two beds of bioclastic-intraclastic rudstone separated by an internal scour surface. Broken oncoids present. Upper bed grades to coarse grainstone. Imbricated intraclasts give a paleocurrent direction of 17° .

(4) Planolites-burrowed shale

(5) Interbedded calcisiltite and shale (lowest bed is a normally graded fine-grained packstone). Limestones average 4 cm thick, shale comprises 2-10% of the unit's thickness. Parallel lamination is the only structure. Fossils include trilobites, brachiopods and calcispheres. Horizontal burrows (*Helminthopsis*) at top.

(6) Thick shale with lens of fine-grained packstone.

Figure II-2: Sample Stratigraphic column

Loc. 1:
Klock Quarry
Page 1 of 3

Loc. 1
Part 2 of 3

Loc. 1, Part 3 of 3

Loc. 2: Highway 17
roadcut near Stittsville

Loc. 3:
Lac des Fees
Parkway, Hull

Hull Beds
Bobcaygeon Fm

Loc. 4: Rue Pharand, Hull

Loc. 5: Railway cut in Baker Park, Hull

Locality 6:
Boul. de
Maisonneuve,
Hull

NOTE: Bobcaygeon thickens
toward the western end of
the exposure

Hull Beds
Bobcaygeon
Formation

Loc. 7: Hull Promontory.
 7a - west bike path
 7b - east bike path

Loc. 7: Hull Promontory
7c - cliff section on
Ottawa River

Loc. 9.: Primrose St. and Lorne Ave., Ottawa

Loc. 10: Lebreton Core

Simplified stratigraphic column

m = micritic mudstone, wackestone & packstone
 cs = calcisiltite
 pk-sh = interbedded packstone & shale
 fg = finer grainstone
 cg = courser grainstone

SCALE IN
METRES DEPTH

Appendix 2, Table 1: Stratigraphy of the Lebreton core, 100.7 m to 1.54 m depth.

Depth (ft)	Depth (m)	Description
330' 3"	100.7	* Bobcaygeon-Chaumont Boundary (Osman Salad Hersi, pers. comm.)
330' 3" - 296'	100.7 - 91.8	<ul style="list-style-type: none"> • Sharp/stylolitic base • Alternates between medium- to coarse-grained packstone and fine-grained, nodular packstone/wackestone on a 50 cm scale • Courser beds are 10-30 cm thick, and separated by thin, bryozoan-rich shaley partings • Nodular beds contain 1-3 cm thick bryozoan-rich shales
296' - 277'	91.8 - 84.5	<ul style="list-style-type: none"> • HULL-LIKE GRAINSTONE BODY • Sharp-based • Medium- to coarse-grained, well-sorted grainstone • 5 to 20 cm thick, sharply or stylolite-bounded beds • Sharp-based, 20 cm thick calcisiltite or very fine grainstone @ 89.4 m. • Some of the grainstone beds have 1-2 cm thick, gradational calcisiltite/wackestone caps. • Parallel lamination and cross-lamination occasionally visible • Crinoid, bryozoan and brachiopod fragments, very rare Solenopora.
277' - 228' 6"	84.5 - 67.25	<ul style="list-style-type: none"> • RETURN TO BOBCAYGEON LITHOLOGIES • Thin- to medium-bedded (3-15 cm), fine to coarse-grained packstone and bryozoan-rich shales. Alternation between fine- and coarse-grained packstones common. Shales 0.5 - 1 cm thick. • Bryozoans, crinoids, brachiopods.
228' 6" - 221'	67.25-69.7	<ul style="list-style-type: none"> • As above, with thicker bryozoan-rich shales (up to 5 cm)
221' - 210'	69.7-64.1	<ul style="list-style-type: none"> • Coarse- to very-fine grained grainstone/packstone with thin, wispy fossiliferous shaley partings. Finer beds display nodular fabric • 5 - 20 cm thick limestones, shales <1 cm thick. • Normal gradation common; small Chondrites burrows at top of uppermost bed. • Crinoids, ramose & domal bryozoans, brachiopods and mud- filled molluscan voids (gastropods and pelecypods).
210' - 195' 9"	64.1-59.7	<ul style="list-style-type: none"> • *BASE OF HULL FORMATION • Sharp base • Micritic mudstone-wackestone with shaley partings at bedding planes. • 5-20 cm thick beds, shales <<1 cm • Sparsely fossiliferous, ostracods, pelecypods, ?Tetradium • Single, 19 cm thick, graded (course- to fine-grained) packstone layer with articulated pelecypods @ 62.15 m • Locally moderate to heavy bioturbation; nodular fabric is most prominent where bioturbation is heavy and shales most abundant • Upper metre is bithuminous

195'9" - 194'2"	59.7 - 59.2	<ul style="list-style-type: none"> • Sharp base • 10-15 cm thick, well-sorted medium- to coarse-grained grainstone • Some beds normally graded. • Crinoid, brachiopod and trilobite fragments
194'2" - 192'3"	59.2 - 58.6	<ul style="list-style-type: none"> • Sharp base • Micritic wackestone • Becomes muddier towards top • Tetrarium and pelecypods • Large (8 cm "deep" and 3 cm wide) J-shaped burrow at upper surface, with horizontal tube of similar size. Filled by overlying grainstone.
192'3" - 190'3"	58.6-58	<ul style="list-style-type: none"> • Sharp base • Medium-grained, well-sorted grainstone • 10-20 cm bedded • Crinoids, bryozoans and trilobites
190'3" - 184'1"	58 -56.1	<ul style="list-style-type: none"> • Gradational base • Micritic packstone to wackestone, bedding difficult to distinguish • Pelecypods and rare Tetrarium. Solenopora occurs in one bed @ 57.8. • Dolomite-silica concretion @ 57.5 m
184'1" - 173'6"	56.1 - 53.5	<ul style="list-style-type: none"> • Sharp base • Coarse- to fine-grained grainstone to packstone • Overall fining-upwards sequence • Individual beds normally graded • ** Two ten cm thick beds of coarse-grained, well-sorted quartz arenite @ 55.75m
173'6" - 167'8"	53.5 - 51.1	<ul style="list-style-type: none"> • Sharp base • Micritic mudstone-wackestone with sharp-based interbeds of micritic, coarse- to fine-grained packstone; rare millimetre-scale shaley partings in muddier beds. Rare, 5-10 cm thick crinoidal grainstone beds. Single 3 cm thick, bioturbated shale @ 52.6m • Packstone beds are 10-30cm thick, sharp-based and normally graded • Trilobites, Tetrarium, bryozoans (ramose & domal) and pelecypods abundant. • Mudstone is bithuminous.
167'8" - 165'8"	51.1 - 50.5	<ul style="list-style-type: none"> • Sharp-based, medium- to fine-grained grainstone • Single, normally-graded bed. • Crinoids, pelecypods, bryozoans (domal & ramose), brachiopods and small (<1 cm) mudstone intraclasts
165'8" - 162' 10"	50.5 - 49.7	<ul style="list-style-type: none"> • Gradational base • Micritic packstone-wackestone • Whole to disarticulate pelecypods and gastropods.
162'10" - 157'3"	49.7 - 48	<ul style="list-style-type: none"> • Sharp/stylolitic base • 10-30 cm thick grainstone beds, medium-grained and normally graded. • Some have calcisiltite "caps" up to 8 cm thick
157'3" - 155'3"	48-47.4	<ul style="list-style-type: none"> • Micritic packstone-wackestone • 10-20 cm thick beds, most are normally graded from packstone to wackestone.

155'3" - 146'3"	47.4-44.6	<ul style="list-style-type: none"> • Sharp based • Medium- to coarse-grained grainstone, 15-25 cm thick beds • Coarse- to fine-grained; overall fining up • Crinoids, bryozoans and Solenopora • Rare, small vertical burrows • Topmost, 20 cm-thick bed grades into micritic wackestone (in its upper 12 cm)
146'3" - 130'11"	44.6 - 39.9	<ul style="list-style-type: none"> • Sharp base • 10-25 cm thick, often normally graded beds. • Overall coarsening-upwards, except for topmost bed • Crinoids, bryozoans, Solenopora • Uppermost bed grades from medium grainstone to micritic, packstone-wackestone with abundant pelecypods and gastropods.
130'11" - 128'9"	39.9 - 39.3	<ul style="list-style-type: none"> • Stylolitic base • 10-15 cm bedded, medium-grained grainstone • Crinoids, bryozoans (ramose & domal), pelecypods, brachiopods and Solenopora
128'9" - 128'1"	39.3 - 39.05	<ul style="list-style-type: none"> • Sharp base, single bed • Micritic packstone graded to wackestone
128'1" - 121'10"	39.05 - 37.2	<ul style="list-style-type: none"> • Sharp base • 10-15 cm thick beds of course to medium-grained grainstone, often normally graded to fine grained. • Crinoids, bryozoans and Solenopora • Thin shale @ 37.53m • Uppermost, 10cm-thick bed grades to calcisiltite in its upper 5 cm.
121'10" - 119'11"	37.2 - 36.6	<ul style="list-style-type: none"> • Base is scoured and/or stylotized • Medium-grained, well-sorted grainstone, 10-12 cm bedded.
119'11" - 119'4"	36.6-36.4	<ul style="list-style-type: none"> • Calcisiltite
119'4" - 114'3"	36.4 - 34.85	<ul style="list-style-type: none"> • Sharp, ?scoured base • Lowest bed is 20 cm thick, very coarse-grained grainstone at base, grading to medium-grained grainstone. Remaining beds are medium-course grained and ~10-25 cm thick • Crinoids, bryozoans, brachiopods, Solenopora (up to 2 cm)
114'3" - 113'11"	34.85-34.75	<ul style="list-style-type: none"> • Stylolitic base • Calcisiltite
113'11" - 112'10"	34.75 - 34.4	<ul style="list-style-type: none"> • Sharp, ?scoured base • Single bed. Very course-grained grainstone graded to very fine-grained grainstone. Bryozoans, crinoids, pelecypods. Intraclasts up to 5 cm near base.
112'10" - 111'4"	34.4 - 34	<ul style="list-style-type: none"> • Sharp base • Calcisiltite-(or micritic?) wackestone with medium-grained packstone interbeds. • Pelecypods, ?Tetradium fragments
111'4" - 108'7"	34 - 33.1	<ul style="list-style-type: none"> • Scoured base, well-sorted, course- to fine-grained grainstone. • 5-20 cm bedded • Overall fining-up • Crinoids, bryozoans, pelecypods

108'7" - 98"	33.1 - 29.8	<ul style="list-style-type: none"> • Gradational base • Peculiar calcisiltite, bedding indistinct • Mottled appearance, pale grey, rounded "blobs" surrounded by darker grey material. Apart from colour, lithology of "blobs" is identical to the material in which they are set. • Pale "blobs" appear to have possible burrows or borings on their upper edges expressed as 1-5 mm wide by 5-20 mm deep indents filled by darker grey material. • Pelecypods and gastropods common. • Single 10 cm thick, coarse-grained grainstone interbed @ 30.2m
98" - 5'1'	29.8 - 1.54	<p>BASE OF VERULAM FORMATION</p> <ul style="list-style-type: none"> • Burrowed (Chondrites and Planolites) contact. Burrows extend down into calcisiltite and are filled by lowest Verulam grainstone. • Typical Verulam lithologies: conspicuously graded, fine- to coarse-grained packstones are most abundant, separated by 0.5 to 6 cm thick, Planolites-burrowed shales. Calcisiltites and very fine-grained grainstones common. Intraclastic rudstone does not appear to be present. • Brachiopods, crinoids, bryozoans and molluscs are dominant grain types.

Locality 11: Lebreton Street outcrop, Ottawa

Loc. 12: Kippewa Rd. near Bronson Ave, Ottawa

Loc. 13:
Behind/below
Supreme Court
of Canada Bldg,
Ottawa.

Loc. 15:
Nepean Point
Part 1 of 3

Loc. 15,
Part 2 of 3

Lindsay Formation continues to ~55m

Loc. 15: Nepean Point Part 3 of 3

Loc. 16:
Lady Jane
Grey Drive

Loc. 17: Ottawa Rowing Club

*Note: this bed is one of several steep-sided channels incised into underlying strata at or very near this level. Channels are 10-30 cm deep and 50-110 cm wide. Upper portions of channel-fill beds grade laterally into thinner packstones (levees?)

Loc. 18: West side of Rideau Falls,
behind National Research Council
buildings, Ottawa.

Locality 19: Govenor's Bay, Ottawa

20a

Localities 20a and 20b: Aviation Parkway, Ottawa

Note: about six metres of outcrop lies between the two faults. The rocks exposed there are of similar lithological character to those on either side, but details are obscured by heavy fracturing associated with the faults.

20b

Locality 21: Quarry Rd., Ottawa

Locality 22: Brittany Road, Ottawa

**Loc. 23:
Abandoned Quarry
on St. Laurent Blvd,
near Brittany Road,
Ottawa.**

Note: section is unweathered
and true nature of bedding
difficult to distinguish

NOTE: This section may represent either a part of the Hull Beds or a "Hull-like" grainstone body encased within the Bobcaygeon Formation.

Loc. 26: Francon Quarry (south), Ottawa

After Salad Hersi (1998), supplemented
by personal observations

cs = calcisiltite

g = grainstone

pk-sh = interbedded packstone & shale

Hull - barrier-top lithosome?

Hull - barrier-front lithosome

Bobcaygeon lithologies

Loc. 27:
McCarthy Rd. &
Walkley Rd., Ottawa
 (Bobcaygeon Fm)

Page 1 of 2

Loc. 27:
 McCarthy Rd. &
 Walkley Rd., Ottawa
 (Bobcaygeon Fm)

Page 2 of 2

Loc. 28: Russell Core

Simplified stratigraphic column

m = micritic mudstone, wackestone & grainstone
 cs = calcisiltite
 pk-sh = interbedded packstone & shale
 fg = finer grainstone
 cg = coarser grainstone

Appendix II, Table 2: Stratigraphy of the Russel core (loc. 28), 399.3 m to 348.6m

Unit#	Depth (ft)	Depth (m)	Description
1	1309'3" - 1303'	399.3 - 397.4	<ul style="list-style-type: none"> • 3 - 15 cm thick beds of medium- to very fine-grained, normally graded packstone separated by <1 to 3 cm thick, bryozoan-rich shales • Bedding appears wavy to nodular • Light to moderate bioturbation • Bryozoans (ramose), Crinoids, brachiopods and pelecypods in packstone.
2	1303" - 1295'9"	397.4 - 395.2	<ul style="list-style-type: none"> • Similar to above, but packstone replaced by wackestone
3	1295'9" - 1288'3"	395.2 - 392.9	<ul style="list-style-type: none"> • Similar to unit 1, but thinner shales • Aparent stylonodular fabric • Bryozoans (ramose & domal), Crinoids, brachiopods, trilobites, gastropods and pelecypods • Single, overturned stromatoperoid colony @ 393.83m
4	1288'3" - 1284'4"	392.9 - 391.7	<ul style="list-style-type: none"> • 5 to 15 cm thick beds of medium- to v. fine-grained, normally graded packstone with rare, milimetre-scale shaley partings of apparent stylolitic origin • Even-bedded • Rare 1-2 cm thick, brachiopod-rich shales • Crinoids, brachiopods, domal bryozoans and gastropods
5	1284'4" - 1279'	391.7 - 390.1	<ul style="list-style-type: none"> • Medium- to fine-grained, nodular to wavy-bedded packstone-wackestone. Nodules defined by thin (<1 cm) shaley partings. • Nodules/beds 3 to 12 cm thick • Overall fining up (medium- to fine-grained) • Crinoids, brachiopods, bryozoans (ramose & domal) and trilobites
6	1279' - 1275'9"	390.1 - 389.1	<ul style="list-style-type: none"> • 5 to 20 cm thick beds of course- to medium grained grainstone. Normally graded. • 15 cm thick, graded intraclast - domal bryozoans. rudstone @ 390 m • Sharp- to scoured basal contacts • Crinoids, domal bryozoans, brachiopods and trilobites
7	1275'9" - 1266'7"	389.1 - 386.3	<ul style="list-style-type: none"> • 3 to 15 cm thick beds of bryozoan-rich shale interbedded with 2 to 12 cm thick, course- to fine-grained grainstone/packstone. • Mollusc- and trilobite-rich calcisiltites (2-12 cm thick) also present as interbeds, esp. between 387.9 and 387.3m

8	1266'7" - 1257'9"	386.3 - 383.6	(NB - Base of William's [1991] Upper Bobcaygeon @ 386.3 m) • HULL-LIKE GRAINSTONE BODY • Scoured base • Well-sorted, fine- to course-grained grainstone, some beds show weak normal gradation. • RARE, thin (<0.5cm) shaley partings in lower metre • Beds 10-25 cm thick beds, parallel- and cross-laminated • Coursening- and thickening-up from base to 384.3m; overlying beds are ~10-15 cm, fine-medium grained. • Bryozoans (domal & ramose; domal forms esp. common in uppermost bed of coursening-up set), Crinoids, brachiopods, orthocones, trilobites, very rare Solenopora (at top of coursening-up set)
9	1257'9" - 1252'3"	386.3 - 381.9	• 8 to 15 cm thick beds of course- to fine-grained, normally graded grainstone/packstone separated by thin shales (0.5-2cm). • Thin (2.5cm) quartz-sandy bed @ 382.62 m • Light bioturbation; Skolithos & Chondrites • Crinoids, brachiopods, bryozoans (domal & ramose) and trilobites
10	1252'3" - 1248'	381.9 - 380.6	• 3-20cm thick bedded grainstone/packstone • Course- to fine-grained (most beds are medium), normal gradation common. • A few thin shaley partings (<1 cm) in upper 30 cm. • Crinoids, bryozoans (domal & ramose), pelecypod, trilobites
11	1248' - 1245'6"	380.6 - 379.9	• Scoured base • 10 - 40 cm thick bedded, very coarse to fine-grained, normally graded grainstone. • Brachiopods, Crinoids, bryozoans (ramose) and very rare Solenopora.
12	1245'6" - 1244'5"	379.9 - 379.5	• Calcisilite • Wavy-laminated • laminae draped over/compacted around bioclasts • Pelecypods & brachiopods • 1-3 cm thick grainstone interbeds in upper 20 cm
13	1244'5" - 1240'3"	379.5 - 378.3	• 3-15 cm thick beds of fine- to v. fine-grained, normally graded grainstone. • Thicker beds have "lag" of c-vc bioclasts in lower few cm • Light bioturbation in upper few cm • Bryozoans, brachiopods, Crinoids. Gastropods and pelecypods become abundant towards top
14	1240'3" - 1238'4"	378.3 - 377.7	• As above, with thin shaley partings and no "lags" • Thinner bedded (3-10 cm)
15	1238'4" - 1234'3"	377.7 - 376.4	• 3 to 15 cm thick beds of medium- to very fine-grained grainstone. Most beds separated by thin, bryozoan-rich shales (up to 2cm thick). • Planar and wavy laminated (possible HCS in some of the finer beds)

16	1234'3" - 1231'6"	376.4 - 375.6	<ul style="list-style-type: none"> • 2-5 cm thick, irregular to nodular bedded, fine-grained packstone/grainstone separated by 1-2 cm thick bryozoan-rich shales. • Wavy parallel laminae in upper grainstone beds • Crinoidsoids, bryozoans, brachiopods, gastropods & pelecypods
17	1231'6" - 1230'	375.6 - 375.2	<ul style="list-style-type: none"> • Single, normally graded bed of medium- to v. fine-grained grainstone. Planar laminated base passes upwards into low-angle cross-lamination. • Small, rounded intraclasts of fine packstone • Crinoid, brach, trilobites, pelecypod and gastropod fragments
18	1230' - 1226'4"	375.2 - 374	<ul style="list-style-type: none"> • 2 to 10 cm thick beds of very fine- to medium-grained packstone separated by 0.5 to 2 cm thick, bryozoan- and brachiopod-bearing shales • Overall coarsening- and thickening-upwards • Shale chips, brachiopods & Crinoids fragments in packstones
19	1226'4" - 1224'3"	374 - 373.4	<ul style="list-style-type: none"> • 5-10cm bedded, coarse- to very fine-grained packstone. • Fines up bed-by-bed • Packstones separated by thin (0.5-1cm) shales • Fine packstone intraclasts in lower lower beds
20	1224'3" - 1223'	373.4 - 373.0	<ul style="list-style-type: none"> • POSSIBLE SEISMITE • Contorted medium-grained grainstone with ball-and-pillow structures at base • Apparently contorted, overturned very fine-grained grainstone
21	1223' - 1218'8"	373.0 - 371.7	<ul style="list-style-type: none"> • 2-5 cm bedded, fine-grained grainstones separated by thin shaley partings • Crinoids, bryozoans, brachiopods pelecypod & trilobites
22	1218'8" - 1215'6"	371.7 - 370.7	<ul style="list-style-type: none"> • Very fine- to fine-grainstone • Lowest beds are "marbled" in appearance - ?stylonodular fabric with thin shaley partings in lower half, passing up into ~3-5cm, even beds • Overall coarsening-up • Beds separated by thin shaley partings (<1cm) • Tabular cross-laminae @ 378.05m • Crinoids, brachiopods, bryozoans, trilobites
23	1215'6" - 1213'	370.7- 370	<ul style="list-style-type: none"> • Two thick beds: Lower is 40 cm thick intra- and bioclastic rudstone grading into medium-grained grainstone. and Upper is 30 cm thick very coarse to fine grainstone • Both beds contain bryozoans (ramose & domal), Crinoids, brachiopods and trilobites
24	1213' - 1208'6"	370 - 368.6	<ul style="list-style-type: none"> • 2 to 7 cm thick beds of very fine-grained packstone • Beds separated by thin (<1cm) shales • Rare parallel laminae • Thin (1-2cm) Coarse, bioclastic (brachiopod-rich) grainstones interbedded at some levels

25	1208'6" - 1202'7"	368.6 - 366.8	<ul style="list-style-type: none"> • Medium- to very fine-grained, stylonodular packstone • Arranged in 10-30 cm thick fining-upwards packages; original bedding difficult to distinguish • Nodules/beds separated by thin (<1cm) shaley partings • Bryozoans (domal), Crinoids, brachiopods and rare stromatolites
26	1202'7" - 1192'	366.8 - 363.6	<ul style="list-style-type: none"> • Calcisilite/wackestone, 2 to 10 cm thick beds separated by bryozoan-rich shales (0.5-3 cm thick) • Rare medium/fine grainstone-packstone interbeds (up to 10 cm thick) • Pelecypods, gastropods, bryozoans (domal & ramose), Crinoid stems and rare brachiopods
27	1192' - 1188'	3363.6 - 362.3	<ul style="list-style-type: none"> • 5-10cm beds of fine packstone separated by thin (<1cm) shales • Pyritized fossils, including Crinoids, brachiopods, bryozoans (ramose) and gastropods
28	1188 - 1181	362.3 - 360.2	<ul style="list-style-type: none"> • 5-20 cm bedded, medium- to fine-grained grainstones with thin (<1cm) shaley partings. • Crinoids & brachiopods
29	1181 - 1177'11"	360.2 - 359.3	<ul style="list-style-type: none"> • Two thick beds, ~45 cm each -- HULL-LIKE? • Lower is medium- to fine-grained, normally graded grainstone. Contains very thin, wispy stylolitic seams with mm-scale clay accumulation • Upper is fine-grained, parallel- and cross-laminated • Crinoids, brachiopods
30	1177'11" - 1170	359.3 - 356.9	<ul style="list-style-type: none"> • Interbedded medium- to coarse-grained grainstone/packstone with calcisilite/wackestone. • Grainy packages are 20-50 cm thick, and are composed of 5-25 cm thick, sharp- to scour-based beds with rare, mm-scale shaley partings. Beds normally graded and cross- or parallel laminated. Composed of crinoid & brachiopod debris. Sparsely burrowed tops; burrows may be dolomitized • Calcisilite packages are much thinner (5-15 cm) and shalier. Calcisilites 2-5cm, shales up to 4 cm. Bioturbated. Contain crinoids, pelecypods, gastropods, brachiopods and ramose bryozoans.
31	1170 - 1163'1"	356.9 - 354.7	<ul style="list-style-type: none"> • HULL-LIKE GRAINSTONE; base of Salad Hersi's (1998) Hull Formation • Well-sorted, medium to fine-grained grainstone, dominated by crinoids • 15 to 50 cm thick beds • Parallel and cross-laminated • Beds rarely graded.
32	1163'1" - 1158'6"	354.7 - 353.3	<ul style="list-style-type: none"> • Medium-grained grainstone, sharp to scoured bases, beds 20-30 cm thick interbedded with shales of 1 to 8 cm thickness • Planar- and low-angle lamination • Bryozoans (ramose), crinoids, brachiopods pelecypods and rare Solenopora

33	1158'6" - 1154'9"	353.3 - 352.2	<ul style="list-style-type: none"> • 5-10 cm thick beds of medium to fine-grained grainstone-packstone with thin (0.5 to 2 cm) bryozoan-bearing shales • Overall fining up; very sparse, vertical burrows. • Crinoids, brachiopods, bryozoans.
34	1154'9" - 1150'8"	352.2 - 350.1	<ul style="list-style-type: none"> • Single thick bed of well-sorted, coarse- to medium-grained grainstone. • Normally graded, parallel- and cross-laminated • Possibly a set of three ~20-40 cm thick amalgamated beds. • Brachiopods, crinoids, bryozoans (ramose), trilobites and pelecypods. Rare ~2 cm intraclasts of medium/coarse-grained wackestone.
35	1150'8" - 1148"	350.1 - 350.9	<ul style="list-style-type: none"> • 10-15 cm bedded, medium-grained grainstones with a few thin (~0.5 cm) shaley partings. • Moderately- to well-sorted, parallel laminated. • Crinoids, bryozoans (ramose & domal), brachiopods, trilobites and rare Solenopora
36	1148" - 1142'3"	350.9 - 348.4	<ul style="list-style-type: none"> • 2 -10 cm bedded, coarse- to fine-grained grainstone-packstone with a few shale interbeds (0.5 to 2 cm). • Overall coarsening-up • Very sparse burrows • Crinoids, bryozoans (ramose & domal), brachiopods and rare oncoids(?). A few small intraclasts present.
37	1142'3"	348.4 m	<p>Bobcaygeon-Verulam contact</p> <ul style="list-style-type: none"> • Sharp, non-erosive contact • Position in agreement with both Williams (1991) and Salad Hersi (1998).
38	1142'3" - 1000'2"	348.4 - 308.6	<p>VERULAM FORMATION:</p> <ul style="list-style-type: none"> • Interbedded limestone & shale • Limestones are dominated by 3-10 cm thick, normally graded packstone-grainstone (lithofacies V3) with scattered occurrences of other lithofacies • Most shale beds are lightly to moderately bioturbated, containing 1-4 mm wide, cemented tubes that appear to represent Planolite and Chondrites burrows. • Crinoids, brachiopods, bryozoans (mostly ramose), trilobites, pelecypods, orthocones and gastropods common in limestones • Shales are sparsely to non-fossiliferous (brachiopods, bryozoans); organic fossils present in some of the unbioturbated beds (including conularids, skolecodonts and conchostrachans). • Shales range in thickness from a few mm to 12 cm • Thinner shale partings are more-or-less horizontal
39	1000'2" -	308.6 -	<p>LINDSAY FORMATION:</p> <ul style="list-style-type: none"> • Stylonodular wackestone-packstone • Distinct shale beds very rare • Thin shaley partings inclined up to 50°-60° around nodules • Discrete bioclastic grainstone beds up to 15 cm thick not uncommon. • Brachiopod, crinoid, bryozoan and molluscan fragments common.

Loc. 29: Castor River, East of Embrun

NOTE: A further ~2 metres of section
are exposed as flaggy outcrops for about
500 m upstream. The lower beds are
lithologically similar to those in the lower
part of the main section shown in this graphic log.

Loc. 30: Near dam on South Nation River, Crysler, Ont.

Locality 32: McLean Quarry, Finch, Ontario

Loc. 33: Plumadore Quarry, Osnabrock Centre, Ont. (Bobcaygeon Formation)

Loc. 34: Ste.-Isadore Quarry

NOTE. Quarry exposure continues with ~14 m of Lindsay Formation to approx. 25 m total height

Loc. 35: Clifftondale Quarry (Bobcaygeon Fm)

Continues with similar lithologies to 11.2 m

Loc. 36: L'Original Quarry (Bobcaygeon Fm)

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Loc. 36:
L'Original Quarry
(Bobcaygeon Fm)

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Appendix III: Geochemical data

Table III-1: Electron microprobe results.

Abbreviations: CAL=Calcite, DOL=Dolomite, Fr.C.=Fringing Cement, ME=Micrite Envelope, Clr.Sp.=Clear Spar, Incl.=Inclusion, Interst.=Interstitial, Repl.=replacive (of dolomite), Mtx=Matrix. DARK, MED and LIGHT refer to grey shades of dolomite in backscatter images

Samp.	Min.	DESCRIPTION	Ca	Fe	Mg	Mn	Sr	Ba	Si	Na
KQ-00	CAL	Fr.C. in ME	39622	117	482	15	8	18	42	15
KQ-00	CAL	ME	39022	54	488	0	51	0	154	7
KQ-00	CAL	Clr.Sp. in ME	39515	70	295	23	34	54	0	0
KQ-00	CAL	Fr.C. in ME	39880	8	380	0	0	0	0	7
KQ-00	CAL	Mtx	38658	93	338	23	59	27	140	7
KQ-00	CAL	ME	38343	179	404	8	42	9	762	7
KQ-00	CAL	ME	37679	202	464	23	0	27	818	7
KQ-00	CAL	Fr.C. in ME	39851	194	543	8	0	0	0	7
KQ-20	CAL	Incl. in DOL	39315	93	796	39	59	18	150	0
KQ-20	CAL	Interst. CAL	39487	23	193	23	101	36	112	15
KQ-20	CAL	Fr.C. in ostrocod	38701	23	314	31	25	0	89	7
KQ-20	CAL	Fr.C. in ostrocod	39837	16	78	0	110	0	93	0
KQ-20	CAL	Cl. Sp. in ostroc.	39279	0	452	23	8	0	108	7
KQ-20	CAL	Clr. Sp. in ostroc.	38743	0	452	15	34	9	93	7
KQ-20	DOL	DARK	23971	210	13104	23	25	27	56	0
KQ-20	DOL	MED	22920	412	12670	54	17	0	136	0
KQ-20	DOL	MED	23699	1733	11964	101	25	18	61	7
KQ-20	DOL	MED	22656	1088	12314	108	0	0	140	0
KQ-20	DOL	DARK	24128	202	13014	23	0	0	56	0
KQ-20	DOL	MED	22356	264	12887	15	0	18	210	0
KQ-20	DOL	MED	6811	381	3057	15	0	0	210	15
KQ-20	DOL	MED	23070	342	12736	15	17	0	108	0
KQ-20	DOL	MED	23020	1477	13188	116	25	9	215	15
KQ-20	DOL	LIGHT (rim)	21977	3055	10849	93	0	0	145	0
KQ-20	DOL	LIGHT (rim)	23213	4026	11415	163	17	0	93	7
KQ-20	DOL	DARK	22055	443	12000	54	0	0	215	0
KQ-20	DOL	MED	22227	1376	13665	108	0	0	79	7
KQ-20	DOL	MED	22556	1135	13526	62	25	0	126	0
KQ-20	DOL	MED	20583	871	12181	70	0	0	318	7
KQ-20	DOL	DARK	21419	396	12417	31	0	0	173	7
KQ-20	DOL	MED	22291	1104	11693	39	25	9	131	30

Samp.	Min	DESCRIPTION	Ca	Fe	Mg	Mn	Sr	Ba	Si	Na
KQ-50	CAL	Mtx	40802	16	350	0	25	0	28	22
KQ-50	CAL	Mtx	38722	62	362	0	0	18	1061	0
KQ-50	CAL	Mtx	39980	70	350	39	0	0	271	7
KQ-50	CAL	Fr.C. in ostrocod	41138	0	6	0	110	27	0	15
KQ-50	CAL	Fr.C. in ostrocod	39815	16	271	0	0	18	28	0
KQ-50	CAL	Repl. CAL	41516	39	344	8	0	0	337	15
KQ-50	CAL	Incl. in DOL	40952	16	1055	15	25	0	369	7
KQ-50	CAL	Interst. CAL	40259	295	247	77	8	0	126	0
KQ-50	CAL	Interst. CAL	40244	54	199	8	68	27	89	7
KQ-50	DOL	LIGHT (Rim)	22434	2689	10825	54	0	9	234	7
KQ-50	DOL	DARK	22241	257	12332	46	0	27	42	0
KQ-50	DOL	DARK	22191	350	12573	15	8	0	42	7
KQ-50	DOL	DARK	22641	280	12278	8	25	18	56	15
KQ-50	DOL	LIGHT (rim)	20983	2145	8973	77	0	0	2548	15
KQ-50	DOL	DARK	22613	109	12392	15	0	0	9	0
KQ-50	DOL	MED	24700	155	11259	15	8	0	33	0
KQ-50	DOL	DARK	22749	342	12688	31	0	0	65	15
KQ-50	DOL	MED	22784	109	12447	15	0	0	89	7
KQ-50	DOL	LIGHT (rim)	22420	2425	10499	70	17	0	173	7
AB-30	CAL	Fr.C. in ostrocod	39358	93	302	46	42	0	75	0
AB-30	CAL	Fr.C. in ostrocod	40223	62	428	8	34	18	131	0
AB-30	CAL	Trilobite	40351	78	374	31	76	0	9	0
AB-30	CAL	Repl. CAL	38450	365	543	163	25	0	56	0
AB-30	CAL	Repl. CAL	40430	342	416	248	17	0	51	0
AB-30	CAL	Repl. CAL	41009	342	326	263	25	9	56	7
AB-30	CAL	Repl. CAL	39858	552	1061	248	0	0	47	7
AB-30	CAL	Repl. CAL	43296	257	199	108	8	9	215	7
AB-30	CAL	Brachiopod	38815	54	356	15	127	0	23	148
AB-30	CAL	Brachiopod	39587	86	229	23	85	0	14	89
AB-30	CAL	Brachiopod	38229	47	326	8	110	36	37	134
AB-30	CAL	Repl. CAL	38965	350	446	287	17	0	75	0
AB-30	DOL	DARK-MED	23921	2394	9245	62	42	0	47	7
AB-30	DOL	DARK-MED	23649	2495	9462	85	42	0	47	7
AB-30	DOL	DARK-MED	22198	2814	10131	70	0	0	79	15
AB-30	DOL	DARK-MED	23470	2721	9600	101	51	0	42	7
AB-30	DOL	DARK-MED	22198	2635	10565	70	17	0	112	15
AB-30	DOL	DARK-MED	23299	389	11415	77	42	18	42	30

Table III-1 continued.

Table III-2: Major-element geochemistry of ten shale samples as determined by X-ray fluorescence. Results reported as weight percent oxides. * Sample KQ-1 is the K-bentonite from loc. 1.

Element:	SiO₂	Al₂O₃	CaO	MgO	Na₂O	K₂O	Fe₂O₃
Limit:	0.01	0.01	0.01	0.01	0.01	0.01	0.01
AB-11	42.7	12.6	17.2	2.41	0.13	4.32	3.55
AB-15	37.1	9.29	23.9	2.05	0.15	3.3	3.17
AB-26	17.6	5.29	40.1	1.06	0.08	1.65	1.61
AB-42	36	10.7	23.4	2.09	0.11	3.74	2.9
KQ-1 *	52.5	23.9	2.84	3.78	0.07	7.79	2.03
LOR-11	17.8	6.63	38	1.93	0.18	1.89	1.92
MCL-7	34.3	11.5	19.2	6.06	0.18	3.83	3.55
ORC-D	24.4	6.98	34.2	1.62	0.16	2.02	2.09
PQ-15	14.1	5.26	42.2	1.75	0.11	1.33	1.99
PQ-20	47	16.6	8.67	3.5	0.37	5.16	5.09

Element:	MnO	TiO₂	P₂O₅	Cr₂O₃	LOI	Sum	Formation
Limit:	0.01	0.001	0.01	0.01	0.01	0.01	
AB-11	0.03	0.561	0.16	-0.01	16.5	100.2	Verulam
AB-15	0.03	0.471	0.24	-0.01	20.7	100.4	Verulam
AB-26	0.03	0.227	0.1	-0.01	32.6	100.3	Verulam
AB-42	0.03	0.474	0.09	-0.01	20.4	100	Verulam
KQ-1*	0	0.125	0.02	-0.01	6.75	99.8	Hull Beds
LOR-11	0.05	0.272	0.34	-0.01	31.3	100.3	Bobcay.
MCL-7	0.04	0.63	0.69	0.01	19.9	99.8	Verulam
ORC-D	0.03	0.328	0.13	-0.01	28.7	100.7	Verulam
PQ-15	0.05	0.235	0.32	-0.01	32.9	100.2	Bobcay.
PQ-20	0.03	0.893	1.64	0.02	9.1	98.1	Bobcay.

Table III-2: Trace-element geochemistry of ten shale samples as determined by X-ray fluorescence. Results reported as parts per million. * Sample KQ-1 is the K-bentonite from loc. 1.

Element	Cr	Ni	Nb	Formation
Limit	5 ppm	2 ppm	2 ppm	
AB-11	65	19	9	Verulam
AB-15	64	17	7	Verulam
AB-26	35	6	6	Verulam
AB-42	55	14	7	Verulam
KQ-1*	0	8	21	Hull Beds
LOR-11	42	17	5	Bobcay.
McL-7	91	20	8	Verulam
ORC-D	39	8	3	Verulam
PQ-15	60	16	4	Bobcay.
PQ-20	146	45	12	Bobcay